

Article

Evaluating the Performance of MODIS and MERRA-2 AOD Retrievals Using AERONET Observations in the Dust Belt Region

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Abstract

Aerosols from natural and anthropogenic sources exert significant yet highly variable influences on the Earth's radiative balance characterized by pronounced spatial and temporal heterogeneity. Accurate quantification of these effects is crucial for enhancing climate projections and informing effective mitigation strategies. In this study, we evaluated the performance of three widely used aerosol optical depth (AOD) datasets—MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2), MODIS Aqua, and MODIS Terra—by comparing them against ground-based AERONET observations from ten stations located within the dust belt region. Statistical assessments included coefficient of determination (R^2), correlation coefficient (R), Index of Agreement (IOA), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Relative Mean Bias (RMB), and standard deviation (SD). The results indicate that MERRA-2 showed the highest agreement ($R = 0.76$), followed by MODIS Aqua ($R = 0.75$) and MODIS Terra ($R = 0.73$). Seasonal and annual AOD climatology maps revealed comparable spatial patterns across datasets, although MODIS Terra consistently reported slightly higher AOD values. These findings provide a robust assessment and reanalysis of satellite AOD products over arid regions, offering critical guidance for aerosol modeling, data assimilation, and climate impact studies.



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1. Introduction

Aerosols are fine particulate matter consisting of both solid and liquid phases, dispersed and suspended within the atmospheric column. Owing to their extremely small size and low settling velocity, these particles can remain airborne for extended durations. They originate from natural sources such as, dust, sea spray, volcanic eruptions [1] as well as anthropogenic activities, including industrial emissions, vehicle exhaust, and fossil fuel combustion [2], influencing climate and atmospheric processes in distinct ways [3,4]. Despite their critical role, our understanding of aerosol impacts on climate change assessments and global climate predictions remains incomplete [5,6]. To accurately quantify aerosol induced climate forcing, particularly their effect on surface irradiance, comprehensive, long-term monitoring and classification of their optical properties across diverse spatial and temporal scales are imperative [7,8].

The dust belt is a primary source of naturally occurring aerosols, extending across a broad zone that begins along the Atlantic margin of North Africa, traverses the arid regions

of the Middle East (ME), and continues through central and southern Asia, ultimately reaching western China [9–12]. At a global scale, analysis of near surface dust concentration excluding regions such as North America and Europe, reveals a declining trend of approximately 1.2% per year between 1984 and 2012 [4]. The dust concentration pattern in North Africa closely aligns with this global decrease, whereas Northeast Asia exhibits a pronounced negative trend. In contrast, regions spanning the ME and southwestern Asia show a modest increase in dust activity, although a notable decline in particulate levels was evident throughout the 1990s.

Numerous studies have demonstrated that Aerosol Optical Depth (AOD) serves as a reliable metric for estimating atmospheric aerosol concentrations, drawing on data from satellite observations, reanalysis products, and ground based networks [1,13–16]. However, the applicability and accuracy of these datasets can vary regionally, limiting their reliability for localized assessments. Satellite observations offer broad spatial coverage for aerosols monitoring, yet their temporal resolution is often constrained by orbital limitations. Moreover, the accuracy of satellite derived variables may be influenced by several factors, including surface reflectance characteristics, the aerosol retrieval algorithm, and cloud interference, all of which can introduce uncertainties in the retrieved data [16]. Despite these limitations, satellite based observations have substantially enhanced our understanding of aerosol properties, particularly their temporal and geographical variability on a global scale [17–20].

The utility of MODIS AOD products in assessing atmospheric aerosol loads has been extensively documented in prior studies [21–23]. For example, Butt et al. (2017) [14] employed satellite-derived aerosol data from the MODIS Deep Blue algorithm to investigate atmospheric conditions over Saudi Arabia, identifying elevated aerosol concentration in the northeastern regions particularly prominent during the spring months over the period 2000 to 2013. Similarly, Butt and Mashat (2018) [17] applied the Normalized Difference Dust Index (NDDI) technique to satellite observations to monitor dust and particulate storm events across Saudi Arabia between 2002 to 2011.

In contrast, ground-based aerosol measurements provide highly precise and absolute classification of aerosol optical properties, making them indispensable for detailed atmospheric studies. However, their utility is often limited by restricted spatial coverage. Global network of sun photometers, most notable AERONET (Aerosol Robotic Network), play a pivotal role in the continuous monitoring of aerosol characteristics, contributing to the development of local, regional, and global climatology [24]. Furthermore, ground-based aerosol observations serve as critical reference datasets for validating satellite derived measurements and enhancing the accuracy of climate models.

Given their complementary roles, both satellite- and ground-based observations are essential for characterizing aerosol optical properties, particularly in regions such as the dust belt, where atmospheric dust significantly influences climate and air quality. Numerous studies have examined aerosol optical properties using ground based AERONET data [14,16,17,24–26]. For instance, Kaskaoutis et al. (2012) [2] analyzed AERONET measurements from 2001 to 2010 over Kanpur, northern India, to investigate aerosol trends and variability. Their findings indicated an increase in anthropogenic emissions over the region during the study period.

Similarly, Kim et al. (2011) [27] analyzed AERONET data from 14 locations across North Africa and the Arabian Peninsula focusing on the optical properties of dust aerosols in these regions. Their findings indicated that the impact of dust aerosols was more pronounced over the Arabian Peninsula than over North Africa. Arola et al. (2011) [28] employed global AERONET observations to estimate atmospheric concentrations of black carbon and light absorbing organic carbon. Their results showed that during periods

associated with biomass combustion, elevated levels of vertically integrated light-absorbing organic aerosols were observed in regions such as South Asia, East Asia, and South America, whereas comparatively lower concentrations were detected across North America and Western Europe.

