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Performance of MODIS Collection 6.1 Level 3 aerosol products in spatial-temporal variations over land

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A R T I C L E I N F O

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DT
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DTB

A B S T R A C T

This study evaluates the long-term Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6.1 (C6.1) Level 3 atmospheric aerosol products over land. For this purpose, three monthly aerosol optical depth (AOD) datasets, including Dark Target (DT), Deep Blue (DB) and combined DT and DB (DTB) during 2003–2017, are collected. Aerosol Robotic Network (AERONET) Version 2 Level 2.0 (cloud-screened and quality-assured) monthly measurements at 431 sites around the world are selected for comparison. This study attempts to provide a better understanding of the different MODIS products for their applicability at multiple spatial scales and their suitability for representing the long-term trend of aerosol characteristics. Experiments are performed with direct comparisons between MODIS retrievals and AERONET measurements at global, local to site scales. Meanwhile, the spatial and temporal variations are also compared and discussed. Our results illustrate that C6.1 MODIS AOD retrievals are well correlated with AERONET AOD measurements globally, while the DTB product performs best at most regions, yet the DB product is superior at the site scale. In general, Terra AOD products always overestimate while Aqua AOD products are more accurate in describing the annual mean AOD loadings over land. For long-term aerosol trends, there are small differences between Terra and Aqua aerosol products. Among the three aerosol datasets, neither one can consistently outperform the others in both spatial and temporal aerosol variations over land. In general, DTB products can more accurately capture the correct aerosol changes and are strongly recommended for selection in related aerosol studies at the global scale.

1. Introduction

Atmospheric aerosols are liquid or solid particles suspended in the atmosphere. Aerosols can be absorbers and scatterers of solar and terrestrial radiation and condensation nuclei of water droplets and ice crystals, potentially with great effects on climate change (Li et al., 2011; Wang et al., 2014; Guo et al., 2016, 2017; Ramanathan and Carmichael, 2017; Qin et al., 2018a,b), air quality (Li et al., 2017; Okuda et al., 2014; Sun et al., 2016; Wang et al., 2017) and human health (Pope et al., 2002; Pöschl, 2005). In early records, aerosol measurements were mainly ground-based observations. However, these in situ data have extensive spatiotemporal variability and are not sufficient to represent the aerosol characteristics at large and long-term scales. Since the 1990s, satellite aerosol remote sensing has provided an effective way to overcome these shortcomings of surface measurements.

Long-term series of space-borne aerosol products have been accumulated rapidly in the past few decades, which have inspired various studies on the temporal trends of aerosols and their potential effects (e.g., He et al., 2017; Zhang et al., 2017; Qin et al., 2018a,b). Ramachandran et al. (2012) analyzed aerosol trends in India during 2000–2009 using Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 (C5) Dark Target (DT) products and discussed their relationships with several meteorological factors. He et al. (2016) explored the spatial and temporal AOD variations from 2002 to 2015 in China and analyzed the effects of terrain, Normalized Difference Vegetation Index (NDVI) and socioeconomic indices on aerosols based on Aqua-MODIS C6 DT products. Klingmueller et al. (2016) selected Terra-MODIS C6 combined DT and DB (DTB) products to study the aerosol trends over the Middle East during 2000–2015 and explored the attributions of rainfall levels, soil moisture contents and surface winds to aerosol changes. Mehta et al. (2016) presented spatial and temporal variations in global aerosols during 2001–2014 with Terra-MODIS C5.1 DT products.

Many researchers have tried to explore aerosol-cloud-precipitation

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interactions from a climate perspective. Ten Hoeve et al. (2011) examined the microphysical and radiative effects of aerosols on clouds in the Amazon utilizing Aqua-MODIS C5 DT aerosol and cloud products. Small et al. (2011) applied Aqua-MODIS C5.1 DT aerosol products to study the relationship between aerosol, cloud, and large-scale dynamics over Australia during 2002–2009. Costantino and Bréon (2013) analyzed the aerosol interaction with warm boundary layer clouds over the South-East Atlantic based on Aqua MODIS C5 DT aerosol and cloud parameters. Gryspeerdt et al. (2015) ran the Weather Research and Forecasting (WRF)-chem model with Aqua-MODIS C5.1 DT aerosol and cloud products to study the aerosol interaction with warm boundary layer clouds over the Congo Basin.

In the aforementioned studies, we noticed that different authors selected the aerosol datasets for analysis among various versions and collections of different aerosol products. Some studies chose a satellite dataset without specifying the reason, and some studies simply followed previous studies. However, these aerosol datasets, which were generated from different aerosol retrieval algorithms, could have differences in specific regions (Wei et al., 2018a; He et al., 2018). Meanwhile, there are still non-ignorable differences in spectral response and data imaging time between Terra and Aqua MODIS sensors, which can lead to certain differences in their derived aerosol datasets, especially for local regions (Levy et al., 2013, 2018; Pawan et al., 2018). Therefore, it is important to choose an appropriate product for studying long-term aerosol trends and analyzing the relationships among aerosols, clouds, radiation and climate. Otherwise, the results could be inevitably problematic, or the relationships could be misunderstood.

The main purpose of this study is to comprehensively evaluate the newest MODIS Collection 6.1 Level 3 atmospheric aerosol products to show which aerosol dataset is suitable for studying spatial-temporal aerosol variations at different scales. For this purpose, Terra and Aqua MODIS Level 3 monthly DT, DB and DTB products from 2003 to 2017 over land are collected. Comparisons between MODIS aerosol datasets are performed against Aerosol Robotic Network (AERONET) ground-based measurements. The remainder of this manuscript proceeds as follows: Section 2 provides a description of MODIS aerosol retrieval algorithms. Section 3 presents the matching approaches, and the comparison results in global-/regional-/site-scales, spatial and temporal variations are shown in Section 4. A brief summary is given in Section 5.

2. Datasets

2.1. MODIS Level 3 aerosol products

There are two well-known official aerosol retrieval algorithms, including the Dark Target (DT) algorithm over land and ocean, and Deep Blue (DB) algorithms over land. The DT algorithm was developed to retrieve aerosols over dark-target surfaces, while DB algorithms were mainly designed to overcome the flaws in the DT algorithm over bright surfaces. The latest DT and DB datasets in C6 products are generated based on the second-generation operational DT algorithm (Levy et al., 2007, 2013) and enhanced DB algorithm (Hsu et al., 2013). Moreover, to improve the data coverage, a new combined DT and DB (DTB) dataset is introduced over land according to independent MODIS monthly NDVI products by a simple approach that leverages the strengths of DT and DB algorithms (Levy et al., 2013).

Recently, the MODIS C6.1 aerosol product has been released with several improvements upon the previous C6 products (Wei et al., 2019a, 2019b). Compared to C6 products, the C6.1 DT algorithm has degraded the quality of retrievals to zero if more than 50% of coastal or 20% of water pixels exist in a 10 × 10 km grid over land and revised the surface ratios using the MODIS surface reflectance product for main urban regions (Gupta et al., 2016). The C6.1 DB algorithm has detected heavy smoke, reduced artifacts in heterogeneous terrains, improved surface modeling in elevated terrains, and updated regional or seasonal aerosol models over land. However, there is no change in the combined approach of producing DTB datasets between these two collections (Wei et al., 2019a, 2019b).

MODIS has provided two official aerosol products based on the above algorithms. One is the Level-2 atmosphere daily (swath) product at nominal (nadir) spatial resolutions of 10 km (Mx04_L2, where x = O for Terra and x = Y for Aqua) and 3 km (Mx04_3K), and the other consists of Level-3 daily (Mx08_D3), 8-day (Mx08_E3), and monthly (Mx08_M3) aerosol products at a $1^\circ \times 1^\circ$ horizontal resolution. The latter are spatiotemporally aggregated from Mx04_L2 products (Platnick et al., 2015). Compared with C6 products, the C6.1 monthly product requires valid retrievals from at least three days in a month. In this study, three monthly aerosol datasets (including DT, DB and DTB) at 550 nm with coarse spatial resolutions from the common period 2003–2017 are selected for comparison.

2.2. AERONET ground measurements

Aerosol Robotic Network (AERONET) ground-based measurements were collected for comparison purposes in this study. AERONET has provided long-term freely available observations of abundant aerosol optical properties, in which AOD observations are available in a wide spectral range from visible to near-infrared channels (0.34–1.02 μm) every 15 min and have a low bias of 0.01–0.02 in the absence of any significant thin cirrus cloud contamination (Chew et al., 2011). The AOD data are provided in three data quality levels of (L): L1.0 (unscreened), L1.5 (cloud-screened), and L2.0 (cloud-screened and quality-assured) (Smirnov et al., 2000; Holben et al., 2011). Note that AERONET Version 3 data is in processing and coming soon, which will have the stricter quality control and an improved treatment on cirrus cloud contamination (Giles et al., 2019). Nevertheless, AERONET data are widely recognized as a benchmark for evaluating the satellite retrieval products. Therefore, in the current study, AERONET Version 2 L2.0 monthly AOD data were obtained from the AERONET website, and 431 sites over land (Fig. 1) were selected with a criterion that each site had at least 24 monthly data during 2003–2017.

3. Methodology

In this study, Terra and Aqua C6.1 DT, DB and DTB monthly AOD retrievals (MxD08_M3) are compared against AOD data from 431 AERONET sites over land from 2003 to 2017. The present research focuses on three main aspects, including 1) comparison of monthly AODs between MODIS and AERONET data at global, regional and site scales; 2) comparison of annual mean AOD distributions; and 3) investigation of annual AOD trends.

Three monthly DT, DB and DTB AOD retrievals at 550 nm over land (corrected) were obtained from the MxD08_M3 Scientific Data Set (SDS). The monthly retrievals for diverse aerosol products were defined by centering the pixel on the AERONET site, and the corresponding monthly AERONET AOD measurement was regarded as the true value. However, AERONET does not provide AOD measurements at 550 nm; therefore, 550-nm AOD values were interpolated using the Ångström exponent (α) in 440–675 nm reference to our previous studies (Sun et al., 2015; Wei and Sun, 2017). For MODIS AOD retrievals, the annual mean values were averaged pixel by pixel from all available monthly retrievals, and the annual trends were fitted by the generalized least square method based upon de-seasonalised monthly anomaly of MODIS AOD at 550 nm from 2003 to 2017 over land. For AERONET data, only those sites with more than 5 years (120 monthly values) of observations were selected for comparing the AOD trends.

Moreover, to quantitatively evaluate the quality and uncertainty of the retrievals, we referred to several metrics, including the Pearson product-moment correlation coefficient (R), mean absolute error (MAE), root mean square error (RMSE), relative mean bias (RMB), and expected error (EE = [± (0.05 + 20%)], Levy et al., 2013).

