Comparative Analysis of MODIS, MISR and AERONET Climatology over the Middle East and North Africa

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Abstract:

Comparative analysis of MISR, MODIS, and AERONET AOD products performed over seven AERONET stations located in the Middle East and North Africa for the period of 2000 – 2015. Sites are categorized into dust, biomass burning and mixed. MISR and MODIS AODs agree during high dust seasons but MODIS tends to underestimate AODs during low dust seasons. Over dust dominating sites, MODIS/Terra AOD indicates a negative trend over the time series, while MODIS/Aqua, MISR, and AERONET depict a positive trend. A deviation between MODIS/Aqua and MODIS/Terra was observed regardless of the geographic location and data sampling. The performance of MODIS is similar over all region with ~68% of AODs within the $\Delta\tau = \pm 0.05 \pm 0.15\tau_{AERO}$ confidence range. MISR AOD retrievals fall within 72% of the same confidence range for all sites examined here. Both MISR and MODIS capture aerosol climatology; however few cases were observed where one of the two sensors better captures the climatology over a certain location or AOD range than the other sensor.

Keywords: AOD; Remote Sensing; North Africa; Middle East; Validation

1. Introduction

The Middle East and North Africa host the largest dust source in the world, the Sahara Desert in North Africa that may be responsible for up to 18 percent of global dust emission (Todd et al., 2007, Bou Karam et al. 2010, Schepanski et al. 2016). The vast 650,000 km^2 Rub' al Khali (Empty Quarter) sand desert is a major source of frequent dust outbreaks and severe dust storms that has major effects on human activities in the Arabian (Böer, 1997 Elagib and Addin 1997, Farahat et al., 2015).

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Air quality over the Arabian Peninsula has received significant attention during the past 15 years due to unprecedented overall economic growth, and a booming oil and gas industry, however, air pollution studies are still far from complete. Frequently blowing dust storms play a significant role in pollutant transport over the Arabian Peninsula; and major environmental pollution events such as burning of Kuwait oil fields during the 1991, Gulf War resulted in a large environmental impact on the Arabian Gulf Area Sadiq and McCain (1993) and Farahat 2016.

Aerosol optical depth, AOD, is a parameter to measure the extinction of a beam of light as it passes through a layer of atmosphere that contains aerosols. Both satellites and ground-based instrument can be used to measure AOD in the atmosphere, but within the same temporal coordinates and geographic location different instrument could generate different retrievals Kahn et al., 2007, Kokhanovsky et al., 2007, Liu et al., 2008 and Mishchenko et al., 2009.

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Since the turn of the 21st century, an upward trend of remotely sensed and ground-based AOD and air pollutants was observed over the Middle East and North Africa (El-Askary 2009, Ansmann et al. 2011, Yu et al. 2013, Chin et al. 2014, Yu et al. 2015, Farahat et al. 2016, Solomos et al. 2017. This positive trend is attributed to the increase in the Middle Eastern dust activity (Hsu et al., 2012) due to changes in wind speed and soil moisture Ginoux et al. 2001 and Kim et al. 2013. (Yu et al., 2015) concluded that the persistent of the La Niña conditions (Hoell et al., 2013) have caused increment in Saudi Arabian dust activity during 2008 – 2012. Energy subsidies also encourages over energy consumption in the Middle East and North Africa with little incentive to adopt cleaner technology. Lack of applying strict environmental regulations have permitted exacerbated urban air pollution.

During the last two decades, a large number of satellites, ground stations and computational models contributed to build global and regional maps for the temporal and spatial aerosol distributions. While, ground-based stations and field measurements can identify aerosols properties over specific geographic locations, the spare and non-continues data from ground-based sensors scattered over the Middle East and North Africa is not sufficient to provide information on spatial and temporal trends of particulate pollution. On the other hand, satellites imagery could provide a significant source of data mapping over larger areas.

For its wide spatial and temporal data availability space-born sensors are important sources to understand aerosols characteristics and transport, however low sensitivity to particle type under some physical conditions, high surface reflectivity, persistent cloud, and generally low aerosol optical depth could limit satellite data application in characterizing properties of airborne particles, especially in the Middle East.

In order to evaluate the efficiency of space-borne sensors in representing ground observations recorded by AERONET stations we have performed detailed statistical inter-comparison analysis between satellite AOD products and AERONET for seven stations in the Middle East and North Africa representative for dust, biomass burning, and mixed aerosol conditions (Dubovik et al., (2000, 2002, 2006), Holben et al. (2001), Derimian et al., (2006), Basart et al. (2009), Eck el. (2010), Marey et al., 2010, Abdi et al., (2012)). Previously we analysed these seven AERONET stations to understand particles categorization and absorption properties (Farahat et al. 2016), and the current study extends the analysis to the satellite datasets.

In the first part of this article, we validated MISR and MODIS retrievals against collocated AERONET observations. We also assessed the consistency in aerosol trends between space-borne sensors and ground-based data.

In the second part, we evaluated representativeness of satellite-derived aerosol climatology over the study region from the long-term AERONET data for MISR and MODIS AOD products. It is especially relevant for the MISR instrument, as its sampling is limited by once per week observations of the same region from the two overlapping paths. MODIS provides nearly daily observations to the same geographic location; however, the quality of the product diminishes over the bright targets potentially affecting MODIS-derived aerosol climatology. The collocated MISR, MODIS and AERONET data were obtained at the MAPSS website (http://giovanni.gsfc.nasa.gov/mapss.html).

2. Materials and Methods

2.1 MISR

The Multi-angle Imaging SpectroRadimeter (MISR) instrument to measures tropospheric aerosol characteristics through the acquisition of global multi-angle imagery on the daylight side of Earth. MISR applies nine Charge Coupled Devices (CCDs), each with 4 independent line arrays positioned at nine view angles spread out at nadir, 26.1º, 45.6º, 60.0º, and 70.5º. In each of the nine MISR cameras, images are obtained from reflected and scattered sunlight in 4 bands blue, green, red, and near-infrared with a centre wavelength value of 446, 558, 672, and 867 nm respectively. The combination of viewing cameras and spectral wavelengths enables MISR to retrieve aerosols AOD over high reflection surfaces like deserts.

In this study, we use MISR version 22 (V22) AOD retrievals at 558 nm (green band) measured by MISR instrument with a 17.6 km resolution aboard the Terra satellite. MISR Level 2 aerosol retrievals use only data that pass angle-to-angle smoothness and spatial correlation tests (Martonchik et al. 2002), as well as stereoscopically derived cloud masks

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and adaptive cloud-screening brightness thresholds (Zhao and Di Girolamo, 2004). MISR version 23 (V23) retrievals, released on February 2018, was not used in this study, as it has few known issues with the new product that are still under formal validation. Some of these known issues are related to data reliability over bright surfaces compared to dark water, which is significant for our analysis (Garay et al., 2018).

2.2 MODIS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a payload instrument on board the Terra and Aqua satellites. Terra's and Aqua orbit around the Earth from North to South and South to North across the equator during the morning and afternoon respectively (Kaufman et al., 1997). Terra MODIS and Aqua MODIS provides nearly daily coverage of the Earth's surface and atmosphere in 36 wavelength bands, ranging from 0.412 to 41.2 µm, with spatial resolutions of 250 m (bands 1-2), 500 m (bands 3-7), 1000 m (bands 8-36). Located near-polar orbit (705 km), MODIS has swath dimensions of 2330 km × 10 km and a scan rate of 20.3 rpm. With its high radiometric sensitivity and swath resolution MODIS retrievals provides information about aerosols optical and physical characteristics. MODIS uses 14 spectral band radiance values to evaluate atmospheric contamination and determine whether scenes are affected by cloud shadow (Ackerman et al., 1998).

The Deep Blue is a NASA developed algorithm to calculate AOD over land using MODIS data. Bu measuring contrast between aerosols and surface features, Deep Blue retrieves AOD. Over bright land, Deep Blue uses (0.412, 0.470/0.490 µm) and dark land (0.470/0.490, 0.650 µm) for AOD retrievals. Over water, the Deep Blue algorithm is not used.

The MODIS dark-target algorithm derives aerosol characteristics, including AOD, over ocean (dark in visible and longer wavelengths) and dark land surfaces (low values of surface reflectance) (e.g., dark soil and vegetated regions) in parts of the visible (VIS, 0.47 and 0.65 µm) and shortwave infrared (SWIR, 2.1 µm) spectrum (Kaufman et al., 1997).

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Level 2 collection 6.1 of the algorithm are used to retrieve MODIS aerosols' time series data. Levy *et al.* (2010) reported that the dark-target algorithm AOD at 550 nm measurement for (C005) includes uncertainty of $\pm (0.05\tau+0.03)$ and $\pm (0.15\tau+0.05)$ over ocean and land respectively. This uncertainty is caused by uncertainties in computing cloud masking, surface reflectance, aerosol model type (e.g., single scattering albedo), pixels selections and instrument calibration. Both dark target and deep blue algorithms have been used. Dark target retrievals were used over water regions while deep blue data were used over land. Data are available at https://giovanni.gsfc.nasa.gov/giovanni. For regions like Bahrain where large water body surrounds land, a combined Dark Target and Deep Blue AOD for land and Ocean has been applied.

2.3 AERONET

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The Aerosol Robotic Network (AERONET) Holben et al., 1998 and Holben et al., 2001 is a ground-based remote sensing aerosols network that provides a long-term data related to aerosol optical, microphysical and radiative properties. With over 700 global stations, the AERONET data is widely used in validating satellite retrievals Chu et al., 1998 and Higurashi et al., 2000.

The sun photometers used by AERONET include sun collimators to measure spectral direct-beam solar radiation. The collimators are used to determine columnar spectral AOD and water vapour, provided at a temporal resolution of approximately 10–15 min (Sayer et al. 2014). AERONET direct-sun AOD has a typical uncertainty of 0.01–0.02 (Holben et al., 1998) and is provided at multiple wavelengths at 340, 380, 440, 500, 675, 950, and 1020 nm. Seven AERONET sites were selected for MODIS/ Terra, MODIS/ Aqua, and MISR/Terra satellites validation in this study (Table 1.). The sites were selected based on their geographic locations to represent aerosols characteristics over North Africa and the Middle East (Farahat

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et al., 2016). A record of long-term data collection was another factor in the selection process. Level 2.0 Version 3 AERONET data available at https://aeronet.gsfc.nasa.gov have been used in the study.

