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ORIGINAL ARTICLE

Analysis of AOD from MODIS-Merged DT–DB Products Over the Arabian Peninsula

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Abstract
The satellite-based aerosol estimation has attracted immense scientific attention in a multiplicity of applications related to global warming, climate change, and air pollution research globally. Numerous aerosols from widespread deserts across the Arabian Peninsula have a significant function in the regional climate and air quality. The aim of this study is to analyze the spatiotemporal variations of aerosols over the Arabian Peninsula for the period 2003–2017. For this, the study uses the Terra and Aqua Satellite on-board Moderate Resolution Imaging Spectroradiometer (MODIS)-based Merged Dark Target (DT) and Deep Blue (DB) collection of six aerosol products (550 nm). The study also uses the Aerosol Robotic Network (AERONET)-derived AOD to evaluate MODIS-Merged DT–DB AOD across the peninsula. A linear regression technique, root mean square error, mean absolute error, relative mean bias (RMB), and EE envelope (expected error) methods are used to calculate the uncertainty in the MODIS-merged DT–DB AOD products. The results of the spatial distribution show that Terra demonstrates the highest AOD over the southern Red Sea and the west coast of the Arabian Gulf that extends up to central Saudi Arabia. However, the Aqua displays the highest AOD mostly over the southern Red Sea. AOD is increasing annually at Kuwait University, Dhabi, and Hamim stations while decreasing at KAUST and Masdar-Institute. The Solar Village (for Aqua) shows a slightly increasing trend), Dhadnah, and Mezaira showing an almost a stable condition. Aqua has the better retrievals of AOD, which fall within EE envelope (~60−87%) for seven stations, whereas the Terra shows better AOD retrieval only for Dhabi (EE = ~81%). However, RMB reveals the correct information that the merged AOD product overestimates at all stations for both satellites, while the Aqua underestimates for the Solar Village, Kuwait University, and Dhadnah. This under- and overestimation is due to the defective surface reflectance computation and inaccurate use of aerosol model schemes in the Look-Up Table. Further qualitative research is recommended to enhance the aerosol retrieval efficiency of the DB and DT algorithms over the bright-reflecting surface.

Keywords AOD · Atmospheric aerosol · Remote sensing · Arabian Peninsula

1 Introduction

Aerosol particles can change the earth–atmosphere energy balance (Ali et al. 2017, 2019; Butt et al. 2017). Both natural and man-made aerosols have increasing impact on hydrological cycles, ecosystems, climate, human health, and agriculture (Kaufman et al. 2002). The contribution of manmade and natural emissions to the aerosol budget is one of the key elements in the earth's climate system (Butt et al. 2017). For that reason, it is necessary to observe the daily aerosol mutability to measure the global aerosol budget so as to determine the impact of aerosol radiative forcing on climate.

Recently, many well-suited sensors for aerosol studies have been launched for characterizing aerosol properties over local, regional, and global scales. The NASA (National Aeronautics and Space Administration) Terra [Earth Observing System (EOS)-AM] and Aqua (EOS-PM) on-board MODIS instrument is recognized as a successful tool for retrieving aerosol properties from space(Salomonsen et al. 1989). The MODIS sensor efficiently captures the spatiotemporal variability of aerosols at the global scale (Remer et al. 2008; Levy et al. 2013, 2015). The most important product of MODIS sensor is the aerosol product (550 nm), which has been applied to scrutinize aerosol sources, the

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changeability of aerosols, and their effect on the climate and air quality (Levy et al. 2015). The MODIS aerosol products are derived using the Dark Target (DT) algorithm over the vegetated land surface (Kaufman et al. 1997), and ocean (Tanre et al. 1997), while the Deep Blue (DB) algorithm is used over the bright-reflecting surfaces (Hsu et al. 2004). The DT and DB algorithms are continuously being modernized (Levy et al. 2013; Hsu et al. 2013).

The MODIS aerosol products have been extensively employed in numerous studies at global and regional scales (Remer et al. 2008; Ali and Assiri 2016; Klingmuller et al. 2016). Saudi Arabia is one of the major aerosol deposition sources in the world (Rushdi et al. 2010, 2013). In Saudi Arabia, aerosols are highly correlated with the frequency of sand and dust storm events from May through August (Xian 2016). The seasonal and regional distribution of AOD was studied by several researchers (Goudie and Middleton 2006; Farahat et al. 2015; Butt et al. 2017). Therefore, the Arabian Peninsula is most important for studying aerosols using the combined DT–DB aerosol products from MODISTerra and Aqua, along with AERONET ground station-based measurements.

The point-located AEROENT ground monitoring stations concentrate on the changes of regional particle pollutants as well as their distributions which are limited to in-depth studies. As the satellite-retrieved AOD directly belongs to the particle mass loading, many researchers have endeavored to exploit the satellite-retrieved AOD products to balance ground-based particulate matter concentrations (Wang and Christopher 2003; Hoff and Christopher 2009;Van Donkelaar et al. 2010; Song et al. 2014; Ma et al. 2016). Worldwide, the MODIS C6-based aerosol products are currently being investigated by the scientific communities (Bilal et al. 2016, 2017; Georgoulias et al. 2016; Mhawish et al. 2017; Zhang et al. 2017). It has been reported that regional validations are needed for the MODIS-Merged DT–DB AOD product.

Across the Middle East and North Africa, several researchers have used satellite-based MODIS Collection-51 and -06 DB aerosol products to study the spatiotemporal behaviour of aerosols (Sabbah and Hasan 2008; Yan et al. 2013; Farahat et al. 2015; Farahat 2018; Jin et al. 2018; Kumar et al. 2018). Though, several studies on the evaluation of MODIS DB (C-51 and -06) AOD against AEROENT AOD have been conducted over the peninsula (Butt et al. 2017; Ali et al. 2017; Almazroui 2019). However, there have as yet been no studies conducted on the spatiotemporal behaviour of aerosol and its evaluation over the Arabian Peninsula using merged DT–DB products; hence, there is a need to evaluate the merged DT–DB AOD against the AERONET ground station-based AOD.