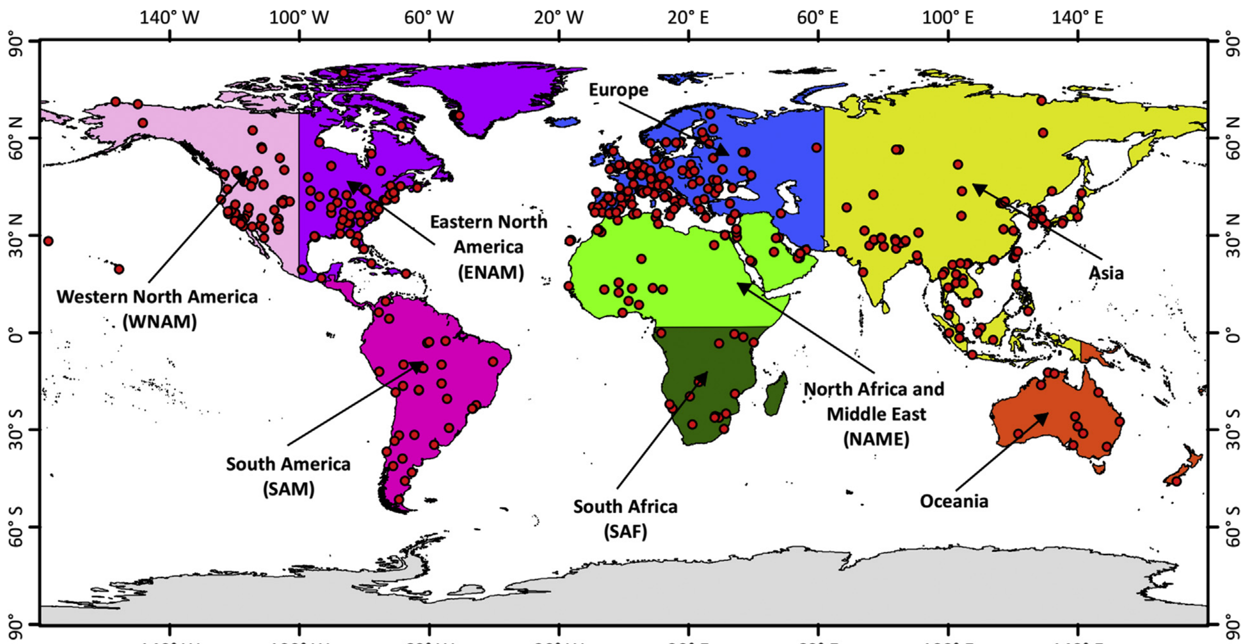

Fig. 1. Geographical bounds of customized regions used in this study. Locations of the AERONET sites are indicated by red dots. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

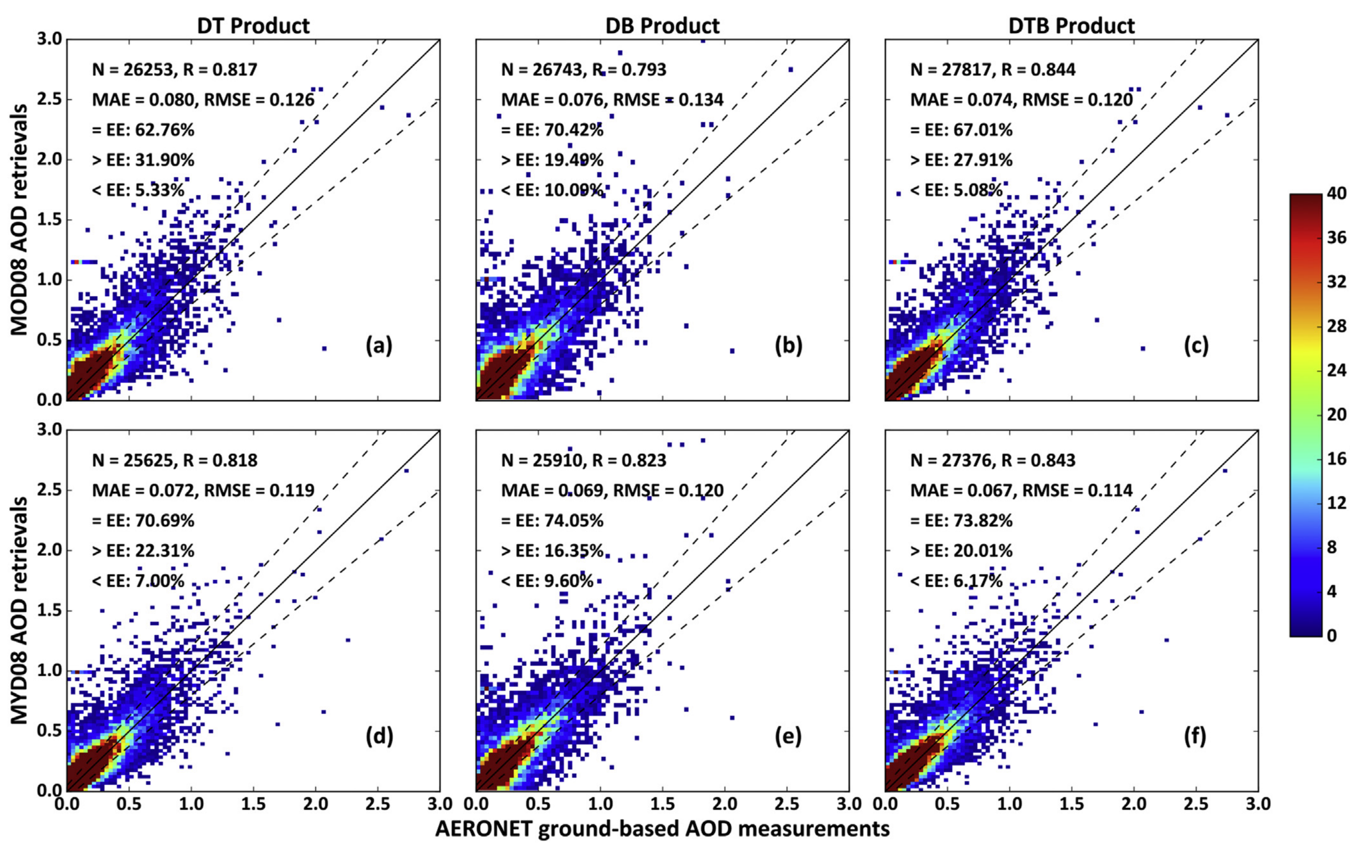

Fig. 2. Density scatterplot of Terra and Aqua MODIS C6.1 DT, DB and DTB monthly AODs retrievals against AERONET monthly AOD measurements over land. Data are from 2003 to 2017. Note. =EE represent the percentages (%) of retrievals falling within, above, and below the EE, respectively.

Table 1
Statistical comparison of concurrent AOD retrievals for Terra and Aqua MODIS monthly AOD products over land. Data are from 2003 to 2017. Note. =EE represent the percentages (%) of retrievals falling within, above, and below the EE, respectively.

Satellite	Product	N	R	RMSE	MAE	RMB	= EE	> EE	< EE
Terra	DT	25332	0.819	0.126	0.081	1.260	62.63	32.13	5.24
Aqua	DT	25332	0.817	0.118	0.071	1.152	70.96	22.04	7.00
Terra	DB	25431	0.811	0.126	0.073	1.084	71.12	18.42	9.86
Aqua	DB	25431	0.826	0.120	0.069	1.058	74.28	16.13	9.59
Terra	DTB	27150	0.844	0.120	0.075	1.221	66.81	28.08	5.10
Aqua	DTB	27150	0.842	0.113	0.067	1.136	74.04	19.79	6.17

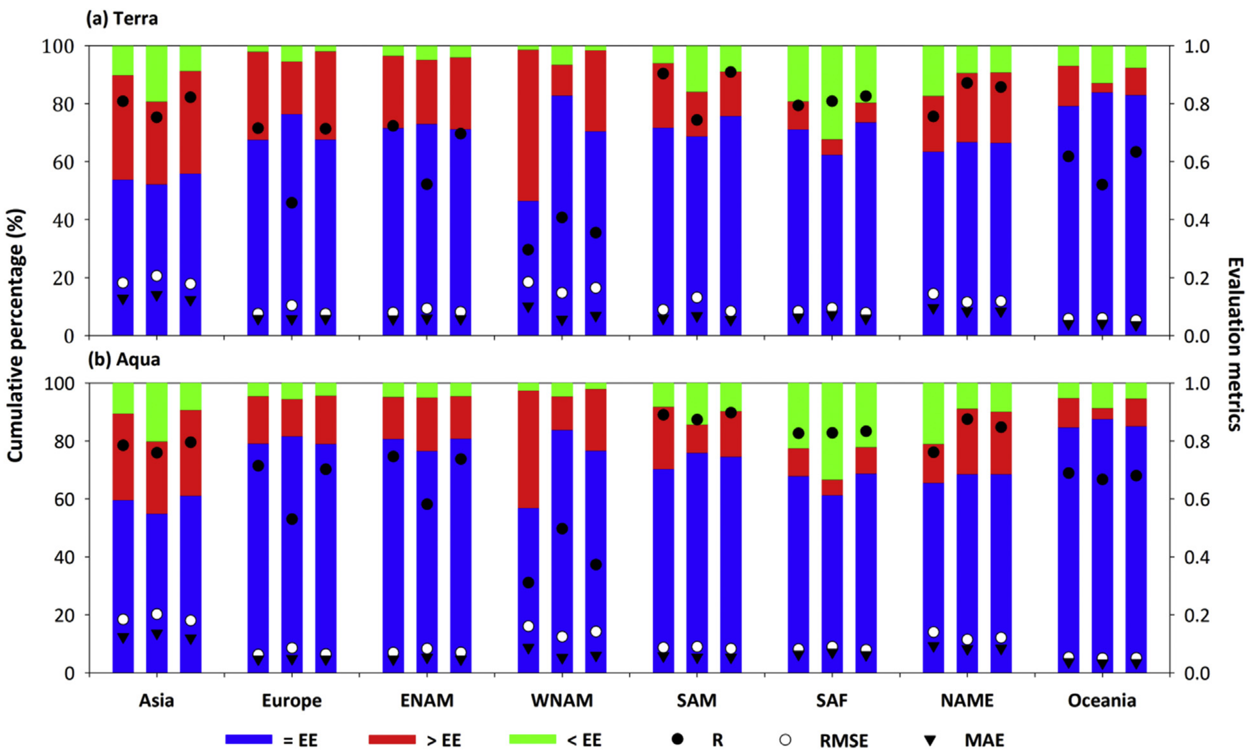

Fig. 3. Cumulative histogram of the percentage of retrievals falling within/above/below EE (= / > / < EE in blue, red and green, respectively) and scatter plots of the evaluation metrics (R, RMSE and MAE, represented with black dots, circles and black triangles, respectively) for Terra (a) and Aqua (b) DT, DB and DTB monthly AOD retrievals (left, middle and right columns, respectively) against AERONET monthly AOD measurements for each region. Data are from 2003 to 2017. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Results and discussion

4.1. Performance of monthly AOD retrievals

4.1.1. Global-scale performance

Fig. 2 shows the overall performance of Terra and Aqua MODIS C6.1 monthly DT, DB and DTB AOD retrievals against AERONET monthly AOD measurements across all 431 sites over land from the common period (2003–2017). We obtained 26253 and 25625 matchups at 425 (out of 431) available sites for Terra and Aqua DT products over land, respectively. The remaining six sites were distributed in arid and desert areas where no retrieval was available for DT products. The Terra and Aqua DT monthly AOD retrievals were highly correlated with AERONET monthly AOD measurements (R = 0.817 and 0.818, respectively). Approximately 62.76% and 70.69% of the Terra and Aqua DT monthly collections, respectively, fell within the EE, with average MAEs of 0.080 and 0.072 and RMSEs of 0.126 and 0.119 for Terra and Aqua satellite-derived products, respectively.