Data Matching Approach

Multi-sensors data matching approach requires using only spatial and temporal matching data to reduce uncertainties associated with using different instruments and clouds shadow Liu and Mishchenko (2008) and Mishchenko et al., 2009.

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The comparison of MISR and MODIS products against AERONET is performed to evaluate satellites' retrieval over individual North Africa and Middle East sites (see Table 1). There is only a small number of AERONET measurements that are perfectly collocated with MODIS and MISR. One way to work with this lack of compatibility problem is to compare satellites measurements nearby a certain AERONET site and comparing AERONET measurements nearly synchronized with the satellite overpass time (Sioris et al. 2017). Another reasonable strategy is to average all satellite measurements with a certain distance of an AERONET location and average all AERONET measurements within a certain time range (Mishchenko et al., 2010). The results presented in this paper are based on the second approach as it compares average spatial satellite measurements with average temporal AERONET measurements. We implemented (Basart et al., 2009) approach in using a spatial and temporal threshold of 50 km and 30 min for MISR, MODIS, and AERONET data matching.

We use the Giovanni Multi-sensor Aerosol Products Sampling System MAPSS (http://giovanni.gsfc.nasa.gov/aerostat/) for the data inter-comparison as aerosols products are averaged from measurements that are within a radius of ~ 27.5 km from the AERONET station and within 30 min of each satellite flyover over this location. These data are represented in the article by MISR / MODIS "matched AERONET data".

"All data" represents AOD products at the selected station. AERONET station 'all data' are obtained through AEROSOL ROBOTIC NETWORK (AERONET) website (https://aeronet.gsfc.nasa.gov/). Daily AOD data with level 2.0 quality was used in the analysis (Smirnov et al., 2000) . Level 2.0 AOD retrievals are accurate up to 0.02 for mid-visible wavelengths.

MISR 'all data' is available through MISR website (https://www-misr.jpl.nasa.gov/getData/accessData/).

3. Statistics

We have used two statistical parameters to compare data retrievals from space-borne and ground based sensors including:

(1) Correlation coefficient (R),

The correlation coefficient is a parameter to measure data dependence. If the value of R is close to zero, it indicates weak data agreement. And values close to 1 or -1 indicate that data retrievals are positively or negatively linearly related (Cheng et al., 2012).

(2) Good Fraction (Gfraction).

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The G- fraction indicator uses a data confidence range defined by MISR and MODIS Bruegge et al., 1998 and Remer et al., 2005 over the land and ocean that combines absolute and relative criterion and weights data equally such that small abnormalities will not affect the inter-comparison statistics (Kahn et al., 2009). In this study, we use MODIS confidence range which defines data retrieval as "good" if the difference between MODIS and AERONET is less than

$$\Delta\tau = \pm 0.03 \pm 0.05\tau_{AER}, \quad \text{Over ocean,} \qquad (1)$$

$$\Delta\tau = \pm 0.05 \pm 0.15\tau_{AER}, \quad \text{Over land.} \qquad (2)$$

where τ_{AER} is the optical depth retrieved using AERONET stations. The Gfraction is the percentage of MODIS data retrievals that satisfies (Equations (1) and (2)) over ocean and land respectively. Optical depth threshold over land (Equation (2)) is higher than over ocean (Equation (1)) due to harder data retrievals and high data instability over land.

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A good aspect of using data confidence range is excluding small fraction data outliers from producing inexplicably large influence on comparison statistics by weighting all events equally.

4. Results and discussion

4.1 Validating MISR and MODIS AOD retrievals against AERONET observations over the Middle East and North Africa

Illustrated in Figures 2, 3 and Tables 2, 3 is a regression analysis of MISR and MODIS Terra AOD products against AERONET AOD over the seven AERONET sites, shown in Table1, from 2000 – 2015.

The correlation coefficient between MISR and AERONET AOD at region 1 is equal to or above 0.85 except in Bahrain during DJF and JJA (Figure (2) and Table 2), which could be attributed to lack of data and the impact of water surface reflectivity over Bahrain. Similar correlation coefficient values were found in region 2 where MISR-AERONET AOD shows less error than MODIS (Figures (2, 3) and Table 3). In general, MODIS-AERONET AOD correlation coefficient is lower than those of MISR at all sites, except Mezaira, where MISR and MODIS matched AERONET AOD correlation almost match. The lowest MODIS-AERONET AOD correlation coefficient was found over Cairo but could be attributed to the lack of data availability at this location (Figs 3e-h). Low values of MODIS-AERONET correlation coefficient is also found over Saada, Taman, and Sedee Boker sites.

Over all AERONET stations, the number of MODIS AERONET matched AODs are 4 to 8 times those of MISR which is expected from the MISR's sampling.

Comparisons show that the difference between MISR and MODIS retrievals at the selected AERONET sites could be significant as expected from the MODIS Dark Target algorithm performance over bright land surfaces Kokhanovsky et al. (2007).

High AOD values over regions 1 and 2 measured by both AERONET and satellites' sensors indicate higher dust activities that peaks during May – Aug during dust storms season. Higher AOD values recorded during SON over Cairo station could be caused by seasonal rice straw burning by farmers in Cairo, an environmental phenomena known as Cairo Black cloud (Marey et al. 2010). As shown in (Figure (3)), the daily variability in MODIS measurements is larger than those of MISR at all the three regions. In general, MODIS tends to underestimate the AOD values on low dust seasons (Figures (2, 3) and Tables 2, 3).

The MODIS underestimated AOD values is more noticeable over Bahrain. This could be attributed to large water body surrounding Bahrain, which should affect surface reflectivity. Moreover, water in the Arabian Gulf has been polluted in recent years (Afnan 2013), leading to possible changes in watercolour and uncertainties in calculating surface reflectivity. The patchy land surface or pixel grid contaminated by water body is the dominant error sources for MODIS aerosol inversion over the land areas (He et al. 2010).

Compared to MODIS, MISR's outperform in retrieving AOD over region 1 including vast highly reflecting desert areas can be attributed to its multispectral and multi-angular coverage, which make MISR provides better viewing over a variety of landscapes. Meanwhile, MISR retrieval also take into consideration aerosols' particles nonsphericity, which could have significant effect on its AOD retrievals (von Hoyningen-Huen and Posse 1997). MISR's retrieval did not well perform over Cairo site due to lack of matched points in most of the seasons (13 in DJF, 5 in MAM & JJA, and 4 in SON during 2000 - 2015).

4.2 Trends of AOD MISR, MODIS, and AERONET retrievals over the Middle East and North Africa

Figure 4 shows time series of monthly mean AOD derived from MODIS/Aqua, MODIS/Terra, MISR and AERONET over a) dust b) biomass and c) mixed dominated aerosol regions. The satellite AOD trends are calculated from the data collocated with AERONET observations.

Trends of aerosol loading from 2000 to 2005 are analysed by plotting fitting lines of monthly mean AOD retrievals by MISR and MODIS/Terra and Aqua. The AOD retrieved by different instrument shows different trends. MODIS/ Aqua and MISR AOD at Solar Village have positive trends, while MODIS/ Terra AOD have negative trends along time series (Fig. 4a). Terra depicts a negative correlation coefficient with time while Aqua shows a positive one. Terra AOD decreases 0.0071/year, while Aqua increases 0.0015/year. Aqua have lower correlation coefficient for AOD compared to Terra, which indicates Aqua performed more stable during the study period. Discrepancy between Aqua and Terra retrievals could be related to instrument calibration, or the difference in aerosol and cloud conditions from the morning to the afternoon. Both MODIS Aqua and Terra are underestimating AOD at Solar Village. MISR AOD trend shows a better agreement with Solar Village AERONET AOD as compared to MODIS.

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In order to understand whether the discrepancy temporal trend of Terra and Aqua is a result of regional conditions or if it exists in all sites, we investigated Terra, Aqua, MISR, and AERONET over other sites.

Both MODIS/Aqua and MODIS/Terra AOD show a stable trend over time at Mezaria site (not shown in the figure) with a correlation coefficient of 0.11 and 0.04 respectively. Both Terra and Aqua AOD increase 0.008 and 0.001/year, respectively. Aqua AOD over Bahrain

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(not shown in the figure) show, less time trend stability compared to those at Solar Village with a correlation where Terra AOD decreases 0.0027/year, while Aqua increases 0.0066/year. Although Solar Village, Mezaria, and Bahrain are all located in or next to a desert region, the inconsistency between Terra and Aqua measurements is subject to the regional conditions. For example, the large water body surrounding Bahrain could mean that the great majority of the MODIS retrievals are from Dark Target algorithm. MODIS/Aqua, MODIS/Terra, and MISR AODs depicts a positive trend over Cairo, however a 2 years of available AERONET data is not sufficient for the trend analysis (Fig. 4b). Over Cairo, MODIS/Terra, MODIS Aqua, and MISR measurements agree on AOD increase by 0.001, 0.0007, and 0.0007/year respectively with correlation coefficients 0.10, 0.04, and 0.22 respectively. Despite the deviation between the three aforementioned sensors, they all agree on AOD temporal trend increase over Cairo. This could be attributed to the high pollution level at the mega city of Cairo due to high population, vehicle emission, and biomass burning. Taman site (Fig. 4c): MISR AOD agrees with Taman AERONET on a positive trend indicating the efficiency of MISR V22 algorithm over green areas with less black carbon particles. Aqua measurements show temporal AOD decrease of 0.0079/year with a correlation coefficient of 0.81 and Terra show AOD decrease of 0.0043/year with a correlation coefficient of 0.35. Meanwhile, MISR shows AOD increase of 0.0014/year with a correlation coefficient of 0.19.

Long-range (2000 – 2015) tendency indicates that contradictory AOD trend of Terra and Aqua is individually explicit for each site and does not necessarily apply everywhere.