To address the aforementioned limitations, data assimilation techniques that integrate ground-based and satellite observations have emerged as a promising approach for improving aerosol representation. Extensive research efforts have contributed to the development of aerosol data assimilation systems at both regional and global scales [29–35]. Among these, the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) has garnered considerable attention in recent years for its AOD output [36,37]. The aerosol datasets generated by MERRA-2 are highly valuable for a range of atmospheric applications. Notably, they are frequently employed as input parameters in air quality forecasting systems and play a critical role in regional climate simulations and chemical transport model applications [38,39]. Beyond these operational uses, MERRA-2 aerosol data have proven instrumental in scientific investigations aimed at understanding aerosol–climate interactions and their radiative impacts on the atmosphere [40,41]. Furthermore, these datasets are also used as *a priori* inputs in retrieval algorithms for other atmospheric constituents derived from satellite observations [42,43].

Aerosol data from MERRA-2 also hold significant value within the framework of Observing System Simulation Experiments (OSSEs), particularly for the design and optimization of observational networks and future satellite sensor missions. Comprehensive technical description and documentation of the MERRA-2 products are available in prior studies and cited references [36,37]. Accordingly, the present study primarily employs MERRA-2, MODIS Aqua, and MODIS Terra datasets in conjunction with AERONET observations as the core sources of AOD data.

The distinctiveness of the present study lies in its integrated analysis of reanalysis data, satellite observations, and ground based AERONET measurements across ten geographically diverse stations situated along the dust belt. These stations encompass a range of environmental settings, including arid, semi-arid, coastal, and metropolitan regions. Investigating AOD climatological variability across such heterogeneous landscapes contributes to a deeper understanding of aerosol dynamics and their role in climate change assessments.

2. Study Area

Given the complexity of aerosol characteristics arising from variations in particle size, shape, and composition we selected data from ten AERONET monitoring sites distributed across the dust belt. These stations include three in North Africa, three in Asia, and four in the ME, as illustrated in Figure 1. Collectively, they represent wide range of environmental conditions, encompassing urbanized zones, hyper-arid terrains, coastal regions, and biomass combustion hotspots.

The AERONET station in Dalanzadgad, one of the three Asian sites, is located in southern Mongolia near the renowned Khongor Sand Dunes, within the arid expanse of the Gobi Desert, characterized by a cold desert climate [1]. Recent infrastructure development has further elevated the region’s relevance for studying both natural and anthropogenic aerosols. The other two Asian stations, Lahore and Dushanbe, are situated in major metropolitan areas of Pakistan and Tajikistan, respectively. Given their urban settings, both sites are expected to exhibit elevated concentrations of anthropogenic aerosols, primarily originating from industrial activities and other human induced processes. In recent years, Lahore has experienced increasing smog events, often exacerbated by transboundary pollution from neighboring India and China [44]. Similarly, the four AERONET stations in the ME are distributed across diverse environments, including coastal, urban, and desert

regions. The KU and MI stations represent urban and coastal settings, SV is located in a desert environment, and KAUST is positioned along a coastal zone.

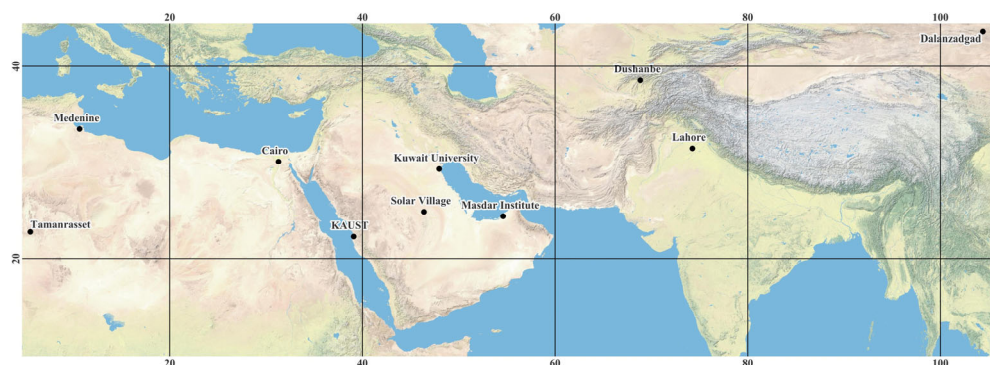


Figure 1. Locations of AERONET stations on dust belt region in the study area.

Lastly, the three AERONET stations in North Africa are situated in environmentally diverse settings. The Cairo station is located in a densely urbanized area, serving as both the capital and the largest metropolis of Egypt. The Medenine station positioned in southeastern Tunisia is influenced by its proximity to the Mediterranean coast and its location near the northern boundary of the Sahara Desert. This region is periodically affected by strong winds, including the Sirocco, a hot, dry wind originating in the Sahara that contributes to elevated levels of airborne dust and sand. The Tamanrasset station, located in southern Algeria within the central Sahara Desert, lies in an expansive arid landscape. The surrounding terrain exhibits characteristic Saharan features, including extensive dune fields, rugged highlands, and sparse xerophytic vegetation adapted to extreme dryness [1].

3. Data

This study employs data from MERRA-2, MODIS Aqua, and MODIS Terra, alongside long-term ground-based observations from AERONET stations distributed across ten locations.

3.1. MERRA Data

MERRA-2 is a hybrid reanalysis product that integrates data from the MERRA system, the Gridpoint Statistical Interpolation (GSI) data assimilation system, and the Goddard Earth Observing System (GEOS) atmospheric model. Its AOD component is constructed using bias-corrected observations derived from multiple satellite sensors, including the Advanced Very High-Resolution Radiometer (AVHRR), MODIS, and the Multi-angle Imaging Spectroradiometer (MISR). These satellite-derived observations are further supplemented by ground-based AOD measurements from the AERONET program [45,46]. For the present study, both hourly and monthly AOD data from the MERRA-2 reanalysis product, spanning the period from 1980 to 2024 and obtained via the NASA Giovanni web portal (<https://giovanni.gsfc.nasa.gov/giovanni/> accessed on 14 January 2025) have been employed.