An increasing number of data samples from all selected 431 sites were collected from DB monthly products over land because the DB algorithm negated the shortcomings of the DT algorithm on aerosol retrieval over bright surfaces. The Terra and Aqua DB monthly retrievals exhibited similar good correlations with AERONET AODs (R = 0.793 and 0.823, respectively). Compared to the DT retrievals, the DB retrievals showed higher percentages of retrievals falling within the EE with smaller average MAEs but slightly larger RMSE values.

The DTB monthly products provided the maximum number of data samples and showed the highest correlations with AERONET AOD data among the three datasets at the global scale. Meanwhile, the DTB monthly products showed the lowest estimation uncertainties with the smallest MAE and RMSE values; however, the fractions of DTB matchups within the EE were generally higher compared to DT products but lower compared to DB products.

For statistical significance in the comparison between Terra and Aqua products, the concurrent AOD monthly retrievals were extracted for DT, DB and DTB products and compared against AERONET AODs over land (Table 1). Aqua MODIS monthly DT retrievals exhibited 71% of data samples falling within the EE with an average MAE of 0.071 and an RMSE of 0.118, showing better performance compared to Terra MODIS monthly DT retrievals (approximately 63%, MAE = 0.081, and RMSE = 0.126). Similar conclusions could be obtained from DB and DTB products, where Aqua DB and DTB monthly retrievals showed higher percentages of data samples within the EE with lower average MAE and RMSE values compared to Terra DB and DTB monthly

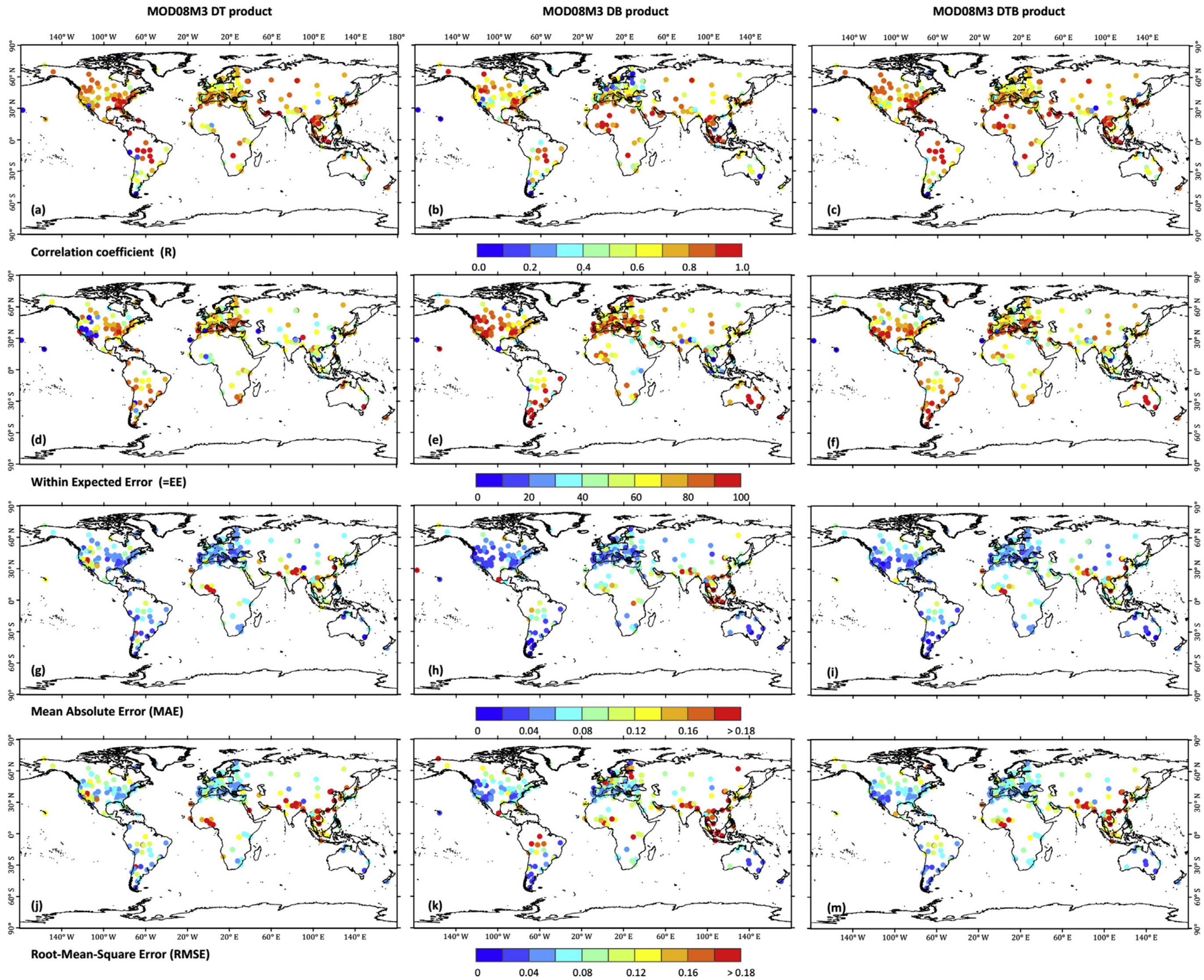

Fig. 4. Comparison between Terra MODIS DT, DB, DTB monthly AOD retrievals and AERONET monthly AODs for each site with respect to (a–c): correlation (R); (d–f) percentage of retrievals within the EE (%); (g–i) MAE and (j–m) RMSE, respectively. Data are from 2003 to 2017.

retrievals. These results suggest that Aqua AOD monthly products were overall superior and less biased compared to Terra over land at the global scale.

4.1.2. Regional-scale performance

Because geographical features, local climates, and human activities are changing over land, different regions have different aerosol characteristics. We consider eight main regions: Asia, Europe, Eastern North America (ENAM), Western North America (WNAM), South America (SAM), North Africa and the Middle East (NAME), Southern Africa (SAF), and Oceania (Fig. 1). Thus, the Terra and Aqua MODIS monthly AOD retrievals were compared against AERONET monthly AOD measurements for each region (Fig. 3).

The DT, DB and DTB aerosol monthly products showed distinctly different performances in different regions; however, for each specific region, the three Terra satellite-derived products performed similarly compared to products derived from the Aqua satellite with close accuracy and estimation uncertainty (Fig. 3). According to the statistics, the number of data samples for the Aqua satellite was generally smaller than that for the Terra satellite, presumably due to more clouds being present in the sky in the afternoon. But the comparison results illustrate that the three MYD08 monthly datasets were generally more accurate compared to the MOD08 datasets, with higher correlations against surface measurements and higher percentages of data samples falling within the EE with lower MAE and RMSE values over most regions, specifically Asia, Europe and North America. These results suggest that the Aqua MODIS products were generally superior to Terra products at the regional scale.

In general, the three datasets showed similarly good performance over Oceania, Eastern North America, South America and Europe, with more than 79%, 71%, 69% and 68%, respectively, of the data samples falling within the EE and relatively low estimation uncertainties. These regions featured typical dark surfaces with wide and dense vegetation and were thus favorable for accurate aerosol retrieval (Wei et al., 2018b). In contrast, all three aerosol datasets exhibited the worst performance over Asia compared to other regions, with less than 62% of the data samples falling within the EE, and RMSE and MAE values greater than 0.12 and 0.18, respectively, indicating significant overestimations of the monthly aerosol loadings. The main reasons were likely the complex surface structures and inseparable aerosol mixtures from both natural and anthropogenic sources, specifically in East Asia and South Asia. These factors would increase the complexity and difficulty in aerosol retrieval (Wei et al., 2017, 2018a).