The objectives of the present study are as follows: The first aim is to scrutinize the mean annual and seasonal AOD spatial distribution for the period 2003–2017. The second intent is to calculate the temporal variations and trends in AOD. The final objective is to evaluate MODIS-Merged DT–DBAOD against AERONET AOD (550 nm) over the Arabian Peninsula.

2 Materials and Methods

2.1 Study Area

The Arabian Peninsula is confined by the Red Sea (west coast), the Arabian Sea (south coast), and the Arabian Gulf (east coast) (Fig. 1). The most important attribute of the study area is desert except for the southwest region, which is covered by mountains and which receives a lot of rainfall compared to the remaining areas of the peninsula. Saudi Arabia is the largest country in the study area, covering almost 80% of the peninsula, and encompassing the world's largest sand desert (the Rub Al-Khali) (Almazroui et al. 2012). During the summer, the heat is intense in almost all peninsula locations and reaches as high as 54 °C at some locations (weather online). The spring and autumn seasons are mild, while winter is relatively cold. Low amounts of annual rainfall (77–102 mm) have been recorded during recent decades (Almazroui 2011). There are eight ground-based AERONET stations used in this study. KAUST (King Abdullah University Science and Technology) and the Solar Village are situated in Saudi Arabia, whereas Kuwait University Station is located in Kuwait city, and Dhabi, Dhadnah, Hamim, Masdar-Institute, and Mezaira stations are located in the UAE.

2.2 Data Used

In the current study, the Level-3 collection-06 monthly, gridded, and merged DT–DB AOD (550 nm) products from MODIS/Terra and Aqua are used for the period 2003–2017. The Collection-06 Level-3 MODIS-Merged DT–DB AOD spatial data were downloaded from NASA GES DISC (https://giovanni.gsfc.nasa.gov/giovanni/), while for validation, Level-2 MODIS-Merged DT–DB AOD point data have been downloaded from https://giovanni.gsfc.nasa.gov/mapss/. AERONET is a worldwide ground-based remote-sensing aerosol network partnership established by NASA in the 1990s (Toledano et al. 2007). In this work, level-2 daily mean AODs at 500 nm from AERONET have been interpolated to a common wavelength of 550 nm based on the power law (Ali et al. 2017). Table 1 displays the information from the eight AERONET stations and their data period over the Arabian Peninsula.

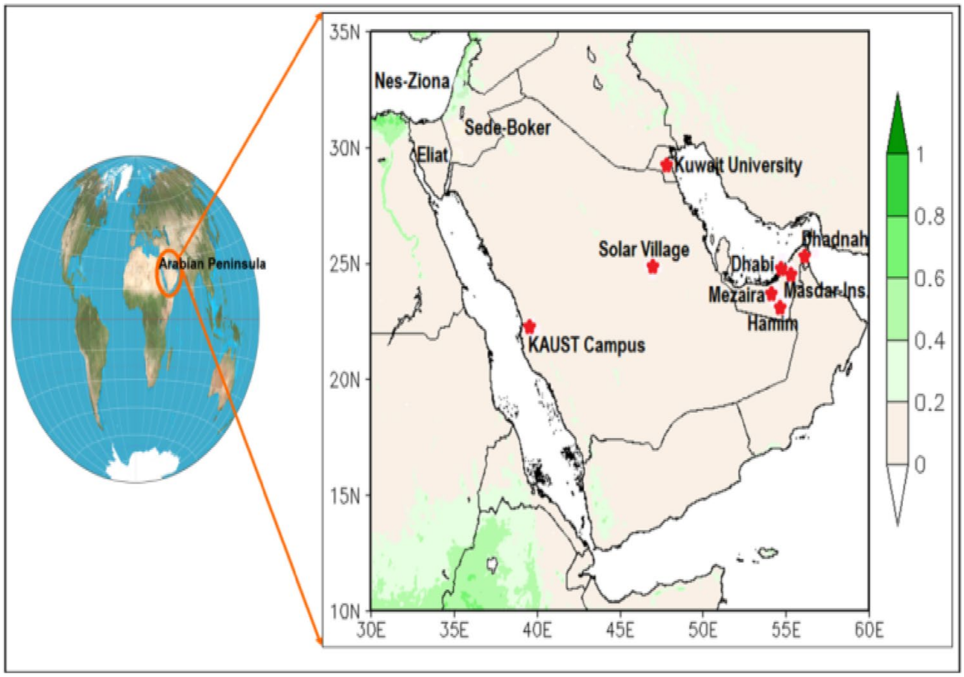


Fig. 1 Map of the study area with AERONET station sites used for evaluating Terra/Aqua on-board MODIS-Merged DT–DB AOD (550 nm) over the Arabian Peninsula. The Normalized Difference Vegetation Index (NDVI) is shown in color

Table 1 Geographic information in each AERONET sites over Arabian Peninsula

Country	Site name	Lon (°E)	Lat (°N)	Altitude (m)	Data observing period
Saudi Arabia	KAUST Campus	39.103	22.305	11	Feb, 2012–Mar, 2015
	Solar Village	46.397	24.907	764	Jan, 2003–May, 2013
Kuwait	Kuwait University	47.971	29.325	42	Nov, 2007–June, 2010
UAE	Dhabi	54.383	24.481	15	Jan, 2003–Aug, 2008
	Dhadnah	56.325	25.513	81	June, 2004–June, 2010
	Hamim	54.300	22.967	209	June, 2004–Jul, 2007
	Masdar-Institute	54.617	24.442	4	June, 2012–Nov, 2014
	Mezaira	53.779	23.145	204	June, 2004–Sept, 2014