AOD difference between Terra and Aqua could be used as another indicator of the long-range satellites performance. AOD difference (Terra AOD minus Aqua AOD) varies from -0.01 to 0.19, -0.10 to 0.18, -0.02 to 0.13 over Solar Village, Taman, and Cairo respectively (Fig. 5). Over the Solar Village, Terra overestimates AODs during 2002-2004 and

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Deleted: indicating data stability over this site underestimates the AOD after 2005. Although Cairo and Taman show similar trend however over/underestimation amount is not unique for all sites. This is an indication that Aqua and Terra retrievals disagreement takes place regardless of the region but site sampling has significant effect on the amount of contradiction.

Statistical comparison between MISR and MODIS/Terra AODs at corresponding AERONET stations is performed by calculating Gfraction using of $\Delta\tau = \pm 0.05 \pm 0.15\tau_{AERO}$ as a confidence interval. Over the region 1, MISR AODs retrievals are more accurate than MODIS retrievals. MODIS, however, perform better over region 2 sites with high percent of the data points falling within the confidence range (Tables 2 and 3). High light reflections from the desert landscape surrounding region 1 could have an effect on MODIS retrievals.

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Excluding Bahrain and Cairo for low data retrievals the performance of MODIS tends to be similar over all region with ~ 68 percent of AODs retrievals fall within the $\Delta\tau = \pm 0.05 \pm 0.15\tau_{AERO}$ confidence range of the AERONET AOD while MISR retrievals show better data performance with ~ 72 percent falls within the same confidence range. This could be attributed to low number of retrievals available for Bahrain and Cairo compared to other sites. Vast sea region surrounding Bahrain and complex landscape in Cairo could also have an impact on retrievals.

4.3 Evaluating the MISR and MODIS climatology over Middle East and North Africa

Comparisons between MISR and MODIS AOD at selected AERONET stations over the 2000 – 2015 period are illustrated in Figures 6- 12.

Figure (6a, b) shows histogram of the MISR, MODIS and AERONET AOD at Solar Village for MISR and MODIS data points collocated with AERONET observations. The mean, standard deviation, and number of measurements are also presented.

MISR tends to underestimate the frequency of low AODs compared to AERONET but overestimate the frequency of high AODs. MISR histograms show prominent peaks at 0.55

and 0.75 not seen in AERONET. MISR and AERONET AOD climatology agree well with one another. MODIS also tends to underestimate the frequency of low AOD events and overestimate the frequency of high AOD events. High surface reflectance could cause overestimation in MODIS AODs (Ichoku et al., 2005). Both MISR and MODIS provide a good representation of the AOD climatology as compared to AERONET at the Solar Village. Mezaria station, which is located at an arid region in the UAE, has a similar climatology to the Solar Village site with dust dominating aerosol. Figure (7a, b) shows histogram of the MISR, MODIS and AERONET AOD at Mezaria.

Unlike Solar Village, there is a big difference between the number of samples in the matched data set and full AERONET climatology. For MISR there are 116 matched cases and for MODIS there are 498 compared to the 1517 for the entire site. This has an impact on the overall assessment showing significant differences between the matched data and the full climatology for both MISR and MODIS. First, for the MISR case, the matched AERONET data have the highest frequency at AODs of 0.3 and 0.35, but the climatology shows the highest frequency at an AOD of 0.25. Second AODs in the range of 0.3 to 0.45 are oversampled relative to the climatology, and AODs less than 0.3 and greater than 0.5 are under-sampled with no AODs greater than 0.8. MODIS matched AERONET data show prominent peaks at 0.3 and 0.4 compared to the climatology that has a single peak at 0.25. Similar to MISR AODs are under-sampled less than 0.3 and greater than 0.6.

MISR AOD retrievals matched to AERONET capture the variability in the distribution, but as in the case of Solar Village the frequency of low AOD events is underestimated and the frequency of high AOD events is overestimated. However, MISR does capture events with AODs greater than 1. A similar situation is seen in the MODIS comparison, but MODIS appears to do a better job capturing the overall shape of the AERONET AOD histogram for this site.

The Bahrain AERONET site is located in Manama fairly close to the Arabian Gulf, a location very different from the previous two sites. The site is also located in an urban area suffers from significant load of anthropogenic aerosols as a consequence of rapid Aluminium industrial development (Farahat 2016). Figure (8a, b) shows histogram of the MISR, MODIS and Bahrian AERONET measurements with statistical analysis displayed. The AERONET data matched to MISR show significant peaks at 0.25, 0.35, and 0.5 not seen in the all data climatology that has a single peak at 0.35. AODs less than 0.25 and greater than 0.6 are not representative in the matched data set at all. MISR is representing the peaks at 0.25 and 0.35 in the matched data set but misses the peak at 0.5. Ångström exponent (AE), dependency of the AOD on wavelength, can also be used to determine particles' size where the smaller the particle the larger the exponent. AE analysis show that the first peak at 0.25 is indicative of industrial particles with high AE values and the second peak at 0.35 indicates dust aerosol. The MISR climatology agrees well with the AERONET all data climatology for all AODs. MODIS on the other hand shows an extremely large frequency of AODs at 0.1 not represented by AERONET coupled with an underestimation of AODs greater than 0.3. This could be attributed to the size of the matching window and MODIS retrievals preferentially coming from the Arabian Gulf.

SAADA station is located close to some hiking trails at the Agoundis Valley in the Atlas Mountains about 197 km from the city of Marrakesh.

MISR AODs matched to AERONET agree well with MISR full climatology retrievals over SAADA station. Both retrievals slightly underestimate SAADA full climatology and over estimates SAADA matched data retrievals at AODs equal to 0.1 while show good agreement for AODs greater than 0.1. MODIS matched to AERONET retrievals overestimate the frequency of AODs greater than 0.3. While MODIS AODs matched to AERONET captures climatology at AODs between 0.2 to 0.25, AODs frequency retrievals are under-sampled at

AODs between 0.1 to 0.15 with about 13 % less events than SAADA all data retrievals at AODs equal to 0.1.

Figure (9a, b) indicates right skewed distribution of SAADA AODs towards small AOD values with 11.5 % and 30.1 % of AODs > 0.4 as measured by MISR and MODIS respectively. Taking into consideration MODIS overestimation we conclude that SAADA site is characterized by small AODs values and this could be related to the land topography where the station is located.

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While MISR is capturing high AODs climatology over SAADA, both MISR and MODIS are underestimating the frequency of lower AODs events. Nevertheless, MISR captures the climatology of AODs less than 0.1 missed by MODIS retrievals.

Taman AERONET station is located at the oasis city of Tamanrasset, which lies in Ahaggar National Park at southern Algeria.

Figure (10 a, b) depicts that Taman AERONET AOD climatology is similar to those at SAADA and has a high frequency of low AODs events. Both MISR AODs matched to AERONET and MISR all data do not well capture the frequency of AODs less than 0.1 or larger than 1 while well describe the climatology for AODs in the range of 0.1 to 1. MODIS AODs matched data to AERONET correctly describe climatology with slight overestimation of AODs frequencies between 0.05 – 0.15 while not capturing AODs frequencies greater than 1. MISR and MODIS show similar prominent peaks at 0.1, 0.25, and 0.35, not observed in Taman AERONET AOD climatology, with more peaks observed by MISR at 0.5, 0.6, and 0.8. Average AODs in SAADA and Taman is ~ 50 percent less than observed at Solar Village, Mezaria, and Bahrain sites.

Except for AODs greater than 1 where ground observations could be more robust, both MISR and MODIS retrievals can provide very good climatology matching over Taman site.

Taking into consideration lower number of MISR matching AERONET observations compared to MODIS ~ 33 and 43 percent over SAADA and Taman respectively, MISR is outperforming over these two sites, which can be attributed to its multiangle viewing capabilities over complex terrains including mountainous areas (Atlas Mountains).

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Cairo is a mega city well known for its high pollution due to traffic and agriculture activities. MISR and MODIS matched data correctly capture AOD climatology over Cairo compared to AERONET as shown in Figure (11a, b). MISR retrievals collocated with AERONET capture prominent peaks of AERONET AOD at 0.15 – 0.25 and 0.5 with small underestimation observed at 0.3. MISR 'all data' AOD climatology over Cairo station agrees better with AERONET AOD climatology vs. collocated dataset with some oversampling at 0.15. Frequency of high AODs retrievals at 0.7 and 0.8 have not been captured by MISR matched or all data retrievals. MODIS matched to AERONET AODs are also able to well present Cairo climatology data with a high overestimation of AODs frequency between 0.05 - 0.2 and an underestimation of AODs larger than 0.4.

The complex landscape and home-grown emissions in Cairo could impose major challenges in MODIS AODs retrievals. Moreover, Cairo is one of the most densely populated cities in the world that hosts major commercial and industrial centers in North Africa. Cairo also has complicated aerosols structure developed by long range transported dust in the spring, biomass burning in the fall, strong traffic and industrial emissions (Marey et al., 2010).

Over Cairo station, MODIS correctly represents ground observations for AODs between 0.2 - 0.4 while MISR all data better represents AOD climatology for AODs greater than 0.4. There is not enough collocated MISR-AERONET AODs to evaluate MISR 'matched AOD' climatology.

MISR, MODIS climatology at SEDEE Boker are illustrated in Figures (12a, b).

MISR ‘matched’ AODs frequency show significant underestimation for AODs less than 0.2 and an overestimation between 0.2 – 0.4 compared with AERONET retrievals. MISR correctly captures the climatology for AODs events greater than 0.4. MISR ‘matched’ and ‘all data’ retrievals peaks at 0.25 and 0.2 respectively producing high frequency of AODs oversampling compared to AERONET. MISR data retrievals do not capture the climatology for AODs less than 0.1 over this site coincident with what was previously observed over other sites. MODIS matched AERONET data underestimates frequency of AODs less than 0.2 while overestimates the frequencies between 0.2 - 0.6, and well match frequencies of higher AODs events larger than 0.6. MODIS retrievals are characterized by two prominent peaks at 0.1 and 0.25 that are not found in the AERONET matched data.

At Sedee, MISR and MODIS retrievals are better in matching frequency of high AODs retrievals (greater than 0.4) than the frequency of low AODs. This could be an effect of possible long-range transport to Sedee Boker site (Farahat et al. 2016) along with complex mixtures of dust, pollution, smoke, and sea salt that could result in uncertainties in MISR and MODIS aerosol model selection.