3.2. MODIS Data

The MODIS combined Dark Target-Deep Blue (DT-DB) AOD product is particularly effective over bright surface conditions, such as deserts and snow-covered regions. The DT-DB algorithm exploits the lower reflectance in blue wavelengths to enhance aerosols detection in environments characterized by high surface albedo [47]. Consequently, MODIS DT-DB AOD products are especially well suited for regions like Saudi Arabia, where

arid desert surfaces dominate the landscape [48]. In this study, MODIS DT-DB AOD data acquired from NASA's Giovanni portal (<https://giovanni.gsfc.nasa.gov/giovanni/> accessed on 14 January 2025) hosted by the Goddard Earth Sciences Data and Information Services Center (GES DISC) are employed for statistical analysis.

3.3. AERONET Data

To evaluate the performance of MERRA-2 and MODIS DT-DB AOD products, ground-based aerosol observations from AERONET stations within the study region were employed. A detailed overview of the instrumentation used in the AERONET network, is available in [24]. This spectral radiometer is designed to measure AOD across eight discrete spectral bands, spanning wavelength from the ultraviolet to the near-infrared (approximately 340 nm to 1020 nm). AERONET provides data in three progressive categories: the first tier comprises raw, unprocessed measurements; the second tier includes datasets filtered to reduce atmospheric interference; and the third tier consists of fully validated and quality-controlled observations. A commonly used spectral band in aerosol monitoring is centered around 500 nm, as measurements at this wavelength are indicative of aerosol loading and atmospheric clarity [49]. In this study, quality-assured AOD observations at 500 nm were used to assess the accuracy of MODIS and MERRA-2 derived estimates across the target region, corresponding to the timeframe outlined in Table 1. The dataset was obtained from AERONET's official website (<http://aeronet.gsfc.nasa.gov/> accessed on 14 January 2025).

Table 1. Geographical location of AERONET stations on dust belt and total number of co-registered measurements with MERRA-2, MODIS Aqua, and MODIS Terra data.

Station Name (Country)	Longitude, Latitude (Elevation in Meter)	Total Number of Co-Registered Measurements of AERONET		
		MERRA-2	Aqua	Terra
Tamanrasset (Algeria)	5.53, 22.79 (1377.0)	3878	3301	3472
Medenine (Tunisia)	10.64, 33.5 (33.5)	698	654	652
Cairo (Egypt)	31.29, 30.08 (70.0)	2997	2555	2676
KAUST (Saudi Arabia)	39.10, 22.30 (11.2)	1536	1309	1338
Solar Village (Saudi Arabia)	46.39, 24.90 (764.0)	3920	2648	3343
Kuwait University (Kuwait)	47.97, 29.32 (42.0)	1112	1043	1067
Masdar Institute (UAE)	54.61, 24.44 (4.0)	1927	1651	1760
Dushanbe (Tajikistan)	68.85, 38.55 (821.0)	2099	1786	1800
Lahore (Pakistan)	74.26, 31.48 (209.0)	2697	2401	2391
Dalanzadgad (Mongolia)	104.41, 43.57 (1470.0)	4759	2832	3434

4. Methodology

Using monthly AOD dataset, annual and seasonal mean aerosol distribution maps were generated for the designated study area with the aid of the GrADS (Grid Analysis and Display System) version 2.2 software. These maps play a pivotal role in assessing and visualizing the spatial and temporal variability of aerosol concentrations across the study area.

AERONET provides high-accuracy aerosol measurements derived from direct solar radiation, and serves as a reliable reference for evaluating satellite AOD retrievals. To quantify the agreement between satellite- and ground-based observations the strength of association between MODIS and MERRA-2 AOD products and AERONET datasets was assessed using linear regression analysis. This approach facilitates a quantitative evaluation of data accuracy and reliability across the study domain.

The primary objective of this study is to assess the performance of AOD from MODIS (Terra and Aqua) and MERRA-2, and to investigate the climatology, trends, and variability of atmospheric aerosol concentrations on both monthly and annual scales. To validate the satellite derived AOD products, ground based AERONET observations at 500 nm from ten stations located within the dust belt region namely; KAUST, Solar Village (SV), Masdar Institute (MI), Kuwait University (KU), Tamanrasset, Cairo, Medenine, Dalanzadgad, Dushanbe, and Lahore are utilized. A suite of statistical metrics, including coefficient of determination (R^2), correlation coefficient (R), Index of Agreement (IOA), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Relative Mean Bias (RMB), and standard deviation (SD) is employed to evaluate the representativeness of MODIS and MERRA-2 AOD data relative to ground-based measurements. Following validation, the inter-annual and seasonal variability of aerosols across dust belt is systematically analyzed using the MODIS and MERRA-2 dataset.

In this study, AOD products from MERRA-2 and MODIS (Aqua and Terra) are validated against ground-based measurements from ten AERONET sites using a suite of statistical techniques. Hourly MERRA-2 AOD data are first temporally averaged and spatially mapped to the geographic coordinates of each AERONET station. This alignment process follows the methodology described in [50], which involves averaging values within a 3×3 grid window centered on the AERONET site. Only the dates on which MERRA-2 data co-register with AERONET observations are retained for analysis. Similarly, daily MODIS DT-DB AOD values corresponding to the AERONET locations are extracted, and only the co-registered dates are included in the comparative assessment.