2.3 Evaluation Methods

The slope, intercept, and significance are calculated using a linear regression method (Wilks 2006). The two factors such as slope and intercept affect the MODIS AOD products. The slope indicates the inaccuracy that arises because of the use of an imperfect aerosol model, while the intercept reflects incorrect surface reflectance estimation (Xie et al. 2011; Ali et al. 2017). A slope value of $m = 1$, and an intercept value of $c = 0$ represent a perfect match between MODIS and AERONET AODs. A negative intercept value reflects overestimation of the surface reflectance, while a positive value reflects underestimation. The correlation coefficient (r) between MODIS-Merged DT–DBAOD and AEROENT ground-based AOD AP is also calculated using the Pearson correlation coefficient method. Several methods such as RMSE (Root mean square error), MAE (mean absolute error), RMB (relative mean bias), and EE envelope (expected error) methods are used to calculate the uncertainty in the MODIS-merged DTDB-AOD products (Bilal et al. 2016; Georgoulias et al. 2016; Almazroui 2019). The above-mentioned methods are as follows

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{AOD}_{\mathrm{Satellite}} - \mathrm{AOD}_{\mathrm{AERONET}}\right)^2} \tag{2}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\left(\mathrm{AOD}_{\mathrm{Satellite}} - \mathrm{AOD}_{\mathrm{AERONET}}\right)\right| \tag{3}$$

$$\mathrm{RMB} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\mathrm{AOD}_{\mathrm{satellite}}}{\mathrm{AOD}_{\mathrm{AERONET}}}\right| \tag{4}$$

$$EE = \pm(0.05 + 0.2 \times AOD_{AERONET}). \tag{5}$$

In addition, a flow chart is provided which explains the step-by-step study working procedure (see Fig. 2). In this study, we have used MODIS Level-2 (point data downloaded link: https://giovanni.gsfc.nasa.gov/mapss/) and Level-3 (spatial data downloaded link: https://giovanni.gsfc.nasa.gov/giovanni/) AOD products at 550 nm. Level-3 is the global gridded averaging data and its format is NetCDF which visualized (desire lat/lon) using the GrADS tool. In contrast, Level-2 data are daily AOD from collocated AERONET and satellite-based MODIS retrievals. Level-2 data sets (AEROENT and MODIS AOD) are plotted based on the Matlab and Excel.

3 Results and Discussion

3.1 The AOD (550 nm) Spatial Distributions

Figure 3 shows the satellite (Terra and Aqua)-based MODIS Collection-06 Level-3 Merged DT–DB AOD patterns over