In the summary, MISR tends to underestimate AODs > 0.4 over Solar Village, Mezaria, Bahrain, and Cairo while agrees with AERONET over SAADA, Taman and Sedee Boker at all ranges of AODs. This could be expounded by insufficient particle absorption in MISR V22 algorithm (Kahn et al., 2005). Spherical particle absorption is produced by externally mixing small black carbon particles.

Percentage of MISR, MODIS, and AERONET AODs greater than 0.4 recorded is shown in Table 4. Over Solar Village, both MISR and MODIS well capture high AODs greater than 0.4 with very good agreement with the ground observations. Over Mezaria, both MISR and MODIS are over estimating the percentage of AODs greater than 0.4 by about 15.5 and 10.5 percent respectively. MISR all data agrees well with AERONET all data in representing high

AOD over Bahrain while MODIS shows significant under-representation of those events by about 15 percent, less than reported by Bahrain AERONET station. At SAADA, MISR AOD agrees with AERONET in showing low percentage of AODs greater than 0.4, while MODIS retrievals overestimate percentage by about 24 percent. MISR AOD over Taman AERONET station shows very good agreement, while MODIS is slightly overestimating AODs. Among all seven sites considered in this study, Sedee Boker shows lowest occurrence of AODs greater than 0.4, which is confirmed by both MISR and MODIS retrievals. Cairo AERONET records the highest frequency of AODs > 0.4, however this is largely underestimated by both MISR and MODIS retrievals.

It can concluded from the previous discussion that atmosphere around SAADA, Taman, and Sedee Boker sites is relatively clean and aerosol loads are small compared to Solar Village, Mezaria, Bahrain, and Cairo, however this could be affected by the location where AERONET station is installed for example SAADA and Taman stations are installed in a remote mountainous region away from urbanization while Cairo station is installed in the middle of large residential region with significant local emissions.

Conclusion

The performance of MODIS, MISR retrievals with corresponding AERONET measurements over different geographic locations in the Middle East and North Africa was investigated during 2000 – 2015.

Long-range observations show dissimilar AODs trends between MODIS/Aqua, MODIS/Terra, MISR and AERONET measurements. MODIS/Aqua matched AERONET retrievals show stable trend over all sites while, MODIS/Terra matched AERONET retrievals show significant downward trend indicating possible changes in the sensor performance.

MISR matched AERONET AODs data depict high correlation compared to AERONET indicating good agreement with ground observations with about 72 percent of AODs retrievals fall within the expected confidence range.

Consistency of MODIS and AERONET AODs vary based on the season, study area, and dominant aerosols type with about 68 percent of the retrieved AODs values fall within expected confidence range with the lowest performance over mixed particles regions.

Comparing satellites' AODs retrievals with corresponding AERONET measurements show that space-borne data retrievals accuracy can be affected by landscape, topology, and AOD range at which data is retrieved.

Few AERONET sites are verified where MISR and MODIS retrievals well agree with ground observations, where other sites only MISR or MODIS could correctly describe the climatology.

The AODs range at which MISR or MODIS could correctly describe ground observation is also investigated over different AERONET sites. Over Solar Village both MISR and MODIS tend to underestimate the frequency of low AODs and overestimate the frequency of high AODs compared to AERONET with MISR histograms show prominent peaks at 0.55 and 0.75 not shown in AERONET. MISR can capture the frequency of AODs greater than 1 mostly missed by MODIS. Both MISR and MODIS are found to provide good representation of the AOD climatology over the Solar Village site.

Similar to Solar Village, MISR underestimates frequency of lower AODs and overestimate frequencies of high AODs over Mezaria. MISR is able to correctly capture the frequency of AODs greater than 1, while MODIS retrievals are found to better represent the overall climatology. This is due to low number of MISR – matched AERONET retrievals compared to MODIS over this site. Prominent peaks at 0.3 and 0.4 were observed in MODIS matched Mezaria retrievals compared to the climatology, which has a single peak at 0.25.

Large water body surrounding Bahrain makes MODIS data preferentially comes from the Arabian Gulf which produces an extremely large frequency of AODs at 0.1 not observed in AERONET measurements paired with an underestimation of AODs greater than 0.3. Meanwhile, MISR retrievals agree well with AODs climatology over Bahrain.

MISR AODs retrievals slightly underestimate SAADA climatology while show good agreement for AODs greater than 0.1. MODIS retrievals underestimate the frequency of AODs retrievals between 0.1 to 0.15, match climatology at AODs between 0.2 to 0.25, and overestimate the frequency of AODs greater than 0.3. SAADA site is characterized by small frequency of low AODs values and this could be related to the landscape nature surrounding Saada station. MISR is found be outperforming over Saada and Taman stations which can be attributed to its viewing multispectral and multiangular capabilities over mountainous regions.

MISR retrievals well capture prominent peaks of AERONET data at 0.15 to 0.25 and 0.5 with small underestimation observed at 0.3 over Cairo. It is recommended to use MISR all data rather than matched data only over Cairo as it is found to do a better job in describing the climatology over this station. MODIS data retrievals are also able to well present Cairo climatology with a high overestimation of AODs frequency between 0.05 to 0.2 and an underestimation of AODs larger than 0.4. While both MISR and MODIS well describe climatology over Cairo station, MODIS can correctly represent ground observations between 0.2 to 0.4.

Over Sedee Boker both MISR and MODIS retrievals well describe the climatology however they are more successful in matching frequency of high AODs greater than 0.4.

Based on analysing frequency of AODs greater than 0.4, it was found that Saada, Taman, and Sedee Boker are having better air quality compared to other sites while Cairo was found to be the most polluted site.

Results presented in this study are important in providing a guideline for satellites retrievals end users on which sensor could provide reliable data over certain geographic location and AOD range.

Adjacent geographic location and local climate among sites does not always guarantee that same sensor will provide consistent retrievals over all sites. For example, Solar Village, and Bahrain AERONET are surrounded by large desert regions in the and sharing almost similar climatic conditions, but MODIS is found to be more successful in describing climatology over Solar Village than over Bahrain and this could be attributed to different factors related to surface reflection, cloud coverage, and the large water body surrounding Bahrain. Thus in order to decrease data uncertainty, it is important to determine which sensor provides best retrieval over certain geographic location and AOD range.

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Author Contributions: Ashraf Farahat analysed the data, performed the statistical analysis and wrote the manuscript.

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Tables' caption

Table 1. Geographic location of the AERONET sites used in this study

Table 2. Statistics for the calculation of MODIS/Terra, MODIS/Aqua, and MISR with that of AERONET measurements over seven sites in the Middle East and North Africa, including R: correlation coefficient, Gfraction: good fraction; N: number of observations

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Table 3. Statistics for biomass and mixed sites, parameters as in Table 3. Caption.

Table 4. Percentage of AODs retrievals greater than 0.4 recorded by AERONET all data, MISR all data and MODIS matched data over seven AERONET sites in Middle East and North Africa.

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Figures caption

Figure 1. Location of the AERONET stations over North Africa and the Middle East. The numbers on the map indicate the site location as 1: Saada, 2: Tamanrasset_INM, 3: Cairo, 4: Sede Boker, 5: Solar Village, 6: Mezaira, 7: Bahrain.

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Figure 2. Scatter plot of MISR AOD versus AERONET AOD based on seasons and aerosols categorization.

Figure 3. Scatter plot of MODIS AOD versus AERONET AOD based on seasons and aerosols categorization.

Figure 4. Time series of monthly mean AOD derived from MODIS/Aqua, MODIS/Terra, MISR and AERONET over a) dust b) biomass and c) mixed dominated aerosol regions.

Figure 5. Long range AOD difference for MODIS/Terra and MODIS/Aqua over the dust, biomass and mixed sites.

Figure 6. Histogram of the MISR, MODIS and Solar Village AERONET measurements a) MISR b) MODIS data retrievals.

Figure 7. Histogram of the MISR, MODIS and Mezaria AERONET measurements a) MISR b) MODIS data retrievals.

Figure 8. Histogram of the MISR, MODIS and Bahrain AERONET measurements a) MISR b) MODIS data retrievals.

Figure 9. Histogram of the MISR, MODIS and SAADA AERONET measurements a) MISR b) MODIS data retrievals.

Figure 10. Histogram of the MISR, MODIS and Taman AERONET measurements a) MISR b) MODIS data retrievals.

Figure 11. Histogram of the MISR, MODIS and SEDEE Boker AERONET measurements a) MISR b) MODIS data retrievals.

Figure 12. Histogram of the MISR, MODIS and Cairo AERONET measurements a) MISR b) MODIS data retrievals.

Table 1.

Location name	Lon./Lat.	Measurement period
Solar Village	24.907º N/46.397º E	2000-2015
Mezaria	23.105º N/53.755º E	2004-2015
Bahrain	26.208º N/50.609º E	2000-2006
Saada	31.626º N/8.156º W	2003-2015
Taman	22.790º N/5.530º E	2000-2015
Cairo	30.081º N/31.290º E	2005 -2007
Sede Boker	30.855º N/34.782 º E	2000-2015

Table 2.

AERONET Site	Sensor	Season	Mean Value		N	R	Gfraction (%)
			AERONET	Satellite			
	MISR	DJF	0.31±0.22	0.38±0.20	338	0.94	60.05
		MAM	0.39±0.27	0.45±0.23	89	0.94	65.16
		JJA	0.39±0.18	0.45±0.17	141	0.90	70.21
		SON	0.27±0.16	0.35±0.14	3	0.99	33.33
Solar Village		DJF	0.27±0.19	0.33±0.17	1500	0.48	51.80

		MAM	0.36±0.24	0.26±0.17	389	0.68	90.23
	MODIS Terra	**JJA**	0.34±0.17	0.42±0.19	429	0.41	54.31
		SON	0.22±0.10	0.36±0.12	471	0.51	28.87
Mezaria	**MISR**	**DJF**	0.33±0.15	0.40±0.17	60	0.89	75.00
		MAM	0.32±0.19	0.41±0.22	13	0.90	69.23
		JJA	0.42±0.13	0.47±0.17	21	0.85	80.95
		SON	0.29±0.07	0.36±0.07	22	0.87	77.27
	MODIS Terra	**DJF**	0.32±0.15	0.35±0.19	198	0.86	74.74
		MAM	0.44±0.33	0.45±0.27	115	0.92	78.07
		JJA	0.39±0.14	0.43±0.20	89	0.81	71.91
		SON	0.28±0.13	0.30±0.16	97	0.87	77.31
Bahrain	**MISR**	**DJF**	0.37±0.11	0.31±0.10	17	0.73	100
		MAM	0.31±0.11	0.28±0.14	3	0.89	100
		JJA	0.40±0.09	0.36±0.09	8	0.69	100
		SON	0.40±0.09	0.30±0.05	4	0.98	100
	MODIS Terra	DJF	0.42±0.29	0.20±0.19	121	0.41	93.38
		MAM	0.50±0.28	0.13±0.15	25	0.26	96.00
		JJA	0.55±0.26	0.31±0.27	42	0.50	88.09
		SON	0.35±0.14	0.21±0.12	29	0.32	93.10

Table 3.