A range of statistical methods is employed to evaluate the agreement between satellite derived AOD products (MODIS and MERRA-2) and ground based AERONET observations. SD is used to assess the dispersion of data around the mean, while R^2 examines the association between satellite and AERONET AOD values. The R quantifies the strength of their linear relationship. Additionally, the IOA defined as, the ratio of mean square error to potential error, ranging from 0 (no agreement) to 1 (perfect agreement), is applied to measure predictive accuracy. Error magnitudes are further evaluated using RMSE and MAE. Finally, RMB is calculated to assess systematic bias and the overall reliability of the MODIS and MERRA-2 AOD datasets.

5. Results and Discussion

5.1. Validation

Although, AOD data from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra across ten stations (Table 1) were assessed for conciseness, scatter plots comparing MERRA-2, MODIS Aqua, and MODIS Terra AOD with AERONET observations at the KAUST station are presented in Figure 2a–c, respectively, in the main manuscript. Scatter plots for the remaining stations are provided in the Supplementary Material. The results of the statistical analysis including the R^2 , R , IOA, RMSE, MAE, RMB, and SD are summarized in Table 2.

As shown in Table 2, the SD values across all datasets range from 0.09 to 0.44. These results underscore the overall reliability and consistency of the datasets across most locations, with the notable exception of Lahore. The discrepancies observed in Lahore may be attributed to several factors, including widespread biomass burning and the city's ranking as the 27th most populous globally. Comparable findings were also reported by [44] in their recent study.

Table 2 further demonstrates that MERRA-2 exhibits reasonably good overall agreement with AERONET observations. Notable strong performance is observed at SV and Medenine, suggesting high model reliability in arid, dust-prone regions. In contrast, the

lowest agreement is found in Cairo likely due to local pollution and complex aerosol mixtures that hinder accurate aerosol detection. RMSE and MAE values are generally modest, although the highest RMSE is recorded in Lahore, indicating substantial deviations in urban or semi-urban environments. The consistently negative RMB across all stations reflects a systematic underestimation of AOD by MERRA-2 relative to AERONET data.

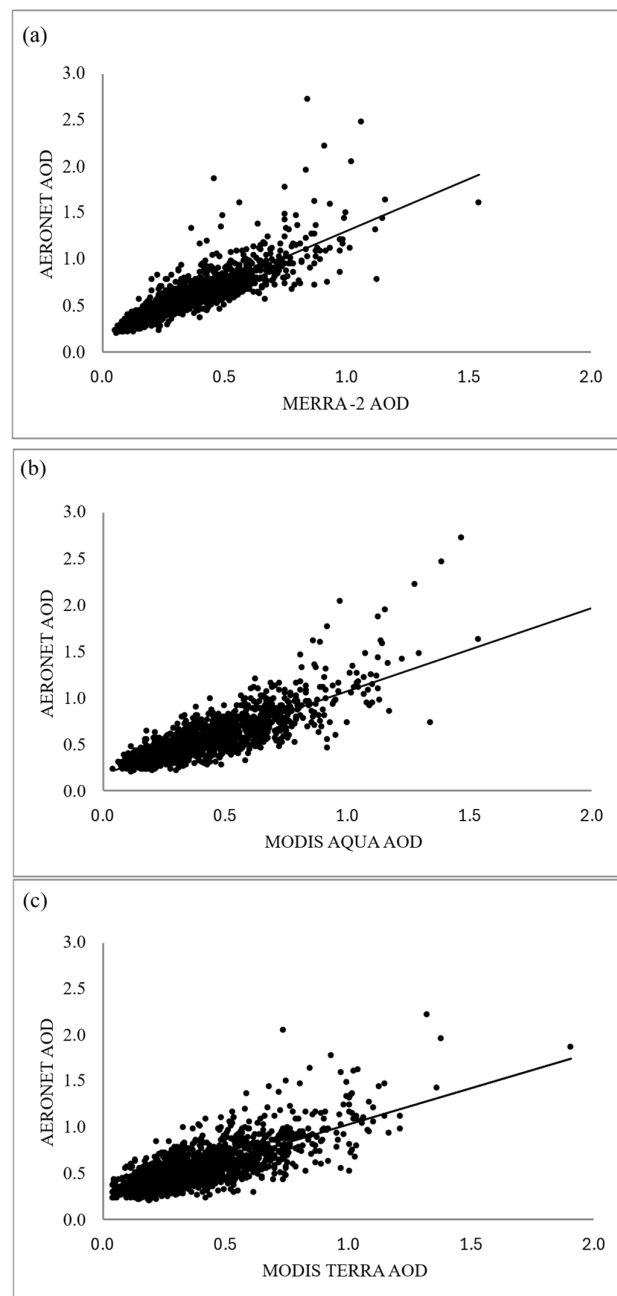


Figure 2. Validation of AOD data at KAUST for (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra with AERONET.

Table 2. Statistical results of AERONET AOD with MERRA-2, MODIS Aqua, and MODIS Terra data.