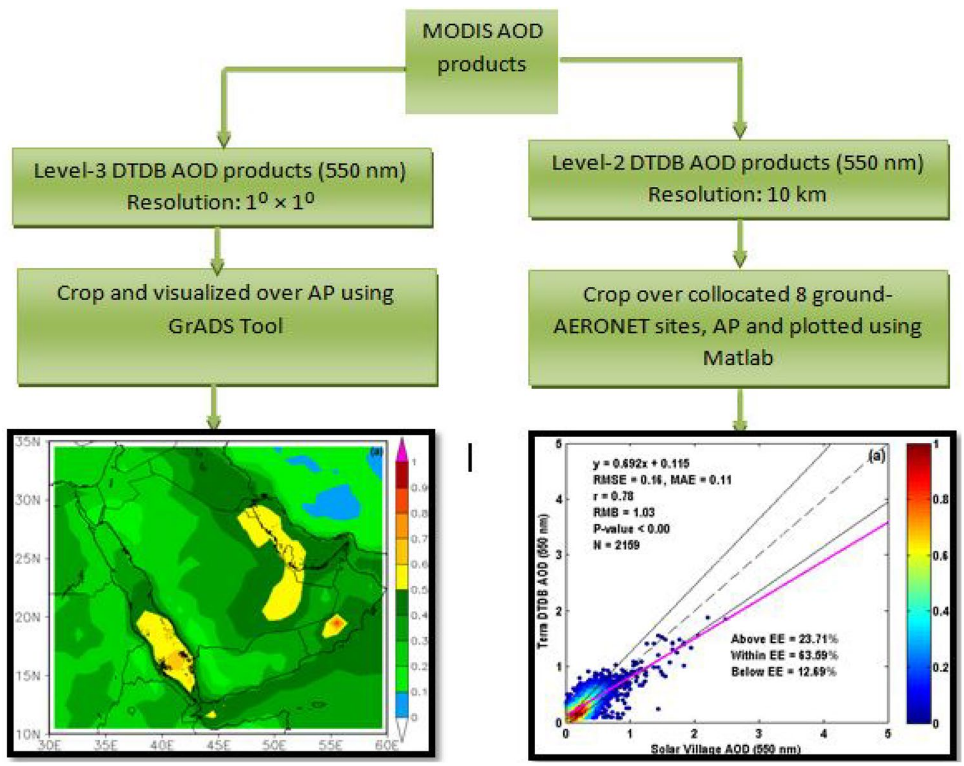


Fig. 2 Flow chart illustrating the step by step study working procedure

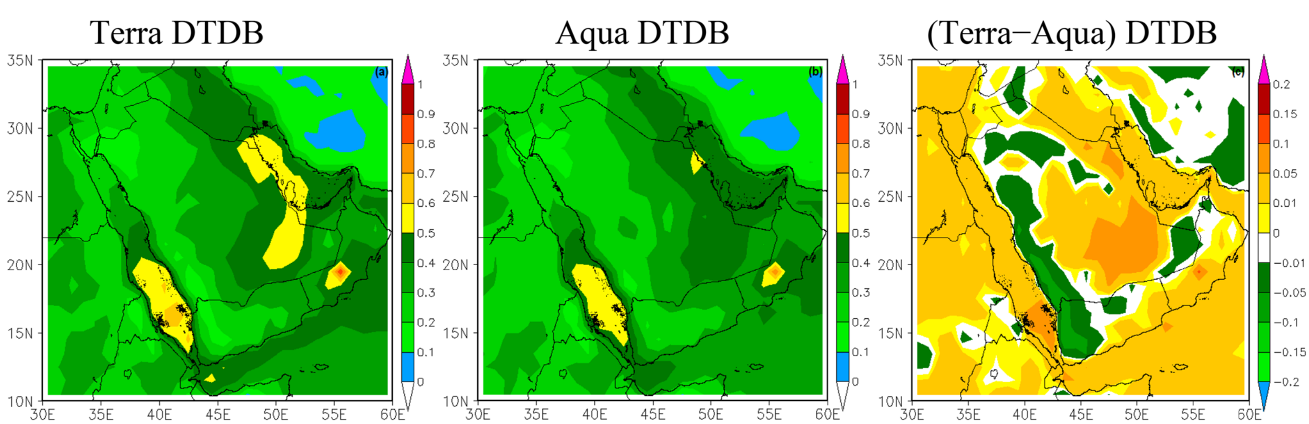


Fig. 3 Spatial distribution of combined DT−DB derived mean annual AOD (550 nm) from Terra and Aqua on-board MODIS monthly aerosol product over AP for the period 2003–2017. Panel **a** is for Terra, **b** for Aqua, and **c** for difference between the two

the Arabian Peninsula for the period 2003–2017. The Terra Satellite displays the highest AOD value (> 0.5) over the west coast of the Arabian Gulf that extends up to central Saudi Arabia as well as in the southern Red Sea (Fig. 3a), while Aqua shows the highest AOD (> 0.5) mostly over the southern Red Sea, as shown in Fig. 3b. The majority of the remaining areas of the Arabian Peninsula display comparatively low-to-moderate AOD levels (0.1−0.5). Furthermore, the subtraction between Terra (which crosses the equator at around 10:30 a.m.) and Aqua (which crosses the equator at about 01.30 p.m.) AOD measurements show large AOD spatial variations over the Arabian Peninsula, as shown in Fig. 3c. This variation might be related to the time difference between the Terra and Aqua satellites, as well as to the blending of two distinct algorithms (DT and DB) (Butt et al. 2017).

Seasonally, large contrasts in AOD patterns are observed over the Arabian Peninsula, as shown in Fig. 4. The merged DT-BD demonstrates the highest AOD measurements in JJA as compared to MAM, particularly over the eastern parts of the peninsula and the Red Sea (Fig. 4a, b, d, e). The Terra Satellite detects a higher AOD amount, particularly in the morning, which is absent from the Aqua Satellite (Fig. 4c, f). In contrast, the lowest AODs are recorded during DJF and SON seasons (Fig. 4g, h, j, k). It is also evident that Terra records slightly higher AOD during SON over major parts of the peninsula, while Aqua shows marginally higher AOD in DJF (Fig. 4i, l).

Several recent studies, however, (Farahat et al. 2015; Jin et al. 2018; Kumar et al. 2018) documented that high AOD values are evident over the Red Sea, and the eastern and southern regions of the Arabian Peninsula. The dust-related AODs are found in abundance over the eastern regions of Saudi Arabia during the MAM and JJA (Goudie and Middleton 2006). Frequent sand and dust storms are observed that enhance the AOD level over the eastern region (Alharbi et al. 2013) and over the Rub al Khali Desert (Farahat et al. 2015) in the peninsula. Sabbah and Hasan (2008) documented that the Solar Village records high levels of dust AODs in MAM. Finally, it is important to note from Figs. 3 and 4 that the AOD has a significant influence on different areas of the peninsula specifically the eastern, southern, and Red Sea coasts due to their desert characteristics, vehicular releases, weighty industrial, and other human activity. Hence, it is concluded that the frequent sand and dust storms associated with industrial actions demonstrate the AOD variations over the various Arabian Peninsula regions.

3.2 Temporal Variations and Trends of AOD

The comparisons between the annual means and standard deviations (SD) of MODIS-Merged DT–DB AOD products and AERONET ground stations data over the peninsula are shown in Fig. 5. The AOD is categorized based on three different threshold values: AOD > 0.5 indicates peak, AOD = 0.20–0.50 defines moderate, and AOD < 0.20 belongs to lower. Both the Terra and Aqua display almost the similar mean annual AOD variations as measured by the AERONET (Fig. 5a, b). Among the eight stations, Kuwait University shows the maximum mean annual AOD in the peninsula. The collocated AOD value is 0.59 (0.57) for Terra (AERONET) and 0.58 (0.61) for Aqua (AERONET). The moderate AODs are observed at the remaining seven stations. The increasing trends of annual AOD are observed for Kuwait University, Dhabi and Hamim stations, while decreasing trends are seen at KAUST and Masdar-Institute. The Solar Village shows (for Aqua) a slightly increasing trend, while Dhadnah and Mezaira show an almost stable condition. In light of the above, it is, therefore, concluded that the AOD is changing (increasing/decreasing) at different locations in the Arabian Peninsula. Using Aqua product, Farahat (2018) also showed increasing AOD trends over the Solar Village as well as a stable trend over Mezaira.

Seasonally, Kuwait University shows the peak AOD, while the rest of the seven stations show moderate AOD in all seasons (Fig. 6). A mixture of increasing and decreasing (including almost stable situation) AOD trends is observed over the Arabian Peninsula. Increasing trends are found for Kuwait University (SON and DJF), Dhabi (JJA), Hamim (JJA), and Mezaira (MAM and JJA). Decreasing trends are observed for KAUST (MAM, JJA, and SON) and Masdar-Institute (JJA and SON). Stable conditions are found for Solar Village and Dhadnah (all seasons), KAUST (DJF), Kuwait University (MAM and JJA), Dhabi and Hamim (MAM, SON, and DJF), Masdar-Institute (MAM and DJF), and Mezaira (SON and DJF).