AERONET Site	**Sensor**	**Season**	**Mean Value**		**N**	**R**	**Gfraction (%)**
			AERONET	Satellite			
	MISR	**DJF**	0.24±0.16	0.22±0.15	149	0.93	97.29
		MAM	0.21±0.13	0.19±0.11	53	0.89	96.15
		JJA	0.29±0.14	0.27±0.15	80	0.93	97.46
		SON	0.19±0.15	0.19±0.12	60	0.94	98.30

SAADA		**DJF**	0.23±0.16	0.32±0.21	550	0.57	57.81
		MAM	0.24±0.18	0.39±0.23	90	0.43	44.44
	MODIS	**JJA**	0.30±0.17	0.45±0.18	201	0.40	45.27
	Terra	**SON**	0.19±0.13	0.22±0.14	162	0.71	72.39
		DJF	0.19±0.23	0.24±0.19	135	0.92	70.89
		MAM	0.29±0.22	0.35±0.24	24	0.97	82.60
	MISR	**JJA**	0.35±0.30	0.39±0.19	36	0.85	71.42
		SON	0.19±0.15	0.19±0.12	60	0.94	98.30
Taman		**DJF**	0.19±0.22	0.18±0.16	319	0.67	81.81
	MODIS	**MAM**	0.24±0.19	0.22±0.17	67	0.55	83.58
	Terra	**JJA**	0.37±0.32	0.29±0.20	69	0.69	84.05
		SON	0.14±0.14	0.13±0.10	117	0.54	84.61
		DJF	0.33±0.20	0.28±0.11	13	0.94	100
		MAM	0.22±0.06	0.24±0.08	5	0.99	100
	MISR	**JJA**	0.43±0.23	0.34±0.11	5	0.99	100
		SON	0.38±0.21	0.29±0.12	4	0.97	100
Cairo		**DJF**	0.33±0.16	0.20±0.11	158	0.30	95.56
		MAM	0.32±0.16	0.12±0.08	39	0.25	100
	MODIS	**JJA**	0.35±0.14	0.28±0.07	58	0.17	94.82
	Terra	**SON**	0.38±0.19	0.20±0.09	29	0.07	93.82
		DJF	0.14±0.06	0.21±0.07	23	0.87	40.90
		MAM	0.14±0.05	0.24±0.09	13	0.68	33.33
	MISR	**JJA**	0.16±0.05	0.24±0.06	163	0.85	33.33
		SON	0.15±0.07	0.23±0.06	72	0.89	33.80
SEDEE_BOKER		**DJF**	0.16±0.12	0.23±0.14	1312	0.36	53.50
		MAM	0.21±0.18	0.24±0.19	338	0.34	65.68
	MODIS	**JJA**	0.16±0.09	0.33±0.13	392	0.27	17.34
	Terra	**SON**	0.16±0.09	0.23±0.12	477	0.46	58.49

Table 4.

	AERONET		MISR		MODIS	
		AOD		AOD		AOD
	N	% > 0.4	N	% > 0.4	N	% > 0.4
Solar Village	3978	28.7	684	32.8	2789	30.1
Mezaria	1650	30.2	547	45.7	498	40.7
Bahrain	1117	33.3	676	35.7	217	18.4
SAADA	3184	10.8	667	11.5	1004	34.6
Taman	1863	17.9	845	22.6	572	9.4
Cairo	269	53.5	620	17.7	284	4.2
SEDEE	5722	4.8	675	9	2519	12.8

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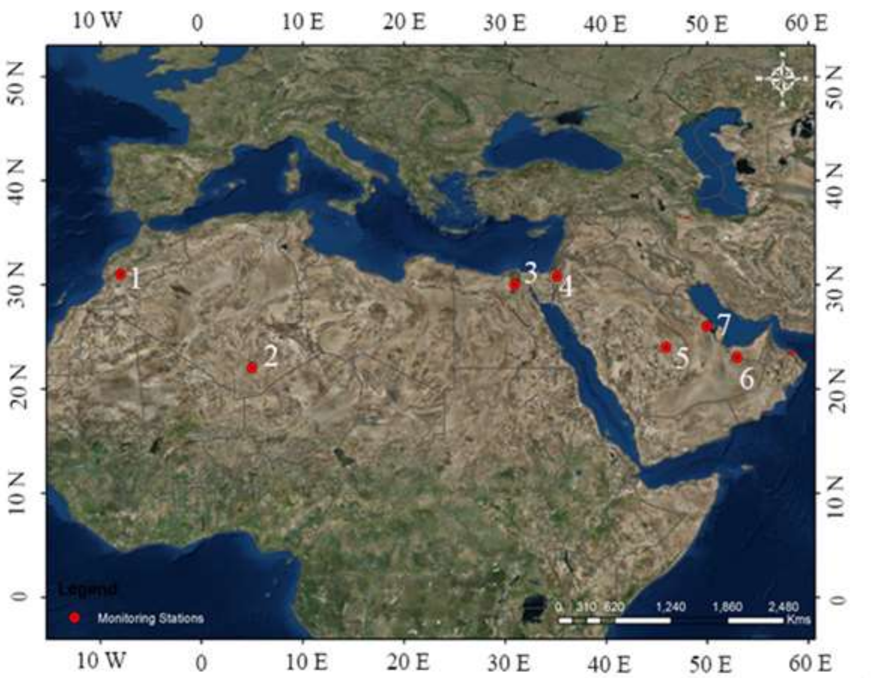
10 W
0
10 E
20 E
30 E
40 E
50 E
60 E
50 N
40 N
30 N
20 N
10 N
0
1
2
3
4
5
6
7
Legend
Monitoring Stations
0
310
620
1,240
1,860
2,480
Kms

Figure 1.

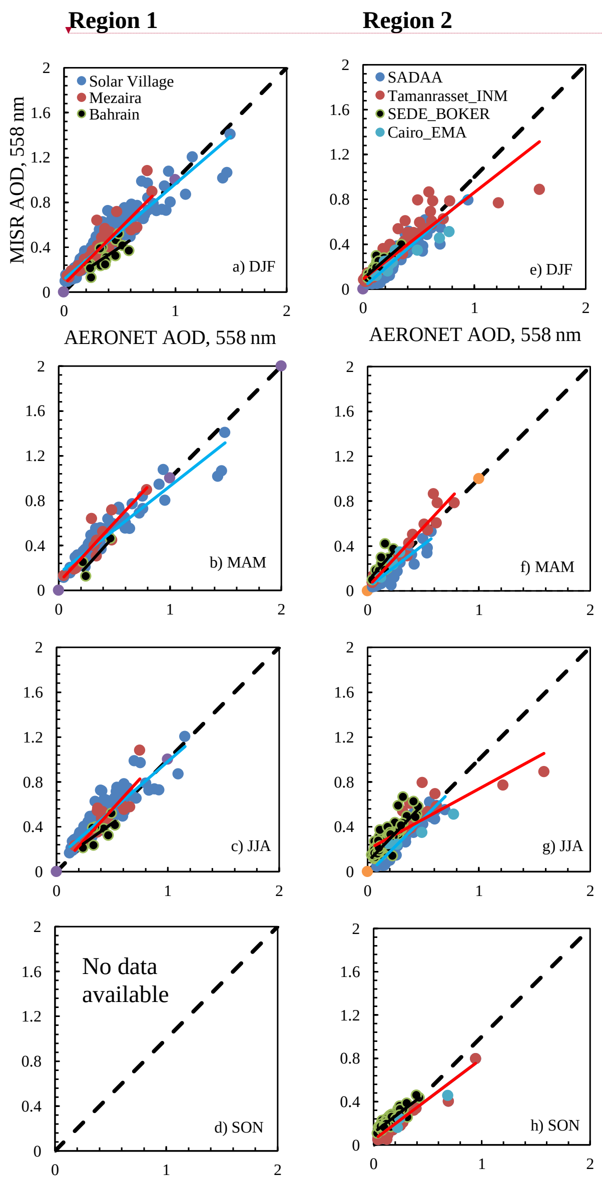
Region 1
Region 2
Solar Village
Mezaira
Bahrain
SADAA
Tamanrasset_INM
SEDE_BOKER
Cairo_EMA
MISR AOD, 558 nm
AERONET AOD, 558 nm
AERONET AOD, 558 nm
a) DJF
b) MAM
c) JJA
d) SON
No data available
e) DJF
f) MAM
g) JJA
h) SON

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Figure 2.