MERRA-2								
AERONET Station	R ²	R	IOA	RMSE	MAE	RMB	SDA	SDM
KU	0.63	0.79	0.84	0.18	0.14	−0.09	0.26	0.21
Lahore	0.49	0.70	0.60	0.44	0.35	−0.34	0.40	0.26
Medanine	0.75	0.87	0.79	0.14	0.13	−0.12	0.15	0.15
MI	0.77	0.88	0.78	0.19	0.17	−0.16	0.20	0.19
SV	0.78	0.88	0.87	0.16	0.12	−0.11	0.23	0.20
Tamanrasset	0.61	0.78	0.78	0.21	0.14	−0.13	0.26	0.18
Cairo	0.24	0.49	0.28	0.35	0.31	−0.31	0.18	0.13
Dalanzadgad	0.52	0.72	0.59	0.13	0.12	−0.11	0.09	0.09
Dushanbe	0.39	0.62	0.42	0.27	0.22	−0.22	0.20	0.10
KAUST	0.72	0.85	0.71	0.26	0.22	−0.22	0.25	0.19
MODIS Aqua								
KU	0.54	0.73	0.82	0.22	0.17	−0.09	0.26	0.28
Lahore	0.61	0.78	0.86	0.29	0.22	−0.11	0.38	0.43
Medanine	0.69	0.83	0.80	0.14	0.12	−0.10	0.15	0.16
MI	0.68	0.82	0.86	0.16	0.13	−0.08	0.20	0.25
SV	0.67	0.82	0.86	0.17	0.14	−0.09	0.25	0.23
Tamanrasset	0.67	0.82	0.87	0.17	0.12	−0.08	0.26	0.23
Cairo	0.39	0.62	0.59	0.24	0.20	−0.18	0.17	0.18
Dalanzadgad	0.28	0.53	0.47	0.16	0.14	−0.12	0.09	0.13
Dushanbe	0.62	0.79	0.81	0.16	0.13	−0.11	0.19	0.19
KAUST	0.64	0.80	0.83	0.20	0.15	−0.12	0.26	0.23
MODIS Terra								
KU	0.55	0.74	0.81	0.22	0.18	−0.11	0.26	0.29
Lahore	0.61	0.78	0.86	0.29	0.22	−0.11	0.38	0.44
Medanine	0.58	0.76	0.77	0.15	0.13	−0.10	0.15	0.18
MI	0.59	0.77	0.82	0.19	0.15	−0.08	0.20	0.27
SV	0.52	0.72	0.83	0.19	0.15	−0.04	0.24	0.25
Tamanrasset	0.67	0.82	0.84	0.19	0.14	−0.11	0.26	0.22
Cairo	0.31	0.56	0.55	0.25	0.20	−0.18	0.18	0.20
Dalanzadgad	0.30	0.55	0.51	0.16	0.14	−0.12	0.09	0.13
Dushanbe	0.68	0.83	0.85	0.15	0.12	−0.09	0.19	0.19
KAUST	0.55	0.74	0.76	0.23	0.18	−0.15	0.24	0.23

Similarly, MODIS Aqua (Table 2) demonstrates improved statistical performance at several stations compared to MERRA-2. For instance, stations such as MI, SV, and Tamanrasset exhibit high IOA values (≥ 0.86) alongside moderate to strong R ($R \geq 0.82$), indicating effective representation of aerosol variability. Notably, Lahore shows better agreement under MODIS Aqua than with MERRA-2. RMSE values remain within an acceptable range, and MAE is generally lower than or comparable to MERRA-2 across most stations. MODIS-Aqua also exhibits a slight underestimation bias, consistent with the trend observed in MERRA-2. The elevated SD values at stations like KU and Lahore suggest greater temporal variability in AOD captured by MODIS-Aqua.

Finally, MODIS-Terra (Table 2) exhibits mixed performance, generally comparable to MODIS Aqua, though with some degradation in statistical strength at specific sites. For instance, SV and MI show lower R² and R values under Terra compared to Aqua, although IOA remains relatively high (≥ 0.82). Notably, Dushanbe demonstrates strong agreement, underscoring Terra's capability in continental or mountainous regions. Cairo and Dalanzadgad continue to present challenges for satellite-based retrievals, reflected in relatively low R² and IOA values. The bias trend remains negative, albeit with slightly

reduced magnitude compared to Aqua, possibly due to differences in retrieval algorithm. RMSE and MAE values are consistent with those of Aqua and MERRA-2, reinforcing the relative stability of performance across platforms.

Overall, MODIS Aqua demonstrates superior performance compared to the other two products, particularly in terms of correlation and agreement metrics across most stations, including those in urban and arid environments. MERRA-2, despite being a reanalysis product, exhibits competitive performance, especially in desert regions. MODIS-Terra shows consistent results, although occasionally weaker than Aqua, likely due to differences in overpass timing and retrieval algorithms. This comparative analysis highlights the value of integrating multiple satellite datasets and accounting for local environmental conditions to enhance the accuracy of aerosol assessments across diverse climatological zones.

5.2. Spatial Analysis

The spatial distribution of annual average AOD derived from MERRA-2, MODIS Aqua, and MODIS Terra is presented in Figure 3a–c, respectively. These figures reveal that all three datasets generally exhibit similar AOD patterns; however, MODIS Terra consistently reports higher AOD values, followed by MODIS Aqua and MERRA-2. Additionally, the maps highlight distinct regional variations in dust loading across the dust belt. According to the annual AOD climatology from MERRA-2, the southwestern region (Sahara Desert) and a small portion of the eastern region (western China) display the highest AOD levels (greater than 0.7 shown in reddish tones). This pattern is more pronounced in the MODIS Aqua and Terra datasets, with AOD values exceeding 0.8 (shown in red), particularly, over Lahore and extending eastward and southeastward across the region. Seasonal distributions of average AOD derived from MERRA-2, MODIS Aqua, and MODIS Terra for winter (Figure 4a–c), spring (Figure 5a–c), summer (Figure 6a–c), and autumn (Figure 7a–c) indicate lower AOD levels during autumn and winter, and elevated levels during spring and summer. Once again MODIS Terra reports the highest AOD values, followed by MODIS Aqua and MERRA-2.