Among the three aerosol datasets, the DT products had the best

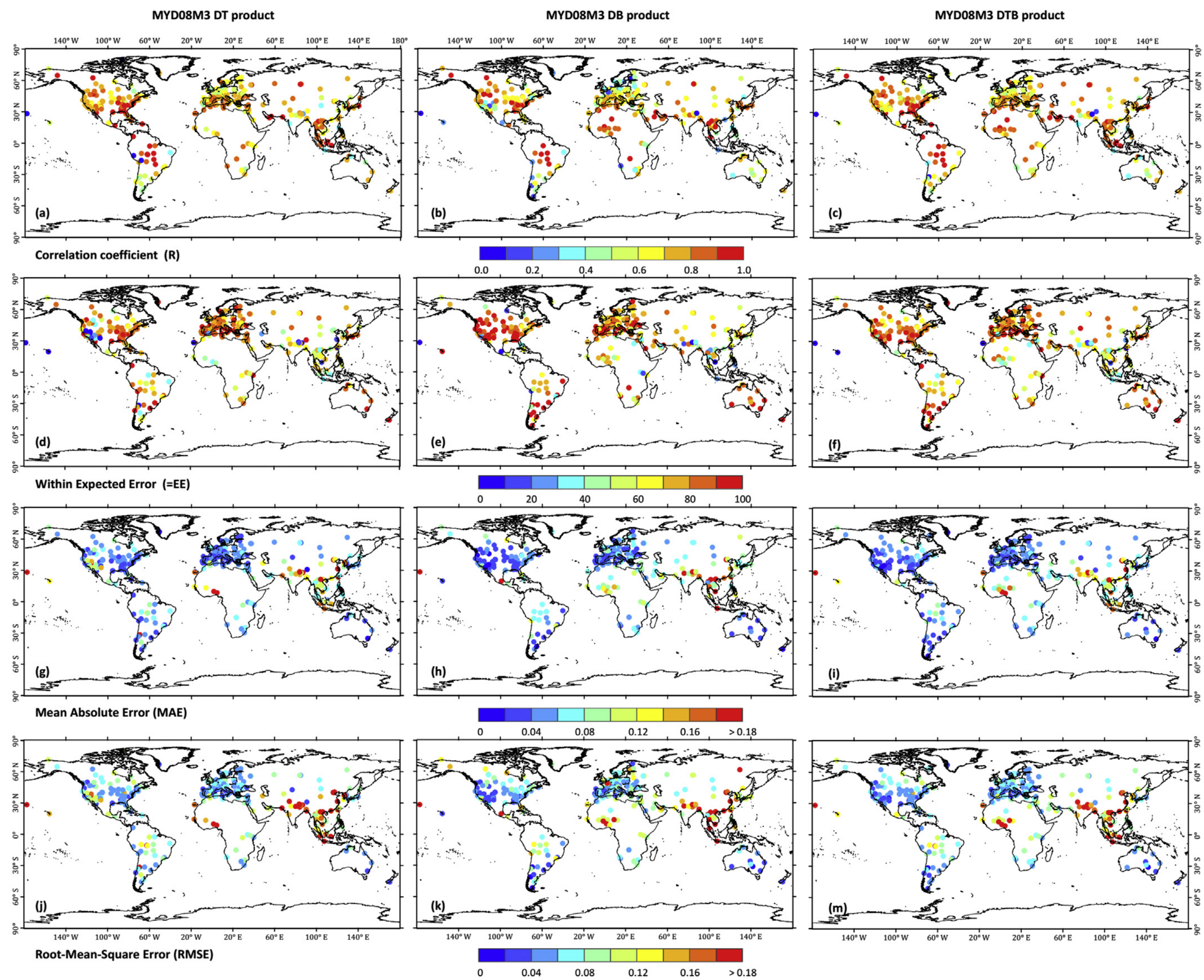

Fig. 5. Same as Fig. 4 but for Aqua MODIS monthly AOD products.

performance over Europe and Eastern North America, but the worst performance over other regions, specifically Western North America, North Africa and the Middle East, where the surface structures were mainly arid/semiarid and desert areas with sparse or little vegetation cover. However, the DB products could significantly improve the monthly aerosol estimations over these bright surfaces. They also exhibited good performance over other dark surfaces, but with generally low correlation with surface measurements. Unlike other regions, the DB algorithm presented opposing underestimates of monthly retrievals over South Africa. The DTB products provided the largest number of monthly observations over most regions and showed superior performance with better statistical metrics over Asia, South America and South Africa. In general, The DTB products were more accurate and less biased than DT products but were not always better than DB products at the regional scale.

4.1.3. Site-scale performance

This section focuses on exploring the performance of the three aerosol datasets at specific locations around the world. To this end, Terra and Aqua DT, DB and DTB monthly retrievals were compared against AERONET measurements at each site over land from 2003 to 2017. For robustness, comparison statistics were only calculated for the individual sites with more than two years of ground-based observations (at least 24 matchups). In general, the DT products had approximately ten fewer sites over bright surfaces compared to the DB and DTB products.

With regards to the Terra satellite (Fig. 4), the three datasets showed similarly good performances at most sites located in southeastern North America, southern Europe and southern South America, showing high correlation ($R > 0.7$) with more than 60% of the samples falling within the EE, MAE and RMSE values below 0.06 and 0.08, respectively. However, although overall good correlation, poor performance was found at sites in South Asia, East Asia and Southeast Asia with less than 50% of samples meeting the requirements of EE, and with MAE and RMSE values greater than 0.12 and 0.16, respectively. The DT algorithm performed poorly at sites in western North America, central Africa and the Middle East, with less than 40% of the collections falling within the EE and large MAE and RMSE values. In contrast, the DB algorithm overcame the difficulties and improved data quality over bright surfaces. However, the DB algorithm always showed large data discrepancies ($RMSE > 0.12$) over northern Europe, the Amazon region and central Africa. In general, the DT retrievals always exhibited better agreement compared to DB at most sites with higher correlation versus the surface measurements. For the DTB dataset, the improved performance is mostly observed at these sites over bright surfaces (e.g., western North America, Asia and Australia) where DT algorithm cannot

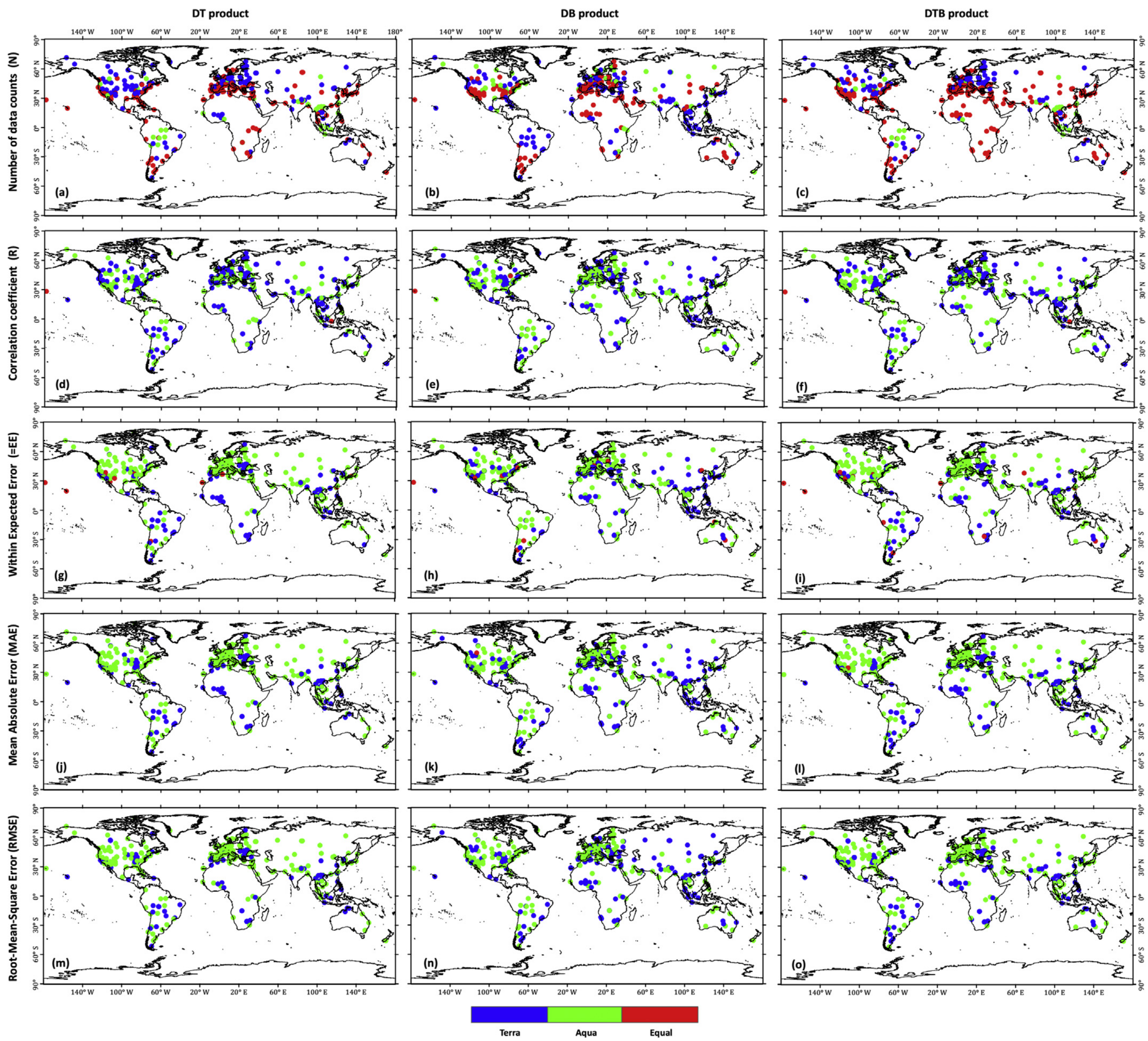

Fig. 6. Maps showing the best performing satellite for DT, DB and DTB monthly aerosol products at each site over land in terms of (a–c) the data count, (d–f) correlation coefficient, (g–i) percentage of data samples falling within the EE, (j–l) MAE and (m–o) RMSE, respectively.

be well implemented.

The three Aqua monthly AOD datasets exhibited similar spatial patterns in terms of correlation, fractions within the EE, MAE and RMSE values compared to Terra products (Fig. 5); thus, similar conclusions could be obtained. However, it was found that the Aqua monthly AOD products were in deeper color in each metric, thus indicating better agreements with AERONET AODs compared to Terra products at most sites. To better compare the three AOD products derived from Terra and Aqua satellites, the best performing satellite products in terms of four main metrics at each site were determined (Fig. 6). The Aqua products provided smaller numbers of data samples at most sites but had the best correlated retrievals at more sites compared to all three Terra products. The most striking aspect was that the Aqua products had better overall performance compared to Terra products, with more than 56% of the sites having higher fractions falling within the EE, lower MAE values at more than 60% of the sites and lower RMSE values at more than 58% of the sites for the DT, DB and DTB products.