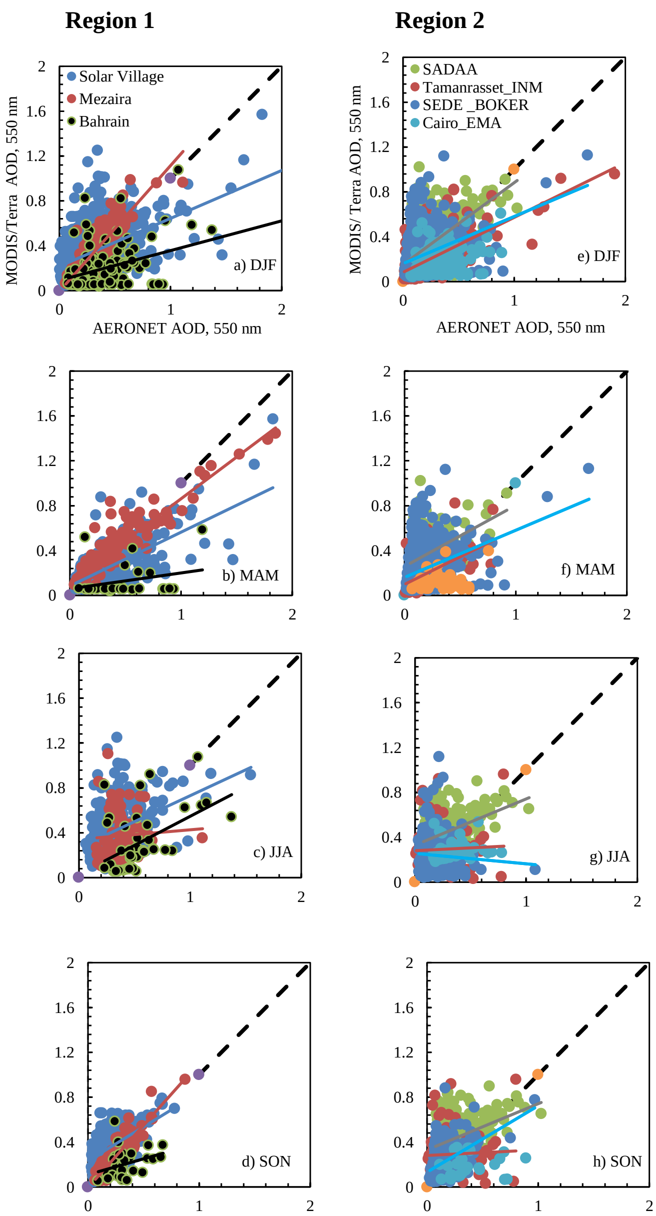

Figure 3.

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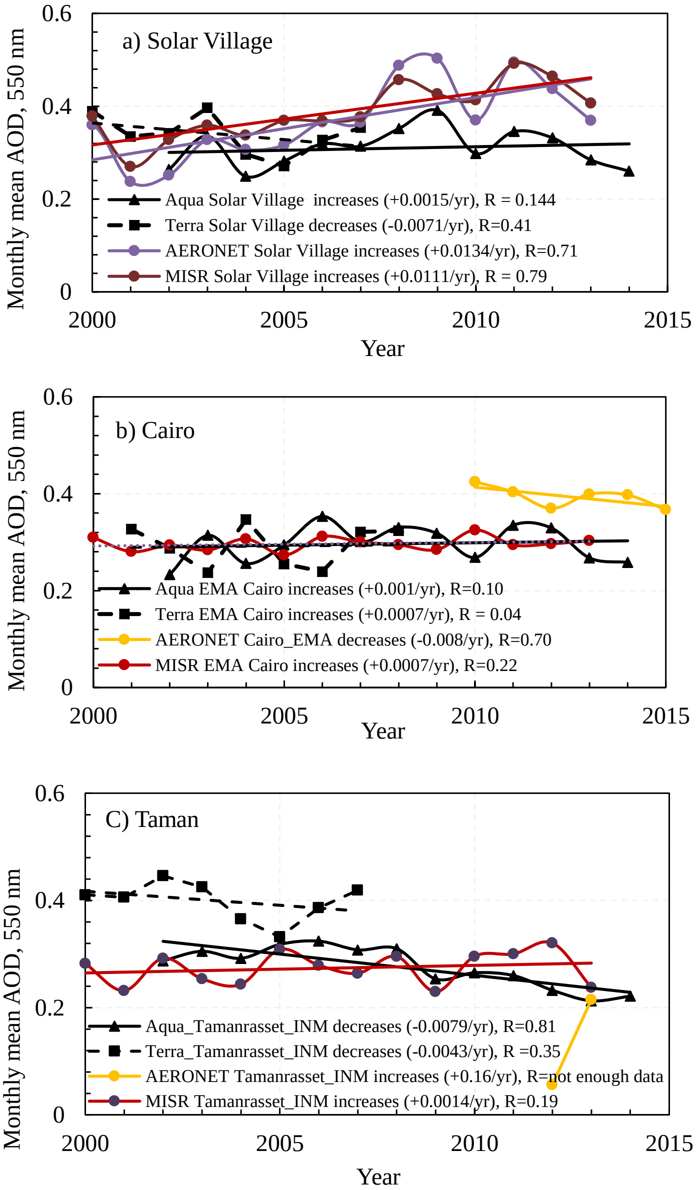

a) Solar Village
Aqua Solar Village increases (+0.0015/yr), R = 0.144
Terra Solar Village decreases (-0.0071/yr), R=0.41
AERONET Solar Village increases (+0.0134/yr), R=0.71
MISR Solar Village increases (+0.0111/yr), R = 0.79
Monthly mean AOD, 550 nm
Year
b) Cairo
Aqua EMA Cairo increases (+0.001/yr), R=0.10
Terra EMA Cairo increases (+0.0007/yr), R = 0.04
AERONET Cairo_EMA decreases (-0.008/yr), R=0.70
MISR EMA Cairo increases (+0.0007/yr), R=0.22
Monthly mean AOD, 550 nm
Year
C) Taman
Aqua_Tamanrasset_INM decreases (-0.0079/yr), R=0.81
Terra_Tamanrasset_INM decreases (-0.0043/yr), R =0.35
AERONET Tamanrasset_INM increases (+0.16/yr), R=not enough data
MISR Tamanrasset_INM increases (+0.0014/yr), R=0.19
Monthly mean AOD, 550 nm
Year

Figure 4.

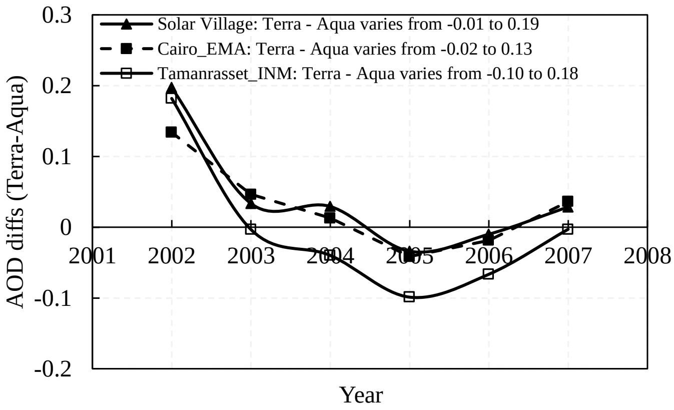
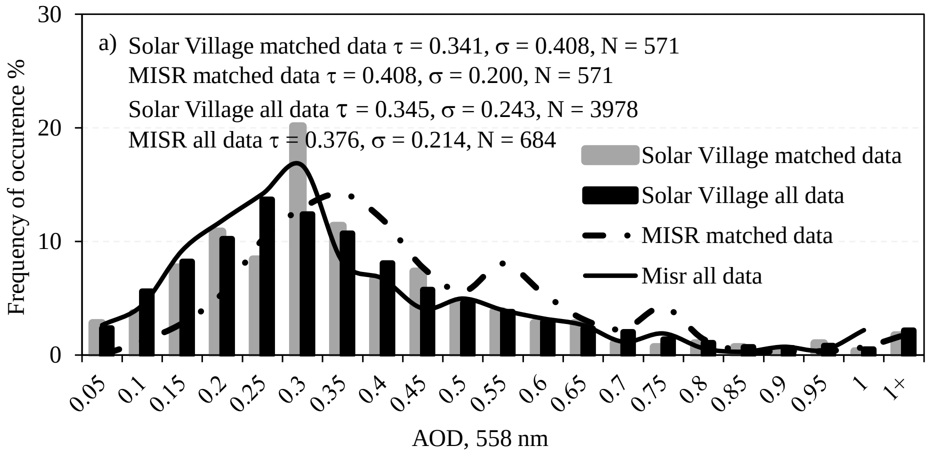


Figure 5.


a) Solar Village matched data τ = 0.341, σ = 0.408, N = 571
MISR matched data τ = 0.408, σ = 0.200, N = 571
Solar Village all data τ = 0.345, σ = 0.243, N = 3978
MISR all data τ = 0.376, σ = 0.214, N = 684
Solar Village matched data
Solar Village all data
MISR matched data
Misr all data
Frequency of occurence %
0
10
20
30
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
AOD, 558 nm

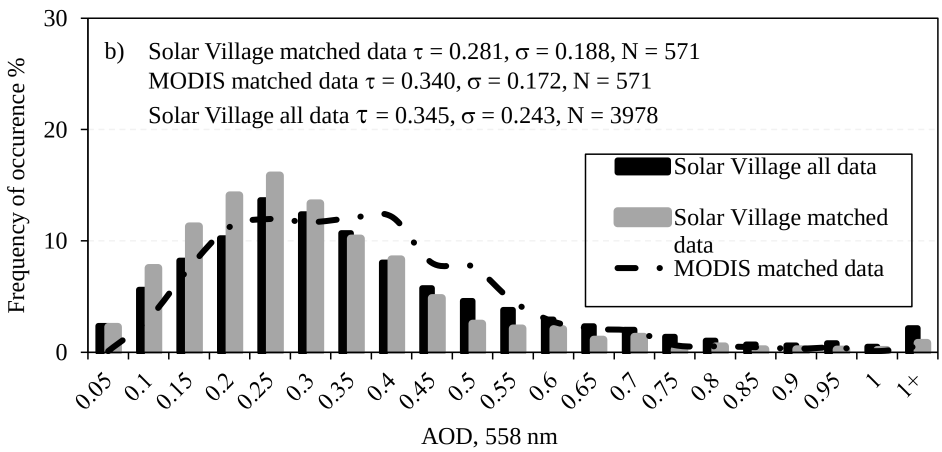
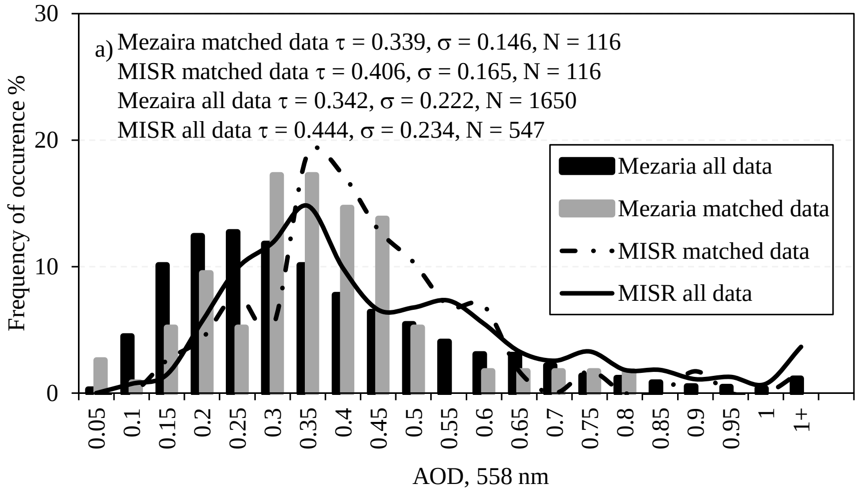

b) Solar Village matched data τ = 0.281, σ = 0.188, N = 571
MODIS matched data τ = 0.340, σ = 0.172, N = 571
Solar Village all data τ = 0.345, σ = 0.243, N = 3978
Solar Village all data
Solar Village matched data
MODIS matched data
Frequency of occurence %
0
10
20
30
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
AOD, 558 nm