Notable variability among the ten AERONET station locations is evident from the annual AOD climatology. In the MERRA-2 datasets, the highest AOD levels (0.5–0.6) are observed at Lahore and KU, followed by moderate to high levels (0.4–0.5) at MI and SV. KAUST exhibits moderate AOD levels (0.3–0.4), while Dushanbe, Cairo, Medenine, and Tamanrasset show low to moderate levels (0.2–0.3). The lowest AOD levels (0.1–0.2) are recorded at Dalanzadgad. For both MODIS Aqua and Terra datasets, Lahore again registers the highest AOD levels (greater than 0.6). Moderate to high AOD levels (0.4–0.5) are observed at MI, SV, KU, and Cairo; KAUST shows moderate levels (0.3–0.4); and Dushanbe, Medenine, and Tamanrasset exhibit low to moderate levels (0.2–0.3). Dalanzadgad consistently records the lowest AOD levels (0.1–0.2). These results clearly indicate that Lahore experiences the highest aerosols loading, while Dalanzadgad exhibits the lowest among the ten stations analyzed. Notably, the spatial analysis findings align well with the statistical results presented in this study.

5.3. Annual and Seasonal Trend Analysis of AOD

This section presents a comprehensive analysis of annual and seasonal AOD patterns based on a comparison between ground based AERONET measurements and satellite derived AOD data from MERRA-2, MODIS Aqua, and MODIS Terra across ten stations located within the dust belt region (Figure 8a–j). Similarly, seasonal trends in AOD derived from AERONET and the three satellites products are illustrated in Figure 9a–j. These stations encompass a range of environmental settings, including arid, semi-arid, urban, and coastal regions. The analysis provides valuable insights into interannual and seasonal

variations in aerosol loading, as well as the strengths and limitations of satellite retrievals across diverse aerosol regimes.

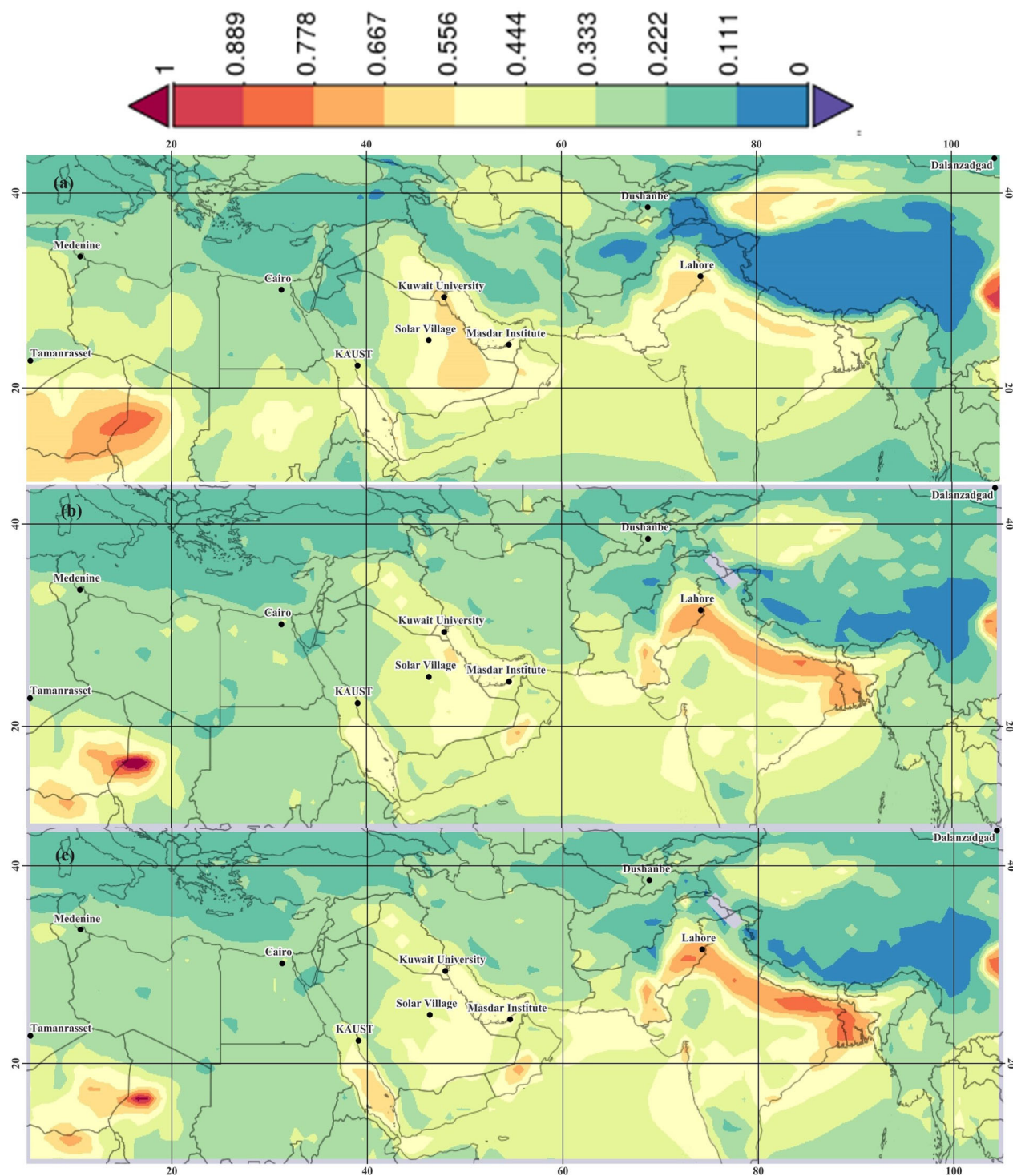


Figure 3. Mean annual aerosol spatial distribution over dust belt region based on (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra.