3.3 Evaluation of MODIS-Merged DT–DB AOD Against AERONET AOD

Figure 7 shows the significant underestimation (slope < 1, intercept positive) of AOD by satellite for Solar Village, KAUST, Kuwait and Masdar-Institute as compared to AERONET. This indicates the inaccuracy of surface reflectance calculation and selection of aerosol model schemes in the Look-Up Table for the Arabian Peninsula. It is observed that Aqua has the better (EE = ~ 60−87%) retrievals of AOD which fall within the Expected Error (EE) envelope for seven stations, whereas the Terra shows the better retrieval of AOD only for one station (EE = ~ 81%). The satellite AOD is within EE range for Dhabi, Dhadnah, Hamim, and Mezaira stations. The RMSE is found less than 0.2 for all stations except for Kuwait University. The MAE is less than 0.1 for KAUST, Dhabi, Hamim, and Mezaira, while other stations show above 0.1. It is important to mention that most of the

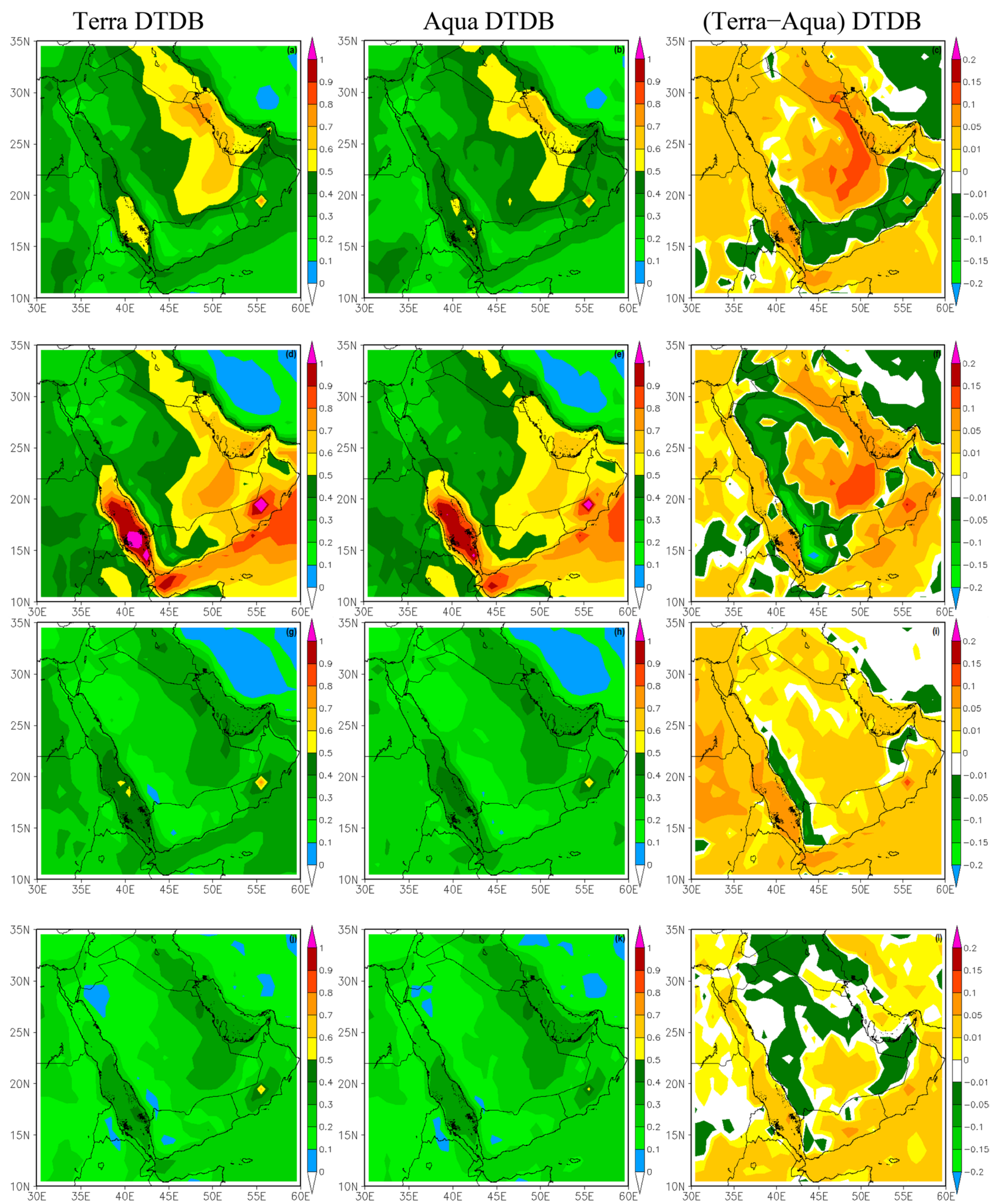


Fig. 4 Seasonal spatial distribution of combined DT−DB AOD (550 nm) obtained from Terra and Aqua Satellite on-board MODIS monthly aerosol product over the Arabian Peninsula for the period 2003–2017 for MAM (**a–c**), JJA (**d–f**), SON (**g–i**), and DJF (**j–l**)

AODs lie within 1. Therefore, the overall AOD underestimation by satellite can be somewhat misleading. The fact is that RMB indicates the overestimation (RMB > 1) of AOD for all stations for both Terra and Aqua, except the Aqua underestimate for Solar Village, Kuwait University and Dhadnah. Seasonally, both Terra and Aqua overestimate for all seasons at KAUST, Dhabi, and Mezaira (not shown). AOD underestimation by satellite is observed for all seasons at Dhadnah except for overestimation for Terra (MAM and DJF). At Solar Village, Terra overestimates for JJA and DJF, while it underestimates for MAM and SON. The Aqua underestimates for all seasons except for the calculation of AERONET for DJF.