Because noticeable differences among the three monthly datasets at the site scale, the best performing algorithm at each site was also determined (Fig. 7). The DB retrievals resulted in the best correlations with surface measurements at more sites located in northern North America, Africa, East and South Asia, whereas the DT or DTB retrievals had almost equally good correlation at sites scattered amongst rest of the world. In general, the DB retrievals had the best performance with the highest percentage of retrievals falling within the EE, lowest average MAE and RMSE values at a larger number of sites over land, specifically in North America, Europe, central Africa and Asia. The DTB retrievals exhibited the same performance as the DB retrievals over arid/semiarid areas where the DT retrievals were rarely valid. However, the DT retrievals performed the best only at a few sparse sites. The DTB retrievals had the same performance as the DT retrievals over Southeast Asia, northern South America and certain sites located in Eastern North America and Europe. Although the DTB retrievals combined the advantages of the DT and DB retrievals, DTB did not perform better compared to DB at more than half of the selected sites. This result indicates that DTB products generated based on independent NDVI data

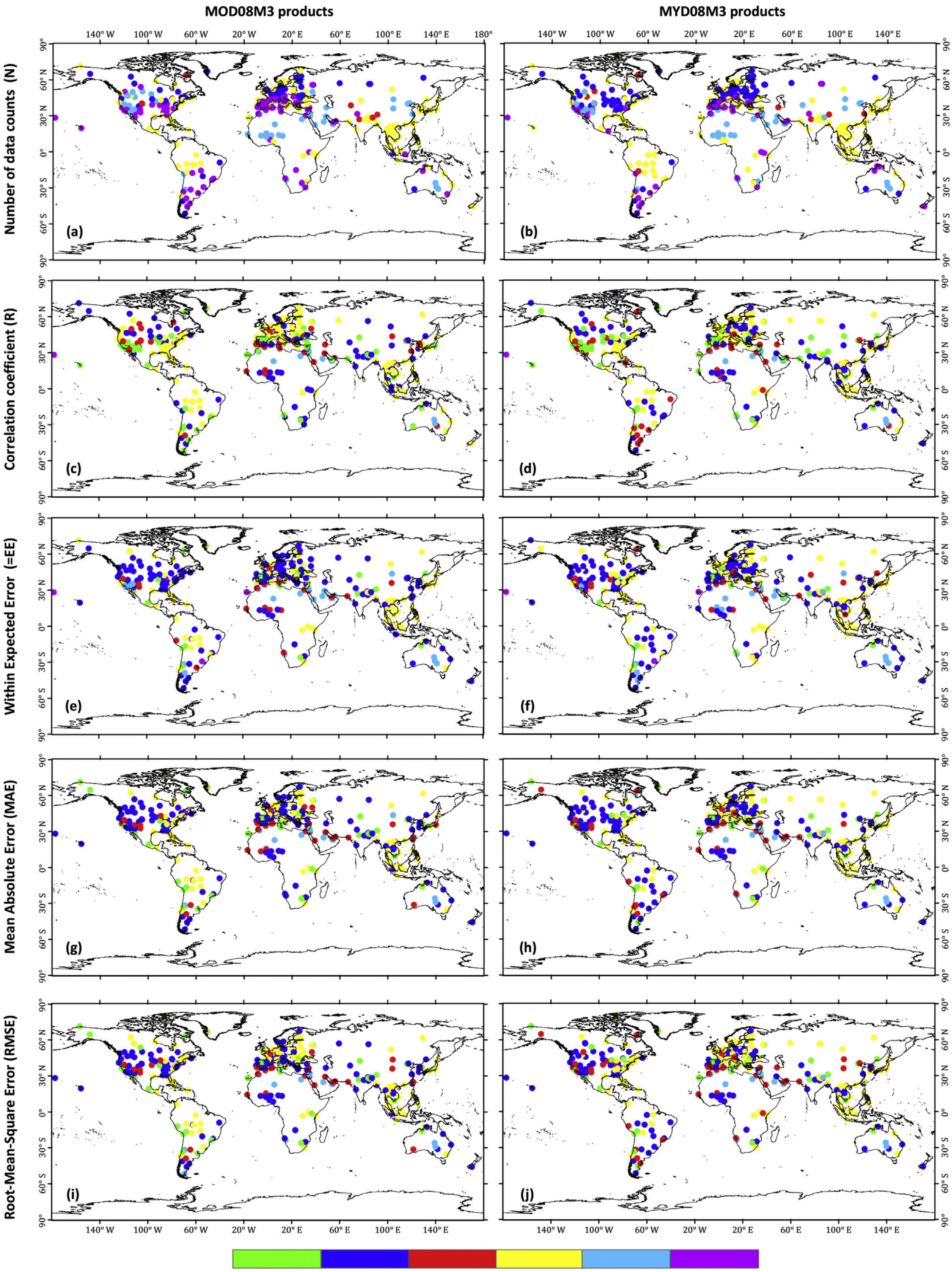

Fig. 7. Maps showing the best performing algorithm of the Terra and Aqua aerosol products at each site over land in terms of (a–b) the data count, (c–d) correlation coefficient, (e–f) percentage of retrievals falling wtihin the EE, (g–h) MAE and (i–j) RMSE, respectively.

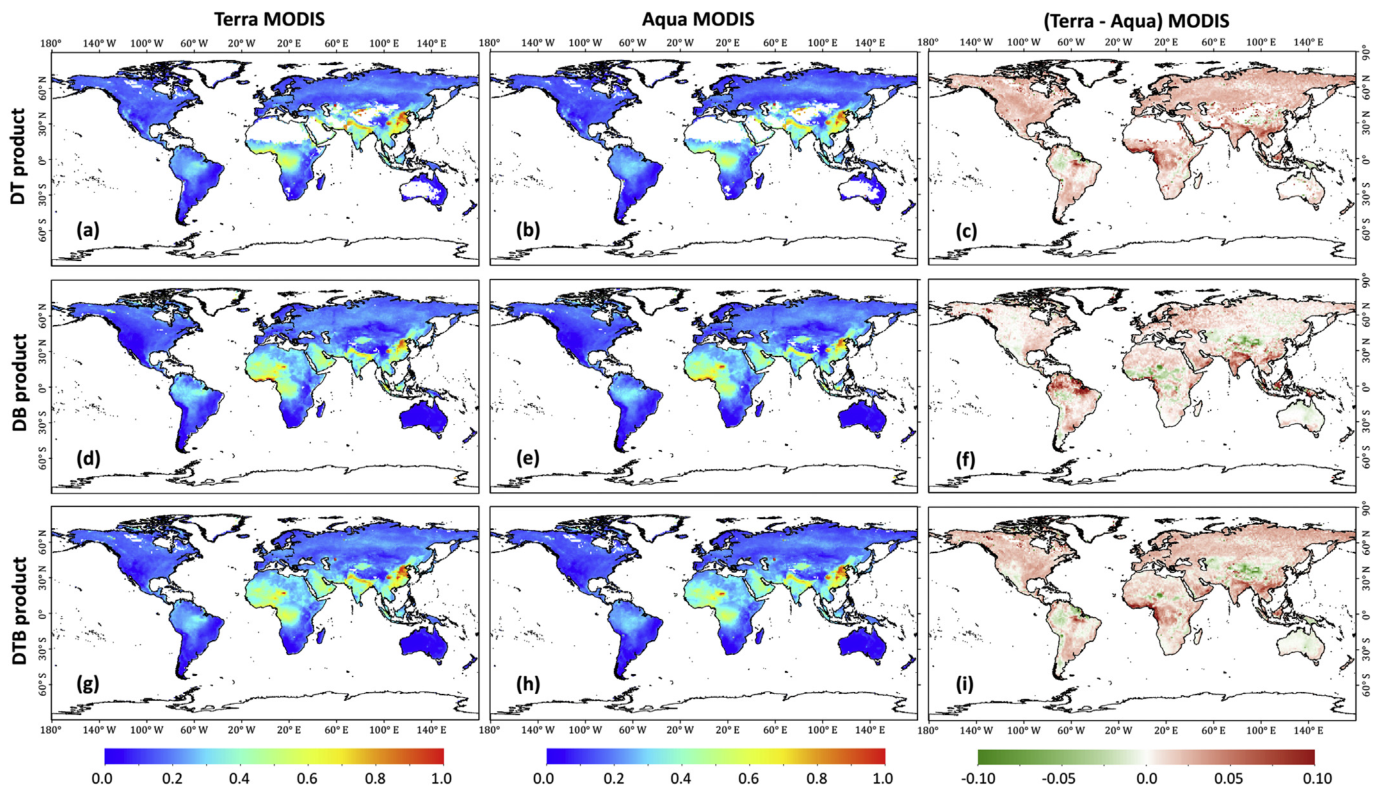

Fig. 8. Spatial distributions of annual mean aerosols over land for Terra and Aqua MODIS over land. The differences between Terra and Aqua (third column) are calculated when both products have concurrent retrieval values. Data are from 2003 to 2017.

Table 2
Statistics of global and regional annual mean AODs for Terra and Aqua C6.1 DT, DB and DTB AOD datasets. Data are from 2003 to 2017.

Algorithm	DT		DB		DTB	
Satellite	Terra	Aqua	Terra	Aqua	Terra	Aqua
Land	0.207 ± 0.009	0.188 ± 0.007	0.203 ± 0.007	0.195 ± 0.007	0.208 ± 0.009	0.193 ± 0.007
Asia	0.254 ± 0.025	0.231 ± 0.025	0.220 ± 0.023	0.213 ± 0.024	0.233 ± 0.024	0.217 ± 0.023
Europe	0.207 ± 0.017	0.185 ± 0.017	0.194 ± 0.013	0.183 ± 0.013	0.195 ± 0.016	0.178 ± 0.016
ENAM	0.159 ± 0.012	0.138 ± 0.012	0.181 ± 0.015	0.167 ± 0.015	0.169 ± 0.013	0.149 ± 0.014
WNAM	0.159 ± 0.017	0.138 ± 0.017	0.125 ± 0.024	0.124 ± 0.024	0.142 ± 0.019	0.125 ± 0.019
SAM	0.173 ± 0.022	0.165 ± 0.019	0.178 ± 0.019	0.161 ± 0.026	0.164 ± 0.022	0.158 ± 0.018
SAF	0.220 ± 0.012	0.204 ± 0.013	0.197 ± 0.010	0.192 ± 0.012	0.216 ± 0.012	0.200 ± 0.012
NAME	0.299 ± 0.015	0.280 ± 0.015	0.343 ± 0.015	0.336 ± 0.016	0.343 ± 0.015	0.330 ± 0.017
Oceania	0.076 ± 0.005	0.073 ± 0.005	0.053 ± 0.005	0.054 ± 0.005	0.062 ± 0.004	0.060 ± 0.004

were not always the best among the three datasets due to the unsuitable merge approach in the processing with DT and DB retrievals (Wei et al., 2019a,b).

4.2. AOD spatial distributions over land

4.2.1. Global and regional AOD distributions

In this section, we focus on the comparison of spatial distributions among the above MODIS aerosol products. For this purpose, 15-year annual mean AOD maps for Terra and Aqua DT, DB and DTB products from 2003 to 2017 over land were averaged (at least 4 monthly values available in a year) from MOD08 and MYD08 monthly products (Fig. 8). In general, the Terra AOD products had very similar spatial patterns compared to Aqua products, where AOD loadings exceeded 0.5 were mainly distributed in central Africa, the Middle East, India and eastern Asia. However, low AOD loads of less than 0.3 were always observed in the rest of the world.

The DT products had the lowest spatial coverage, with numerous missing values over the main bright surfaces (i.e., northern Africa, the Middle East, central Asia and central Australia). However, the DB datasets could provide nearly complete spatial coverage with more successful retrievals compared to DT datasets over land, specifically for arid and desert areas in the world. The DTB products had the same spatial coverage and close annual mean AOD values as the DB products over most bright surfaces, such as Africa, the Middle East, South Asia and East Asia. Meanwhile, the DTB and DT products had similar annual mean AOD values over dark surfaces such as eastern North America, northern North America, and Europe.