Figure 6.


a)
Mezaira matched data τ = 0.339, σ = 0.146, N = 116
MISR matched data τ = 0.406, σ = 0.165, N = 116
Mezaira all data τ = 0.342, σ = 0.222, N = 1650
MISR all data τ = 0.444, σ = 0.234, N = 547
Mezaria all data
Mezaria matched data
MISR matched data
MISR all data
Frequency of occurence %
0
10
20
30
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1 1+
AOD, 558 nm

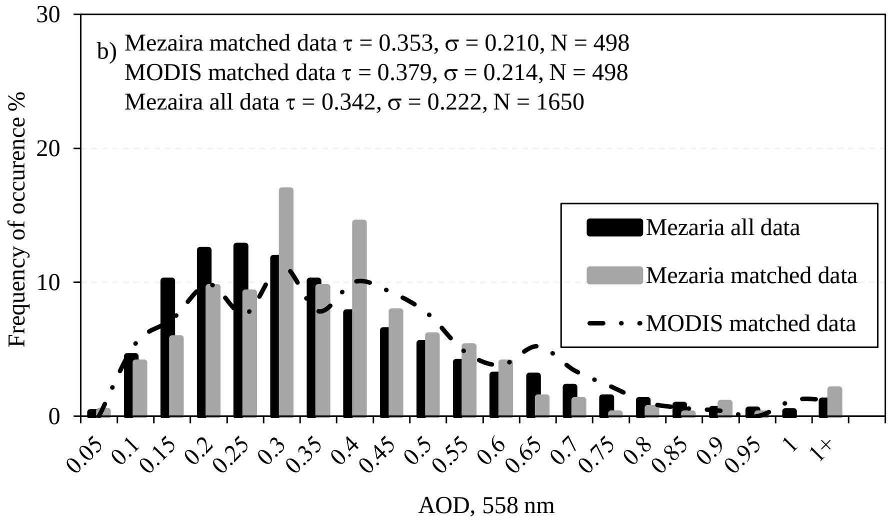
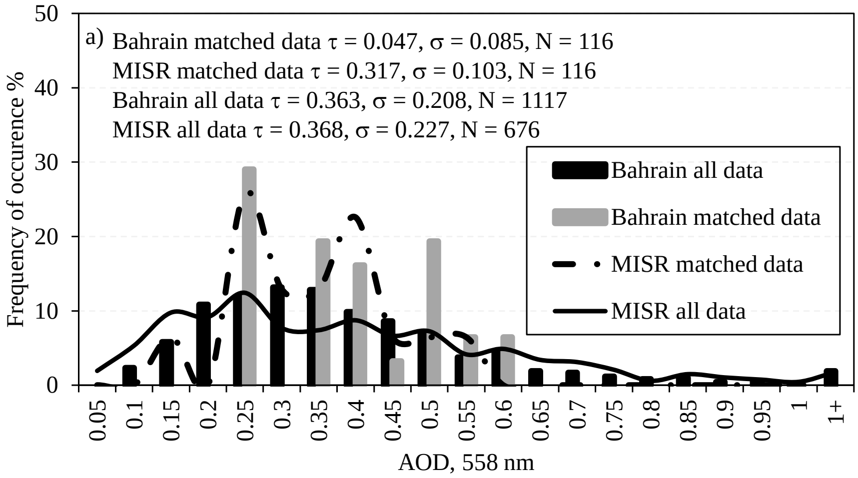

b)
Mezaira matched data τ = 0.353, σ = 0.210, N = 498
MODIS matched data τ = 0.379, σ = 0.214, N = 498
Mezaira all data τ = 0.342, σ = 0.222, N = 1650
Mezaria all data
Mezaria matched data
MODIS matched data
Frequency of occurence %
0
10
20
30
0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1 1+
AOD, 558 nm

Figure 7.



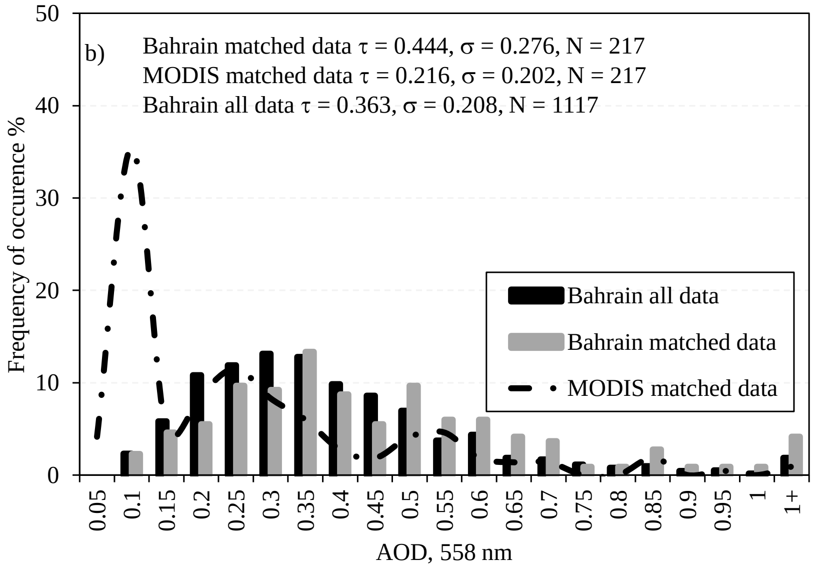


Figure 8.

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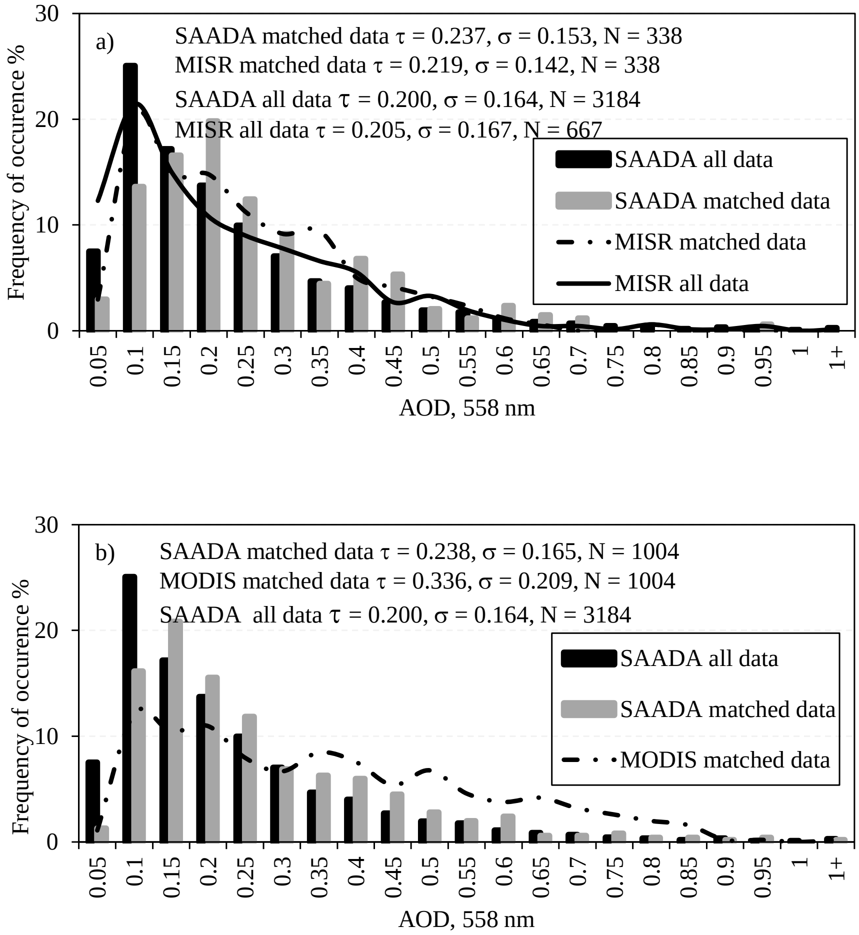

a)
SAADA matched data τ = 0.237, σ = 0.153, N = 338
MISR matched data τ = 0.219, σ = 0.142, N = 338
SAADA all data τ = 0.200, σ = 0.164, N = 3184
MISR all data τ = 0.205, σ = 0.167, N = 667
SAADA all data
SAADA matched data
MISR matched data
MISR all data
Frequency of occurence %
AOD, 558 nm
0
10
20
30
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
b)
SAADA matched data τ = 0.238, σ = 0.165, N = 1004
MODIS matched data τ = 0.336, σ = 0.209, N = 1004
SAADA all data τ = 0.200, σ = 0.164, N = 3184
SAADA all data
SAADA matched data
MODIS matched data
Frequency of occurence %
AOD, 558 nm

Figure 9.