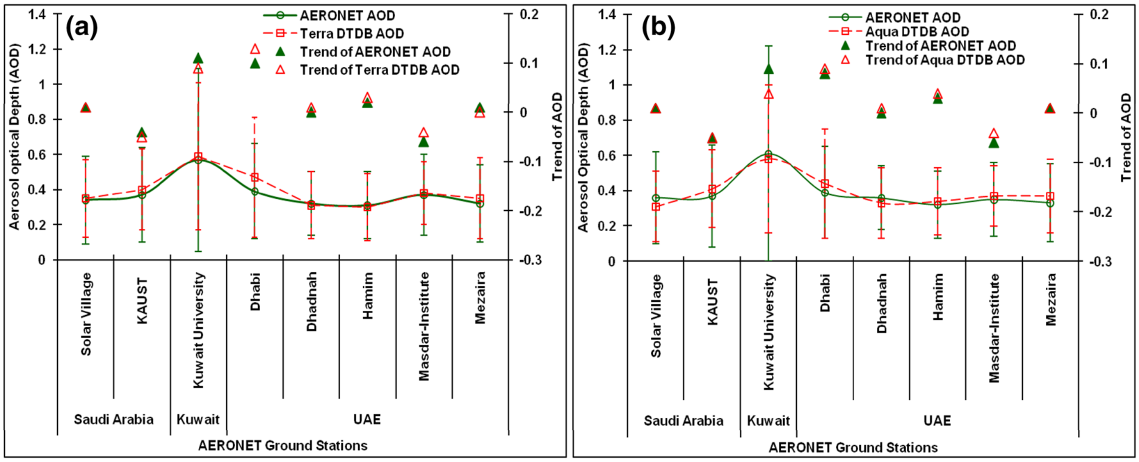


Fig. 5 Variations of mean annual AOD obtained from Terra MODIS-Merged DT−DB and AERONET ground stations over Arabian Peninsula. Panel **a** is for Terra Satellite and **b** for Aqua Satellite

The current study is the first research on the Collection-06 MODIS-Merged DT–DB AOD and its validation against ground-based AEROENT AOD over the Arabian Peninsula. However, the MODIS DB, DT, and merged DT–DB products have been evaluated widely in different regions of the globe. Georgoulias et al. (2016) studied the AOD using DB, DT, and merged DT–DB aerosol products over the greater mediterranean region and documented that Collection-06 has the better agreement with AEROENT AOD. Over north China, Zhang et al. (2016) noted that the Collection-06 Merged DT–DB shows the better estimation of AOD over the Background site, while it is overestimated over the urban areas due to the surface estimation error. In contrast, Zhang et al. (2017) noted that the merged DT–DB aerosol product needed to be improved. It is documented by Mhawish et al. (2017) that the merged aerosol products show the better concurrence with ground-based AEROENT data over the Indo-Gangetic Plain. They also pointed out that the MODIS Collection-06 demonstrates the reliability of the aerosol type and surface reflectance estimation. Other researchers also reported similar results (e.g., Xie et al. 2011; More et al. 2013; Misra et al. 2015).

4 Conclusions

In this paper, the Collection-06 MODIS-Merged DT–DB aerosol products (550 nm) from Terra and Aqua satellite are utilized to portray the AOD spatial distributions as well as temporal variations over the Arabian Peninsula during the period 2003–2017. The MODIS-Merged DT–DB AOD is also evaluated against AERONET ground station-based AOD (550 nm). The ground stations are located over Saudi Arabia (the Solar Village, KAUST Campus), Kuwait (Kuwait University), and the UAE (Dhabi, Dhadnah, Hamim, Masdar-Institute, and Mezaira). The highest AOD is recorded from the Terra Satellite over the west coast of the Arabian Gulf that extends up to central Saudi Arabia and the southern Red Sea, while the Aqua Satellite records similar AOD values mostly over the southern Red Sea. Kuwait University, Dhabi, and Hamim stations demonstrate annually AOD increasing trends, whereas KAUST and Masdar-Institute display decreasing trends. A virtually stable AOD condition is found at the Solar Village (for Aqua a slightly increasing trend), and Dhadnah, and Mezaira show an almost a stable condition. Better AOD retrievals are noted for Aqua Satellite over the seven AEROENT stations, whereas only one station shows better retrievals of AOD for Terra Satellite. Both Terra and Aqua demonstrate the overestimation (RMB > 1) of AOD for all stations, excluding the Aqua underestimation for Solar Village, Kuwait University, and Dhadnah. The use of inappropriate aerosol model schemes and inaccurate surface reflectance estimates in the Look-Up Table leads to the underestimation and overestimation of AOD over the study area.