The spatial (the third column of Fig. 8) and numerical (Table 2) differences of the annual mean AODs over land were calculated for the three aerosol datasets derived from Terra and Aqua satellites. In general, it was found that Aqua AODs were lower compared to Terra AODs over most areas, specifically for DT and DTB datasets. However, DT and DTB datasets showed close inter-annual mean AODs with small differences in the standard deviations at the regional scale (Table 2). For the DT datasets, it was clear that Terra AODs were always larger than Aqua AODs globally except for several parts of northern South America and central Asia (Fig. 8c). Over land, the annual mean Terra and Aqua DT AODs were 0.207 ± 0.009 and 0.188 ± 0.007, respectively. At the regional scale, except for South America and Oceania, large positive

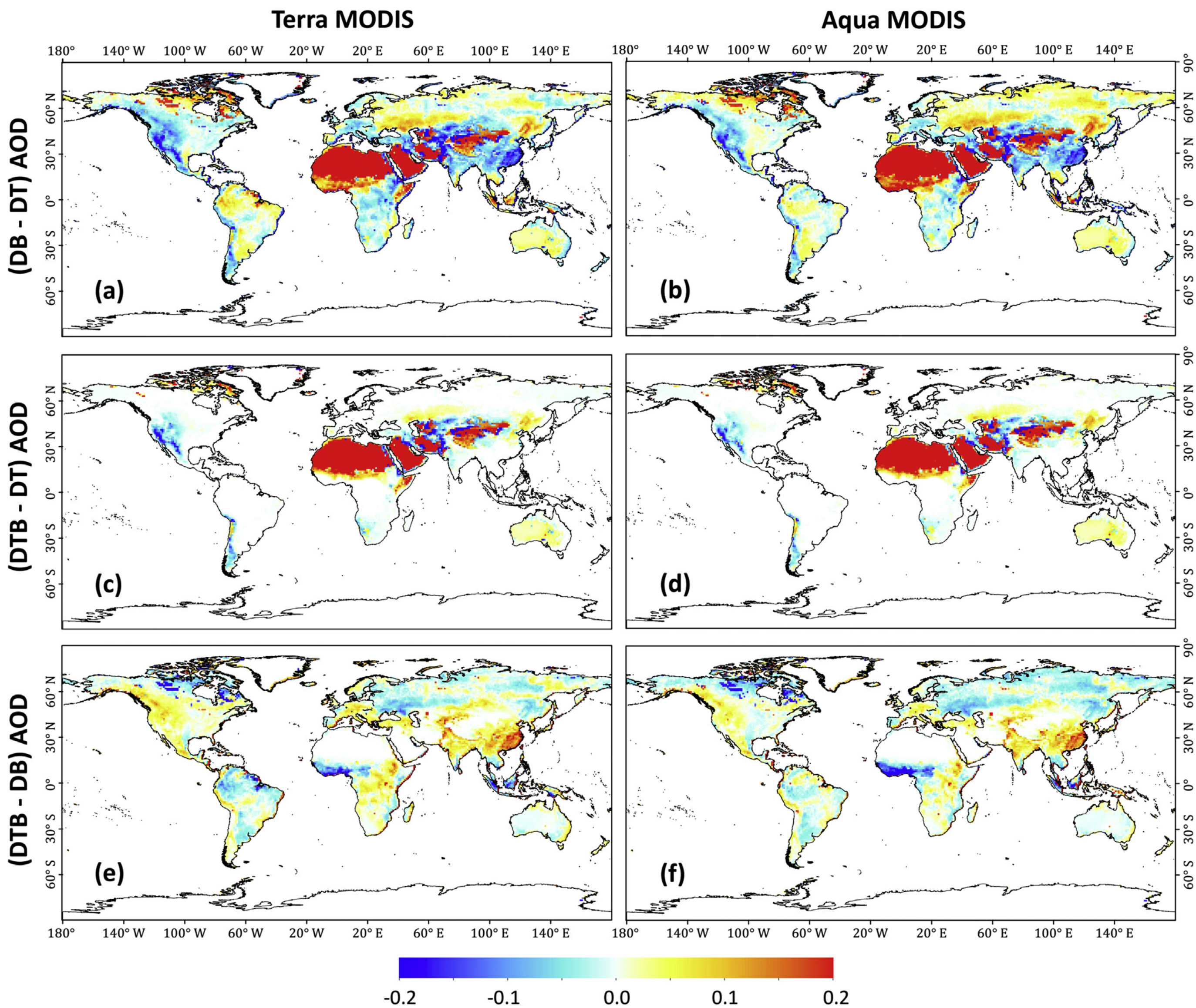

Fig. 9. Annual mean AOD differences (MD) between Terra and Aqua MODIS DB and DT (a, b), DTB and DT (c, d), DTB and DT (e, f) monthly AOD products. Data are from 2003 to 2017.

differences greater than 0.016 existed between the two satellites.

For the DB datasets, it was observed that there were relatively smaller annual mean differences between the two satellites compared to the DT datasets over most areas. However, noticeable positive differences were observed in the Amazon region, India and Southeast Asia, negative differences were found in central Africa, Australia and central Asia (Fig. 8f). The annual mean Terra and Aqua DB AODs over land were 0.203 ± 0.007 and 0.195 ± 0.007, respectively. At the regional scale, except for Oceania, the annual mean Terra AODs were generally larger than the Aqua AODs, particularly for South America.

The DTB datasets had similar annual mean differences compared to the DT products between the two satellites at both spatial patterns and had similar regional statistics but were more consistent with the DB products in those areas where the DT algorithm could not be applied (Fig. 8i). The annual mean AODs over land were 0.208 ± 0.009 and 0.193 ± 0.007 for the Terra and Aqua DTB datasets, respectively.

Fig. 9 shows the 15-year mean AOD differences between DT and DB, DT and DTB, DB and DTB products for the Terra and Aqua satellites from 2003 to 2017 over land. In general, the Terra and Aqua AODs had almost identical spatial patterns of the mean differences among the three retrieval products (each row). However, there were significant differences, as expected, between DT and DB products. Large positive differences (greater than 0.2) occurred in the main deserts (i.e., northern Africa, the Middle East, Northwestern China), where the DT algorithm could not adequately retrieve AOD over such bright surfaces. On the other hand, DB retrievals were much lower than DT retrievals over western North America, southern Africa, south and east Asia, with large absolute differences greater than 0.2. There were few differences between DTB and DT products over most land areas except for large positive differences over the main deserts, as mentioned above, between DB and DT products. In addition, there were negative differences between DTB and DT products over the main semiarid and mountainous areas (i.e., western North America, southern South America and central Asia). The differences between DTB and DB products over land were positive in western North America, southern Africa, south Asia and west Asia but negative over high-latitude areas in the Northern Hemisphere, south of the Sahara Desert and South America. The DTB and DB products were identical over arid and desert areas.

4.2.2. Comparison in annual mean AODs

To evaluate the accuracy of annual mean AOD values for the different MODIS products, the means were calculated and compared

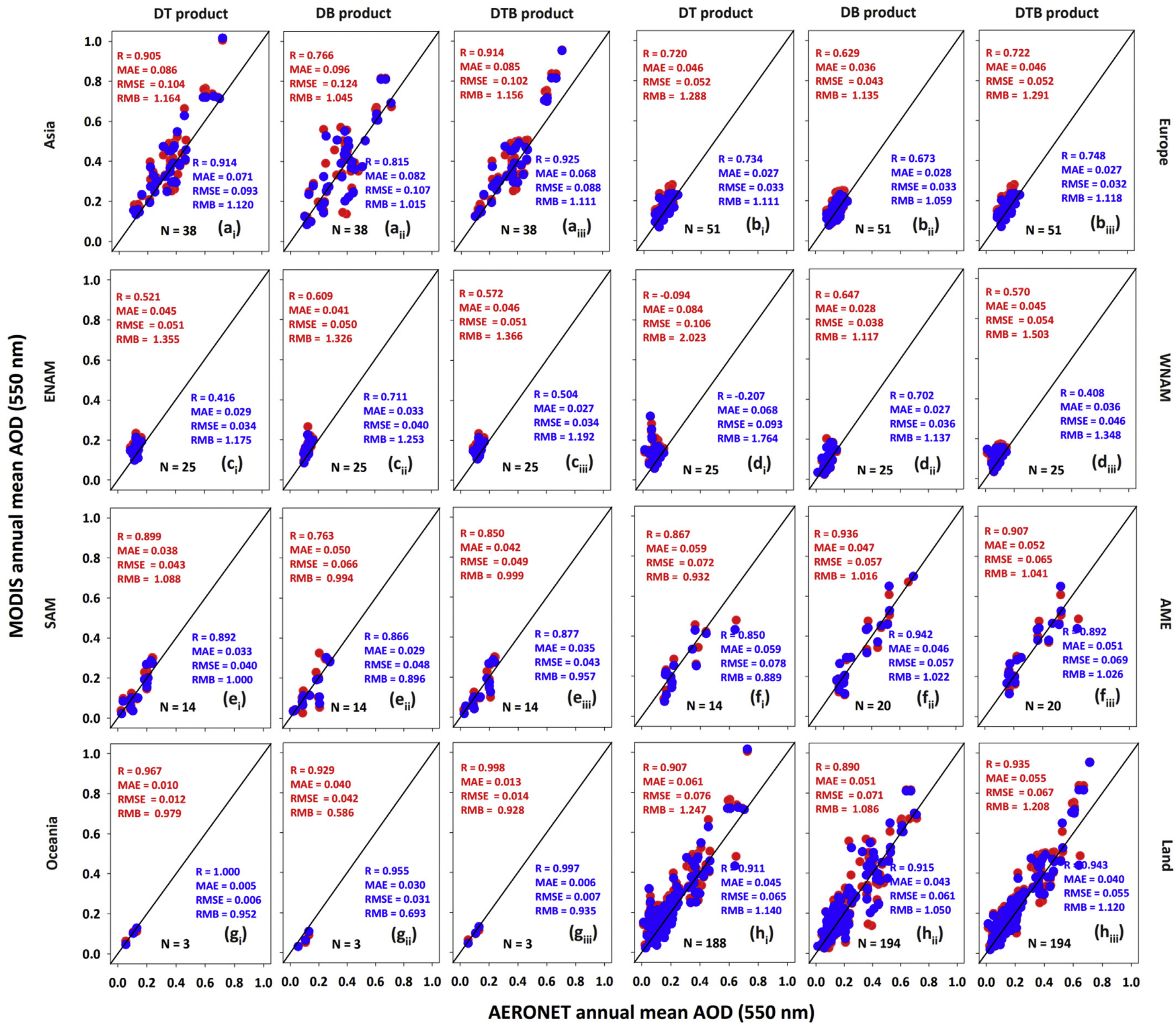

Fig. 10. Comparison of Terra (red dots) and Aqua (blue dots) MODIS DT, DB and DTB annual mean AODs by comparing with AERONET AODs for each region over land. The black solid line represents the 1:1 line. Data are from 2003 to 2017. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

against AERONET AOD measurements at those sites with at least five years of effective ground observations (Fig. 10) over each region. In general, it was found that there were similar performances, with most points overlapping between the Terra and Aqua satellite-derived aerosol datasets in most regions. However, the MYD08 products (blue dots) were generally more accurate with higher correlations and lower estimate uncertainties (i.e., MAE and RMSE) in describing the annual mean values compared to the MOD08 products (red dots). Moreover, the Terra aerosol products seriously overestimated the annual mean values with large positive RMB values, especially for DT retrievals. The Aqua aerosol products were closer to the actual annual mean levels.