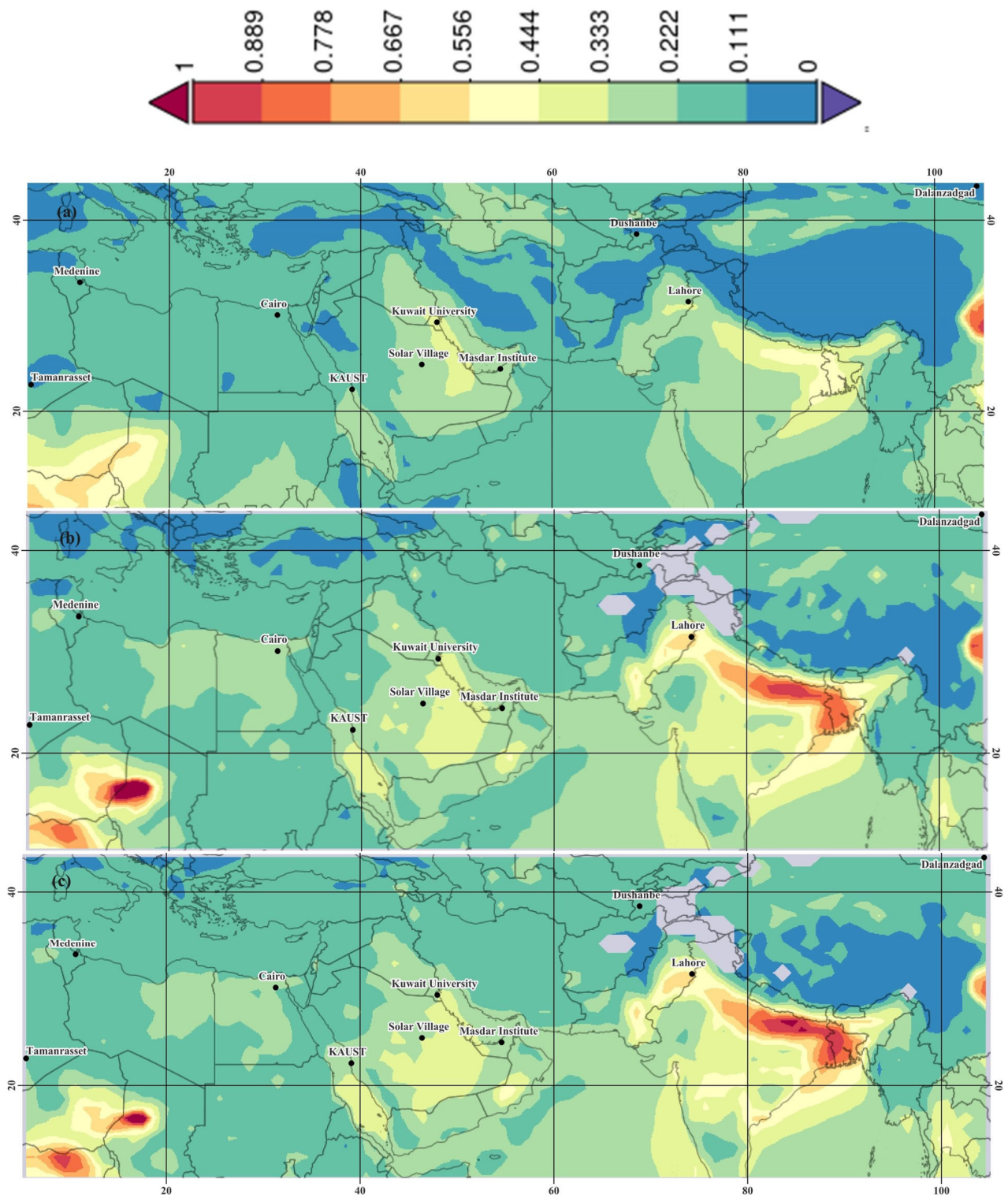


Figure 4. Mean seasonal aerosol spatial distribution over dust belt region for winter season based on (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra.