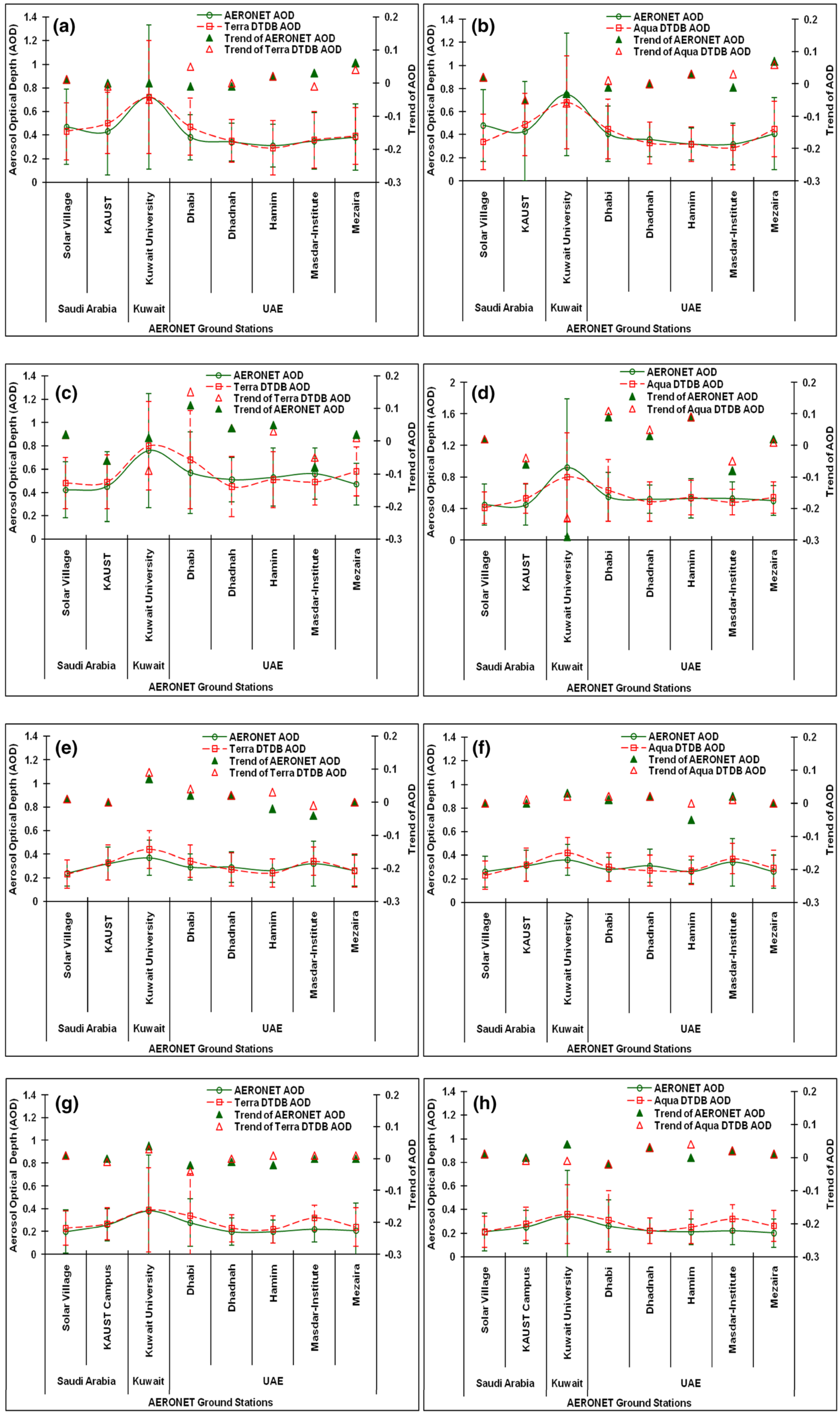


Fig. 6 Terra (left panels) and Aqua (right panels) on-board MODIS-Merged DT–DB and AERONET ground stations–AOD variations over the Arabian Peninsula for MAM (**a**, **b**), JJA (**c**, **d**), SON (**e**, **f**), and DJF (**g**, **h**)

Fig. 7 Overall comparison of Satellite (Terra and Aqua) on-board MODIS-Merged DT−DB AOD and AERONET ground stations measured AOD for Saudi Arabia (panels' **a**–**d**), Kuwait (**e**, **f**), and the UAE (**g**–**p**). Left-side panels correspond to Terra Satellite and right-side panels correspond to Aqua Satellite. The normalized data density is shown in color. The black dash line = 1:1, black solid lines = EE lines, and solid light magenta line = regression line