Despite the overall good agreement in annual mean values between the DT, DB and DTB datasets and surface measurements, noticeable differences could be found at the regional scale. The three aerosol products showed almost equal performances with small differences in the accuracy and estimation uncertainty (± 0.01) in describing annual mean values over Europe and eastern North America. The DT products could most accurately reflect the annual mean values over South America. However, the DB products could provide the most accurate annual mean aerosols over western North America, Africa and the Middle East, while the DTB products were most suitable for analyzing the spatial distributions over Asia.

Due to the sparse AERONET sites in Oceania, the analysis of the data performance was not statistically meaningful. At the global scale, it was observed that the DT annual mean aerosols agreed well with AERONET AODs but showed noticeable overestimates by 25 and 14% for the Terra and Aqua satellites, respectively. The DB product showed an increasingly improved performance with decreasing estimation uncertainties compared to the DT products. However, the DTB products appeared to have the best performances with the highest correlation coefficient, and lowest MAE and RMSE values.

4.3. AOD temporal variations over land

4.3.1. Global and regional AOD trends

In this section, we compare the spatial distributions of the aerosol

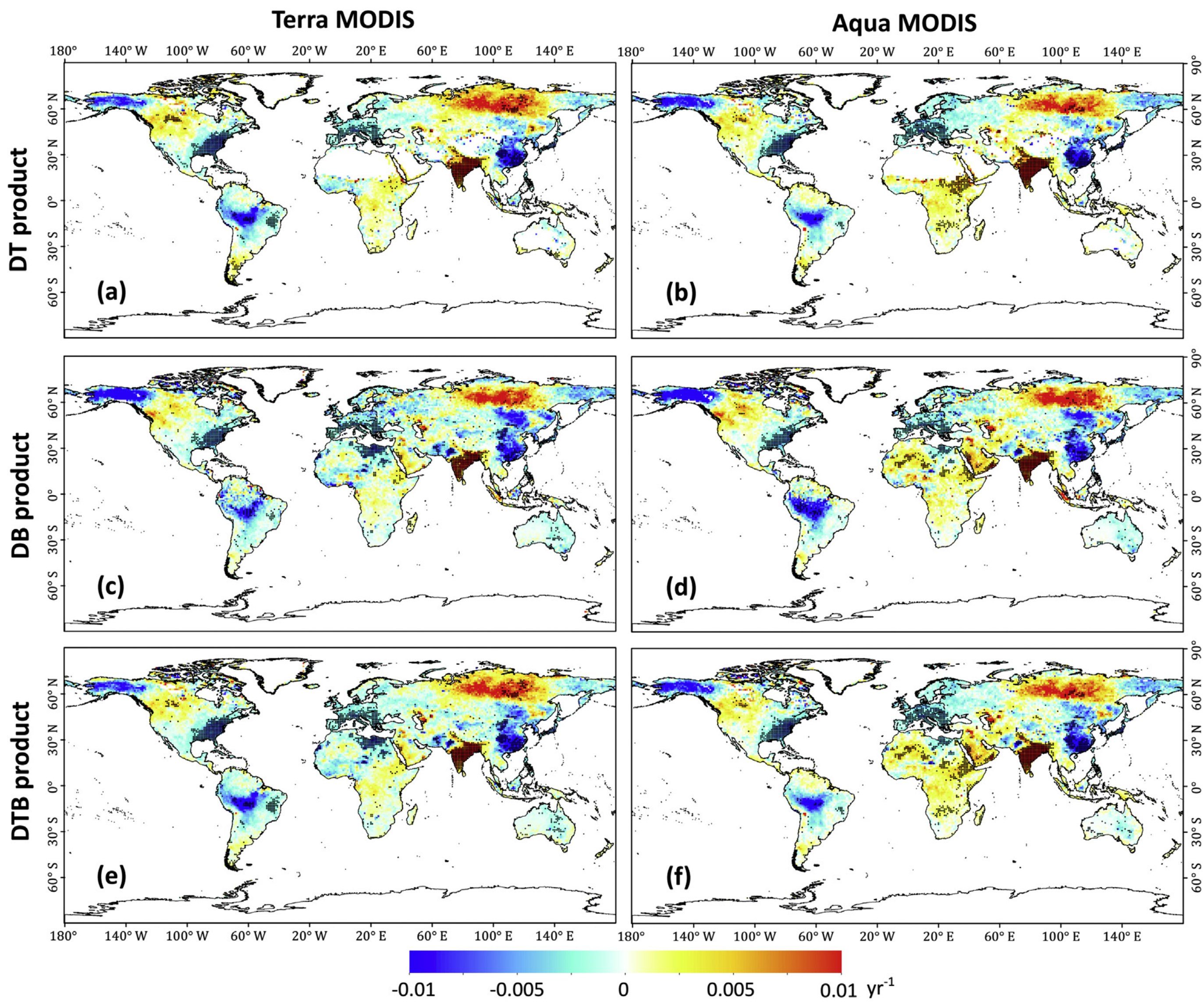

Fig. 11. Linear trend based upon de-seasonalised monthly anomaly of Terra and Aqua MODIS DT, DB and DTB AODs from 2003 to 2017. Units are AOD yr^{-1}. Black spots indicate that trend is significant at the 99% confidence level ($p < 0.01$).

trends among the three DT, DB and DTB AOD products derived from Terra and Aqua satellites from 2003 to 2017 over land (Fig. 11). The annual aerosol trends were calculated from the monthly retrievals (at least 60 monthly values available) with the least square fitting method. Overall, the annual aerosol trends derived from Terra and Aqua satellites for the three aerosol datasets were similar in their spatial patterns globally. The aerosols did not change much and exhibited small and not-statistically significant trends over most land areas. In general, comparatively consistent and significant aerosol trends were observed in India, Europe, southeastern North America and southeastern China. The former showed a very significantly positive aerosol trend of greater than 0.005 per year ($p < 0.01$) in the study period, indicating increasing air pollution. By contrast, significant negative trends (-0.005 yr^{-1}, $p < 0.01$) were observed in the latter three regions, indicating a continuously improving air quality. However, there were nonnegligible differences over local areas, particularly among the three different algorithm-generated datasets. These differences were mainly found in Africa, South America and other individual parts of the world.

Fig. 12 plots the time series of interannual mean AODs from 2003 to 2017 over the global land area and over each region. In general, all six curves derived from the three aerosol datasets for Terra and Aqua satellites were highly consistent with each other ($R > 0.9$, $p < 0.01$) in individual regions. However, the Aqua curve was always below the Terra curve for the same algorithm-generated datasets in most regions. The DT datasets always showed the largest annual mean values (while the DB datasets always showed the smallest values) in most years and most regions, including Asia, Europe, western North America, South America and Oceania. In contrast, over Eastern North America, South America, North Africa and the Middle East, the DT and DB datasets performed opposite to the above phenomena.

For the interannual variations, the aerosol trend fluctuated weakly over the entire 15 years over the global land as well as Oceania. Eastern North America and South America showed overall decreasing aerosol trends, while Africa and the Middle East exhibited increasing trends during the study period. Moreover, a shift in aerosol trends occurred in certain regions. In Asia and Europe, aerosols showed obvious increasing trends in the first several years and then exhibited decreasing trends after 2011. The decline in Asian aerosols might be attributed to the air pollution control policies carried out in China since 2011 (Hu et al., 2017). The peak in European aerosols was possibly due to the two eruptions of the Eyjafjallajökull volcano in Iceland in the spring of 2010 (Karbowska and Zembrzuski, 2016). However, there were irregular