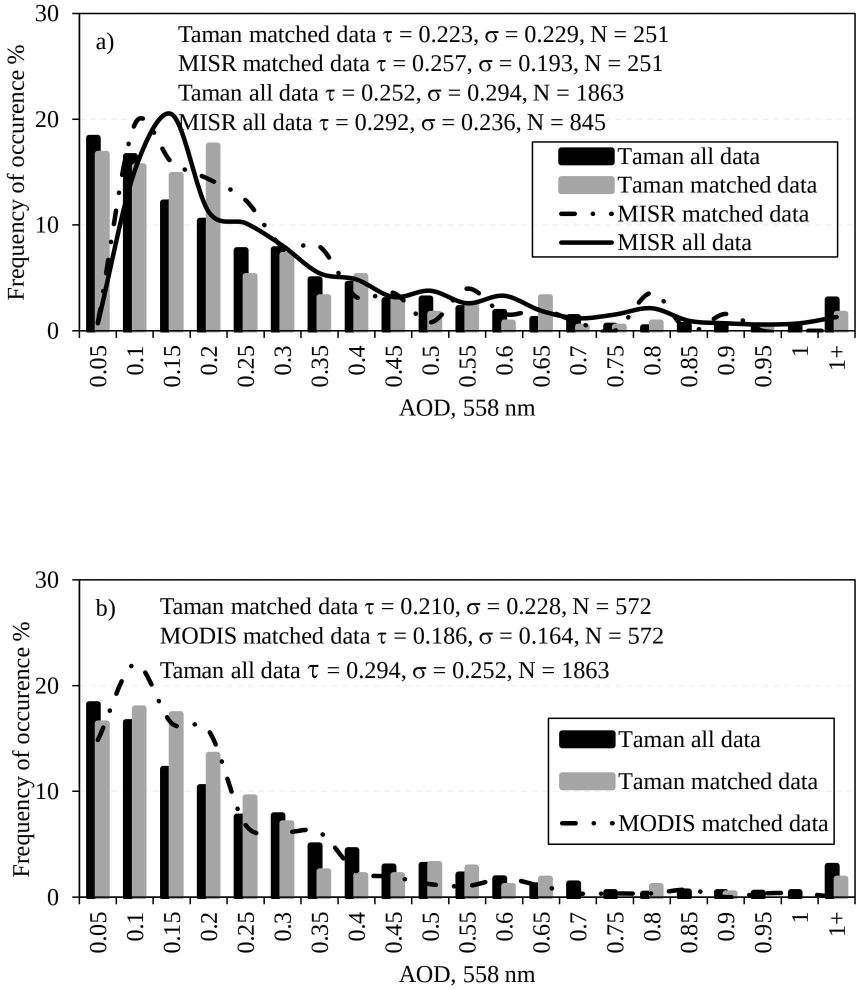
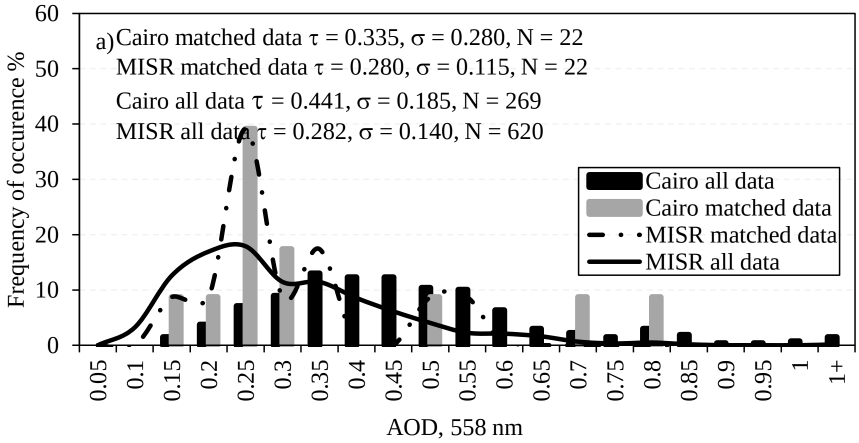

a)
Taman matched data τ = 0.223, σ = 0.229, N = 251
MISR matched data τ = 0.257, σ = 0.193, N = 251
Taman all data τ = 0.252, σ = 0.294, N = 1863
MISR all data τ = 0.292, σ = 0.236, N = 845
Taman all data
Taman matched data
MISR matched data
MISR all data
Frequency of occurence %
0
10
20
30
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
AOD, 558 nm
b)
Taman matched data τ = 0.210, σ = 0.228, N = 572
MODIS matched data τ = 0.186, σ = 0.164, N = 572
Taman all data τ = 0.294, σ = 0.252, N = 1863
Taman all data
Taman matched data
MODIS matched data
Frequency of occurence %
AOD, 558 nm

Figure 10.


a)
Cairo matched data τ = 0.335, σ = 0.280, N = 22
MISR matched data τ = 0.280, σ = 0.115, N = 22
Cairo all data τ = 0.441, σ = 0.185, N = 269
MISR all data τ = 0.282, σ = 0.140, N = 620
Cairo all data
Cairo matched data
MISR matched data
MISR all data
Frequency of occurence %
0
10
20
30
40
50
60
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
AOD, 558 nm

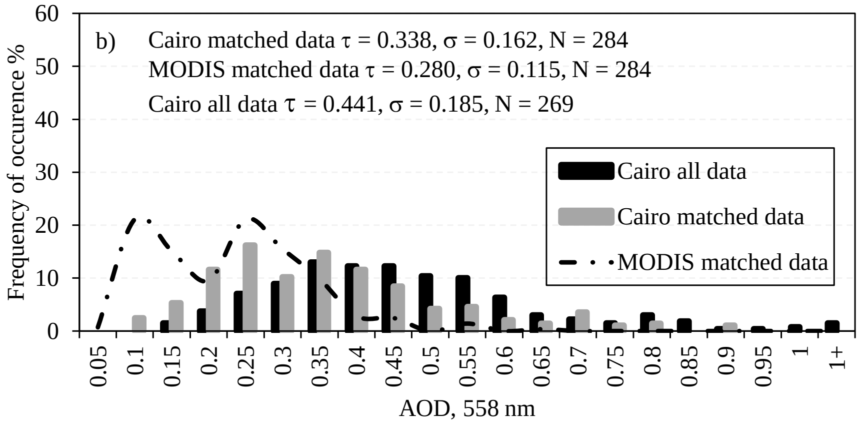

b)
Cairo matched data τ = 0.338, σ = 0.162, N = 284
MODIS matched data τ = 0.280, σ = 0.115, N = 284
Cairo all data τ = 0.441, σ = 0.185, N = 269
Cairo all data
Cairo matched data
MODIS matched data
Frequency of occurence %
0
10
20
30
40
50
60
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
1+
AOD, 558 nm

Figure 11.

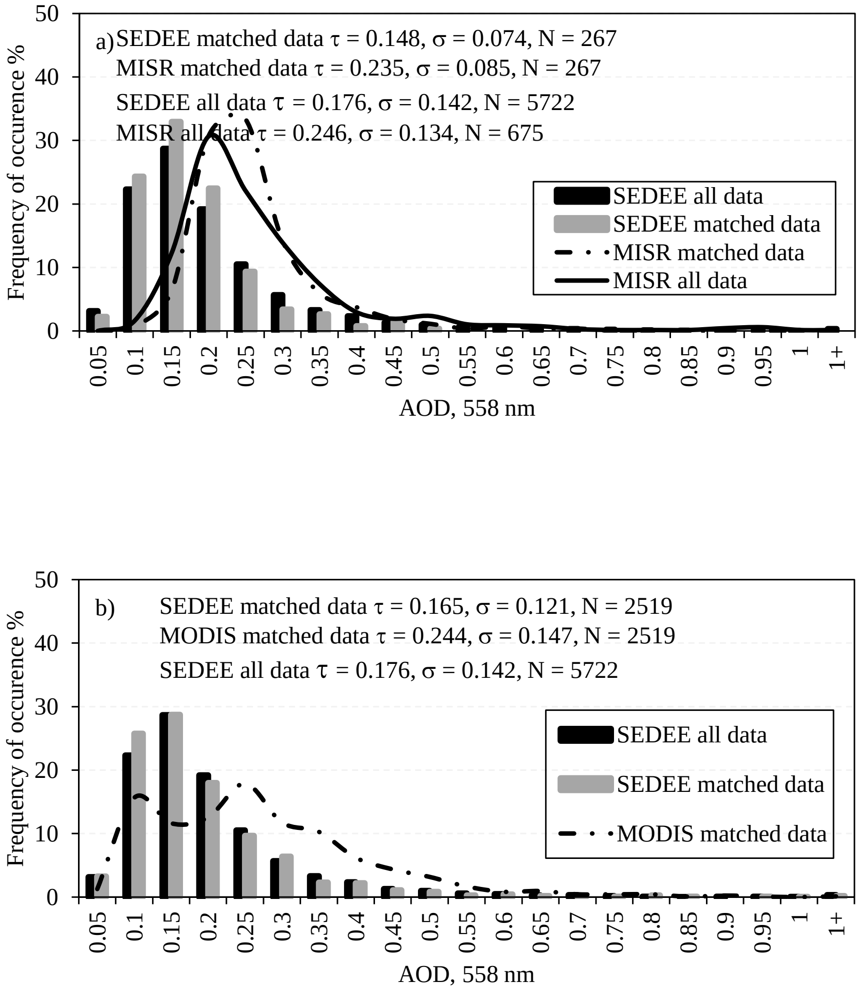

a) SEDEE matched data τ = 0.148, σ = 0.074, N = 267
MISR matched data τ = 0.235, σ = 0.085, N = 267
SEDEE all data τ = 0.176, σ = 0.142, N = 5722
MISR all data τ = 0.246, σ = 0.134, N = 675
SEDEE all data
SEDEE matched data
MISR matched data
MISR all data
Frequency of occurence %
AOD, 558 nm
b) SEDEE matched data τ = 0.165, σ = 0.121, N = 2519
MODIS matched data τ = 0.244, σ = 0.147, N = 2519
SEDEE all data τ = 0.176, σ = 0.142, N = 5722
SEDEE all data
SEDEE matched data
MODIS matched data
Frequency of occurence %
AOD, 558 nm

Figure 12.