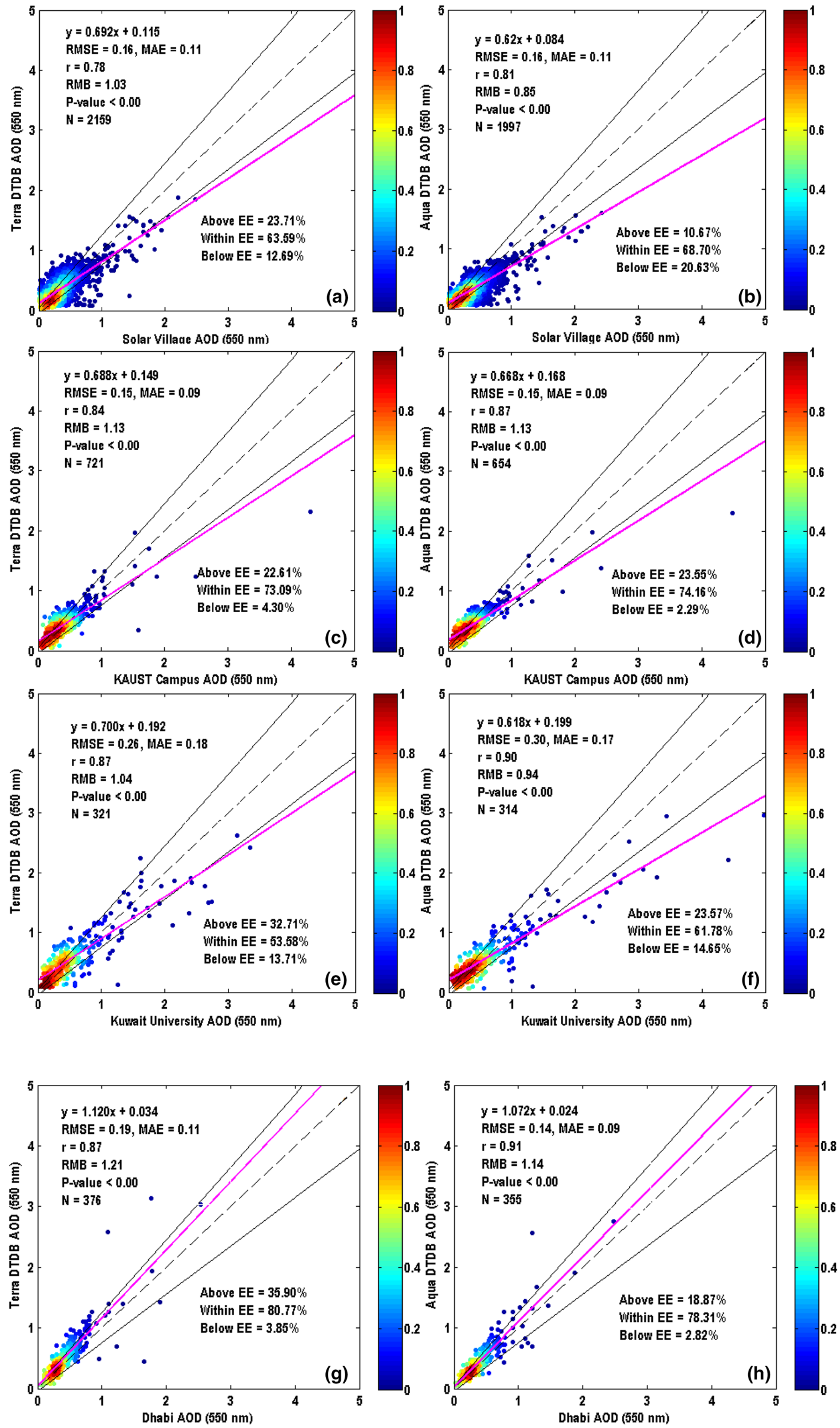
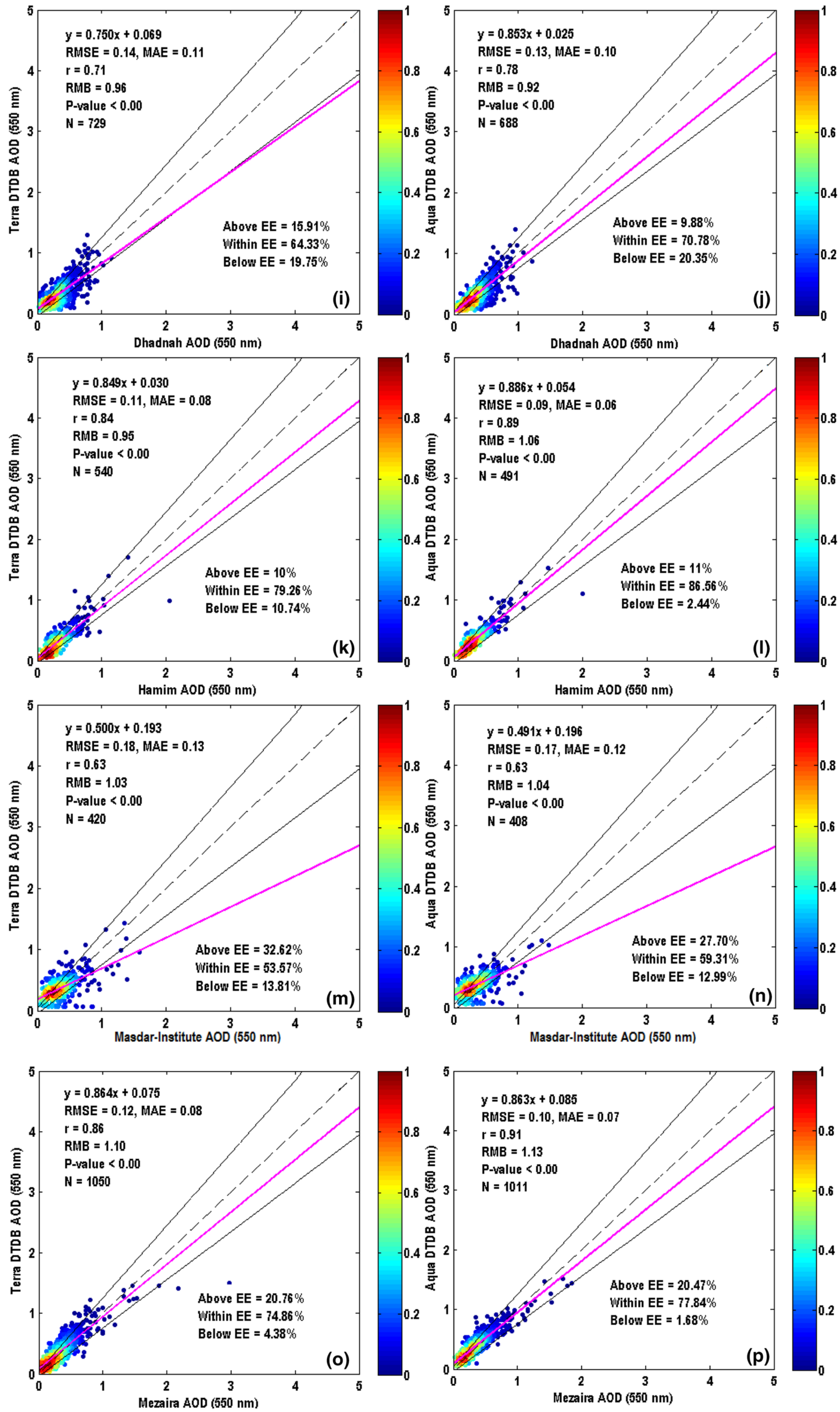


Fig. 7 (continued)



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