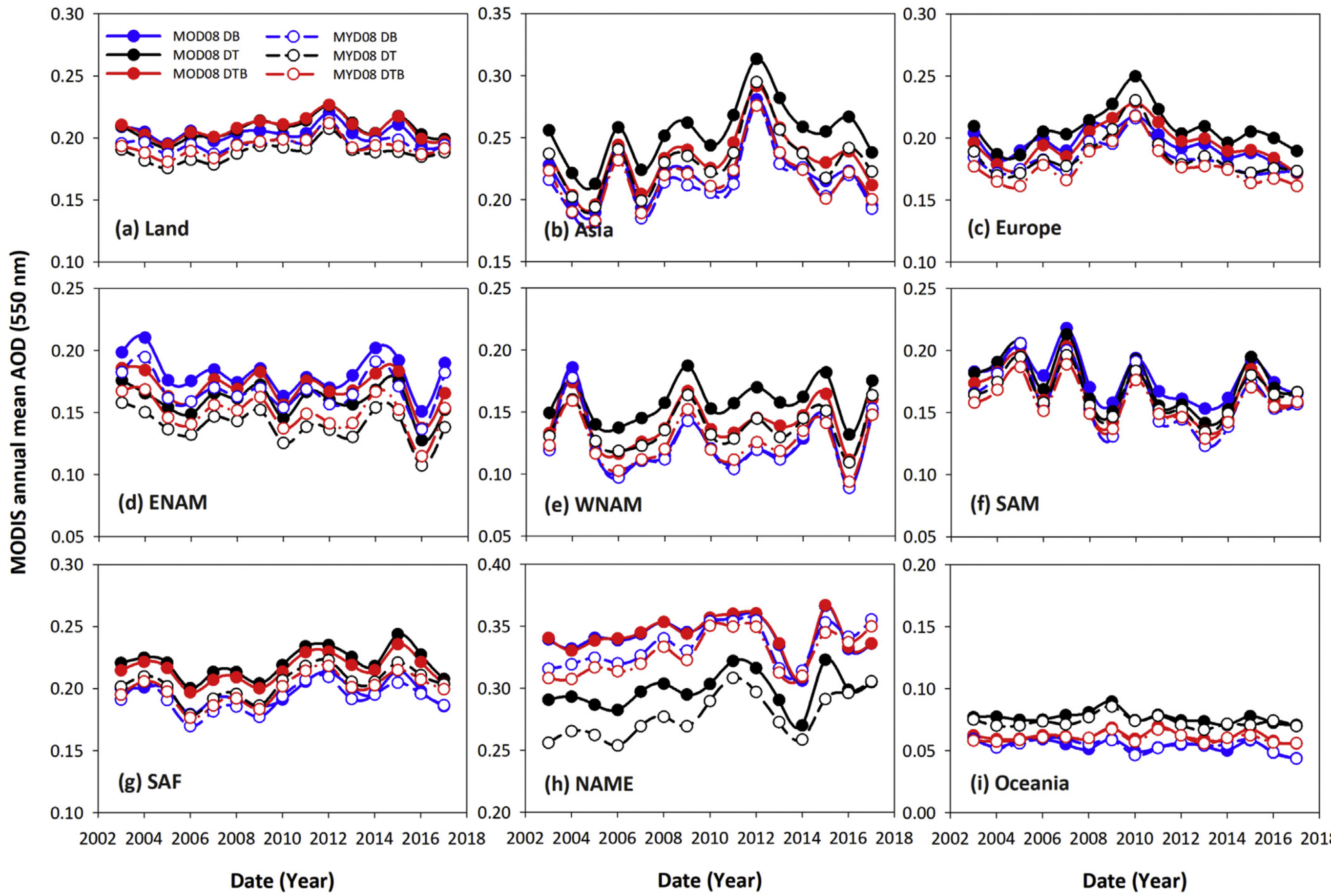

Fig. 12. Time series of annual mean AODs at 550 nm for each region from 2003 to 2017 over land.

fluctuations in the interannual aerosol changes over western North America as well as some other parts of the world.

4.3.2. Comparison in annual AOD trends

To prove the accuracy of the above trends, this section focuses on comparing the annual aerosol trends derived from both Terra and Aqua AOD products over land. For statistical significance, only AERONET sites with at least five years of observations were selected for comparison. Then, the trends of AOD retrievals and AERONET AOD measurements were calculated at each site for each region over land (Fig. 13). The SD values in Figures represent the percentage of points showing common AOD trends with the same sign between MODIS AOD retrievals and AERONET AOD measurements. In general, the annual aerosol trends derived from Terra satellites were not much different from those derived from Aqua satellites, with very similar evaluation metrics over most selected regions. The Terra AOD products showed similar abilities in capturing the annual mean aerosol trends compared to the Aqua AOD products, with most scattered points overlapping in the four-dimensional quadrant spaces in most regions. Particularly for Europe and eastern Northern America, the MODIS products could capture the correct aerosol trends at more than 84% of the selected sites with small estimation uncertainties (i.e., MAE < 0.04 and RMSE < 0.05). In contrast, it was difficult for MODIS aerosol products to capture the correct temporal aerosol variations over western North America, Africa and the Middle East, with fewer sites showing the same signs between the satellite- and surface-derived aerosol trends. Meanwhile, the MODIS aerosol products had relatively large MAE and RMSE values.

However, there were noticeable differences in performance among the three datasets. The DT datasets showed the best ability to capture the annual mean trends at the almost-highest percentage of sites with the lowest estimation uncertainty (i.e., MAE and RMSE) over Asia, Europe, and eastern North America. However, the DB datasets performed the best only at sites over Africa and the Middle East. Of course, the DB datasets should be the best choice for analyzing the temporal variations over arid areas and deserts (i.e., central Asia or central Australia) with very few ground observation stations. In general, the DTB products could capture the correct aerosol trends at most sites located in western North America and South America, but they also showed similar performance compared to the DT products over Asia, Europe, and eastern North America. Meanwhile, the DTB products also had considerable accuracy compared to the DB products over those areas where the DT algorithm could not be well applied.

At the global scale (Fig. 13h), the Terra and Aqua datasets had similar performances with small differences within ± 3%, and a MAE and RMSE value of 0.005 and 0.004, respectively, in terms of the percentage of sites with the same sign for the three aerosol datasets. The DT products could capture the correct AOD trends at approximately 80% of the sites, and the satellite-based trends agreed well with the true trends ($R > 0.71$), with average MAE and RMSE values of less than 0.04 and 0.05, respectively. However, despite the increasing correlations, the annual mean AOD trends from the DB products were less accurate overall than those of the DT products at a smaller number of sites with a larger MAE of 0.05 and RMSE of 0.1 for both satellites. However, the DTB products could capture the most accurate aerosol trends at approximately 79% of all available 194 sites over land with average MAE and RMSE values of 0.034 and 0.049, respectively.

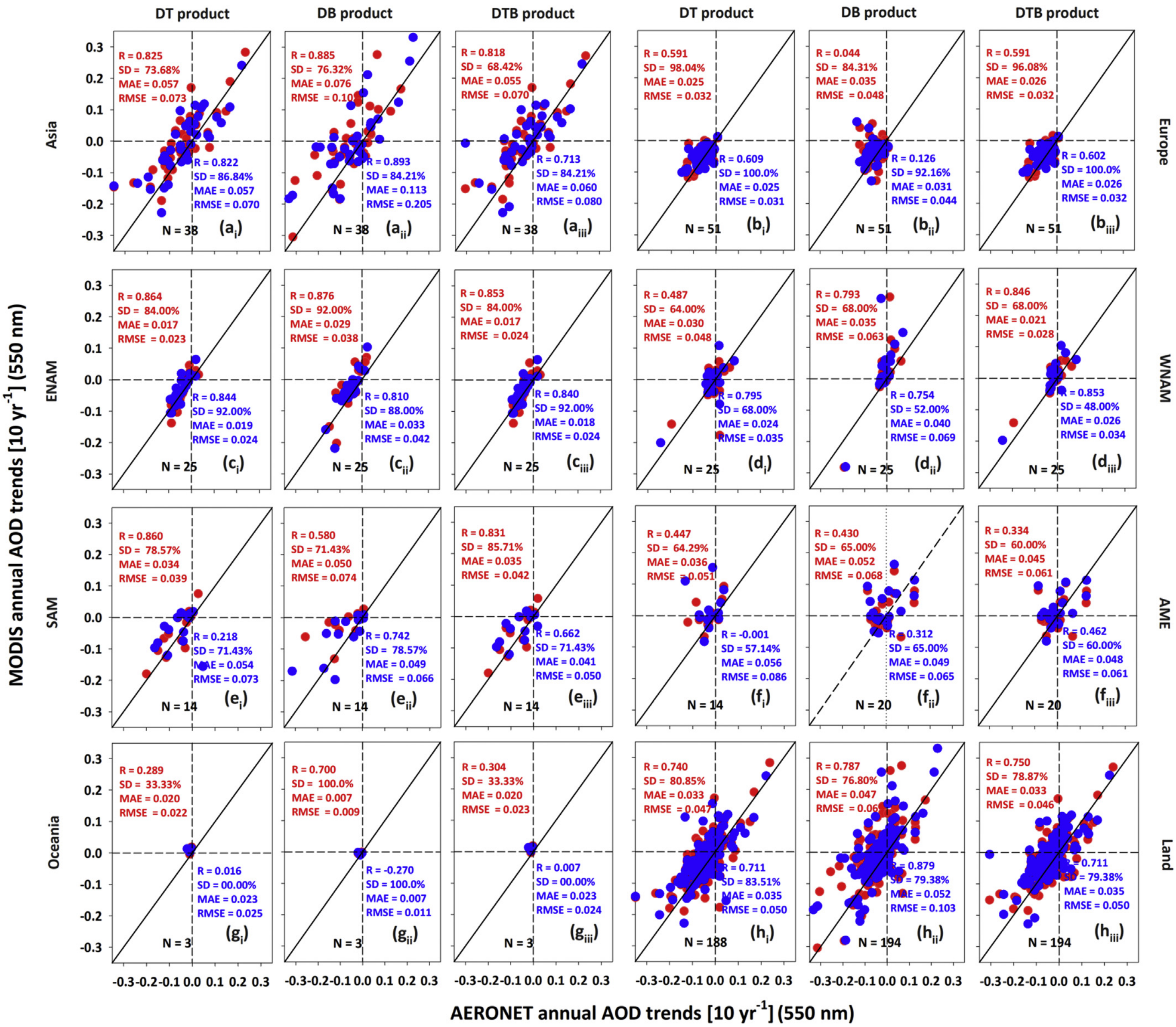

Fig. 13. Comparison of AOD trends (10yr^{-1}) from Terra (red dots) and Aqua (blue dots) MODIS DT, DB, DTB products by comparing with AERONET AODs for each region over land. The black solid line represents the 1:1 line, and black dotted lines respresent the x = 0 and y = 0 lines. Data are from 2003 to 2017. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5. Summary and conclusion

This study tries to provide an overview and initial analysis of the latest Terra and Aqua MODIS Collection 6.1 (C6.1) Level 3 atmospheric aerosol products in charactering the spatial and temporal variations over land. For this purpose, three Dark Target (DT), Deep Blue (DB) and combined DT and DB (DTB) monthly aerosol optical depth (AOD) products during the same period (2003–2017) were collected and compared against ground monthly AOD measurements from 431 Aerosol Robotic Network (AERONET) sites over land. Performance of these monthly AOD retrievals at global, regional and site scales, determination and comparison of the annual mean AOD spatial distributions and temporal variations are carried out. These introductions will allow readers to better understand the key features and differences among different aerosol datasets, and which one is more suitable for use in different applications over various land areas.

Our results illustrated that although the C6.1 DT, DB and DTB monthly AOD retrievals agree well with AERONET AOD measurements at the global scale, noticeable different abilities exist at regional to site scales. The DTB products can provide the largest number of monthly observations with the best performances over most selected regions, yet the DB products are superior at more sites. For spatial distributions, despite similar spatial patterns, the Terra products severely overestimate the annual mean AOD values and are less accurate than the Aqua products over land. Furthermore, for temporal variations, all three aerosol datasets can accurately capture the aerosol trends over most regions, and there are similar performances with small differences between the Terra and Aqua satellite-derived aerosol products. For the three algorithm-generated datasets, neither one can consistently outperform the others despite relatively similar performances in describing the spatial and temporal variations between the satellite-derived and ground-measured AODs in many cases. In general, we strongly recommend that the DTB products (specifically the Aqua satellite products) be selected for use in related aerosol studies (i.e., model simulations and validations, long-term aerosol changes, aerosol-cloud-radiation interactions) at the global scale.

Declaration of interest

Y. Peng designed the research. J. Wei carried out the research and wrote the initial draft. J. Guo and L. Sun helped with the refinement of this manuscript. All authors contributed to the interpretation of the results.

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