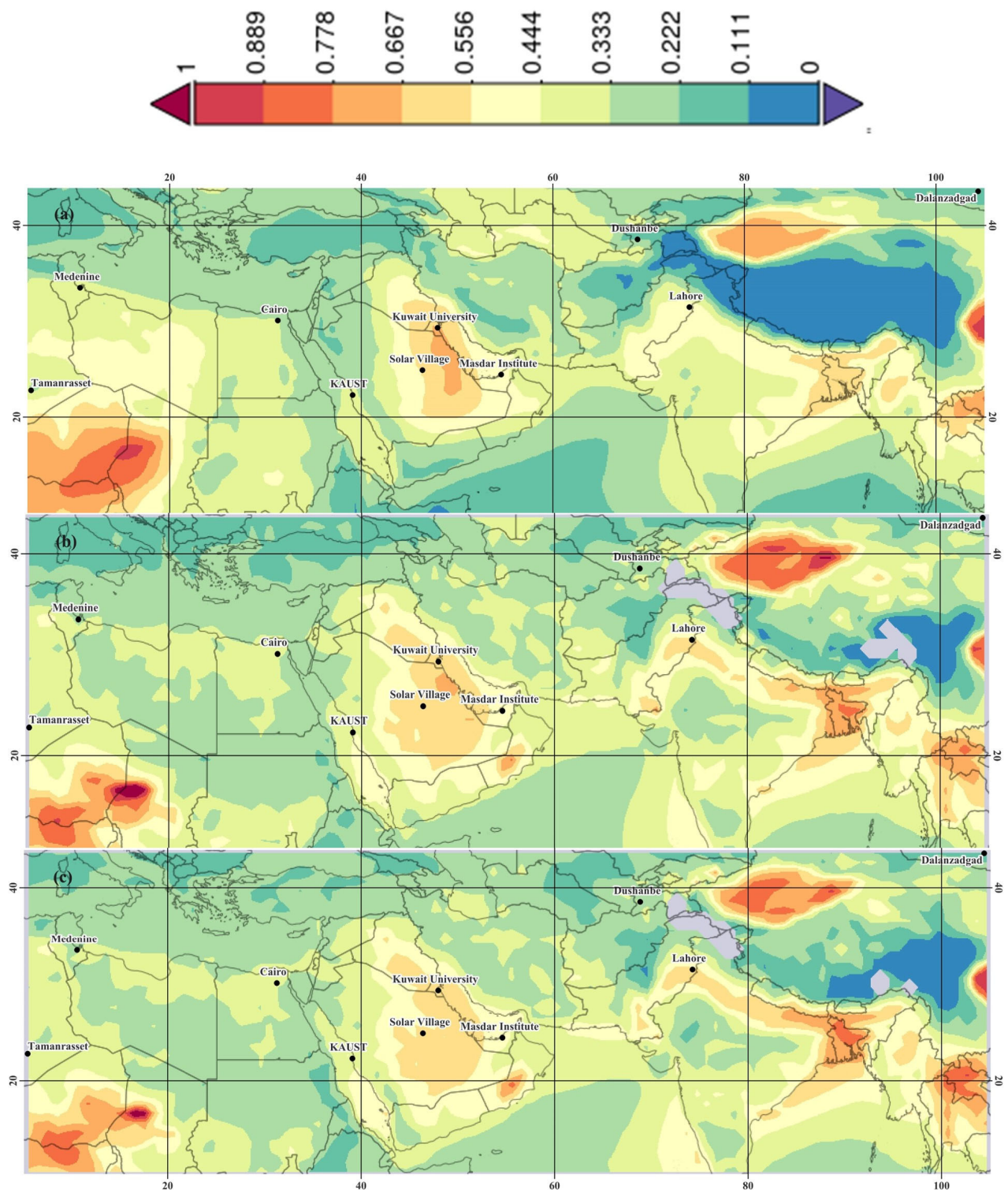


Figure 5. Mean seasonal aerosol spatial distribution over dust belt region for spring season based on (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra.

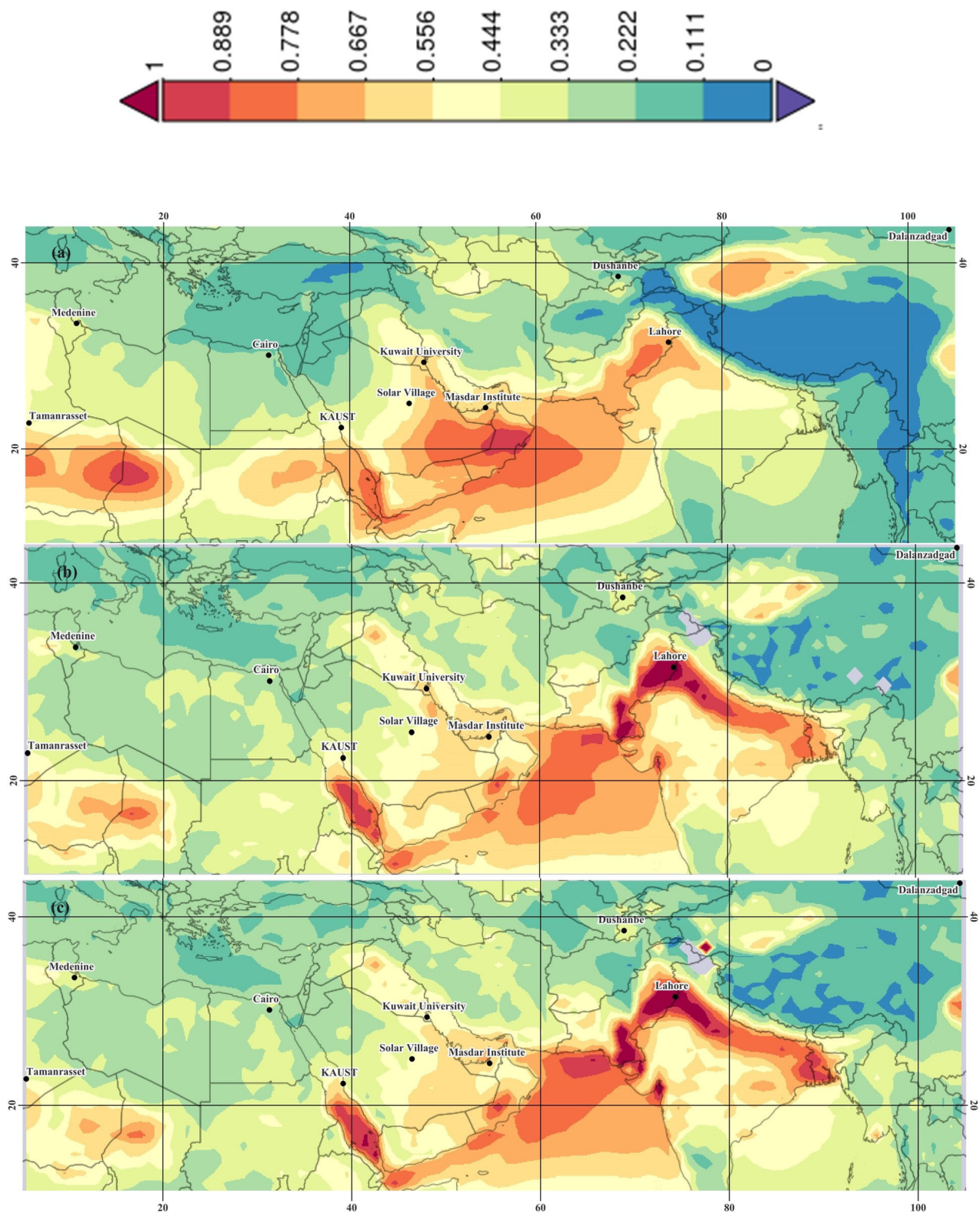


Figure 6. Mean seasonal aerosol spatial distribution over dust belt region for summer season based on (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra.

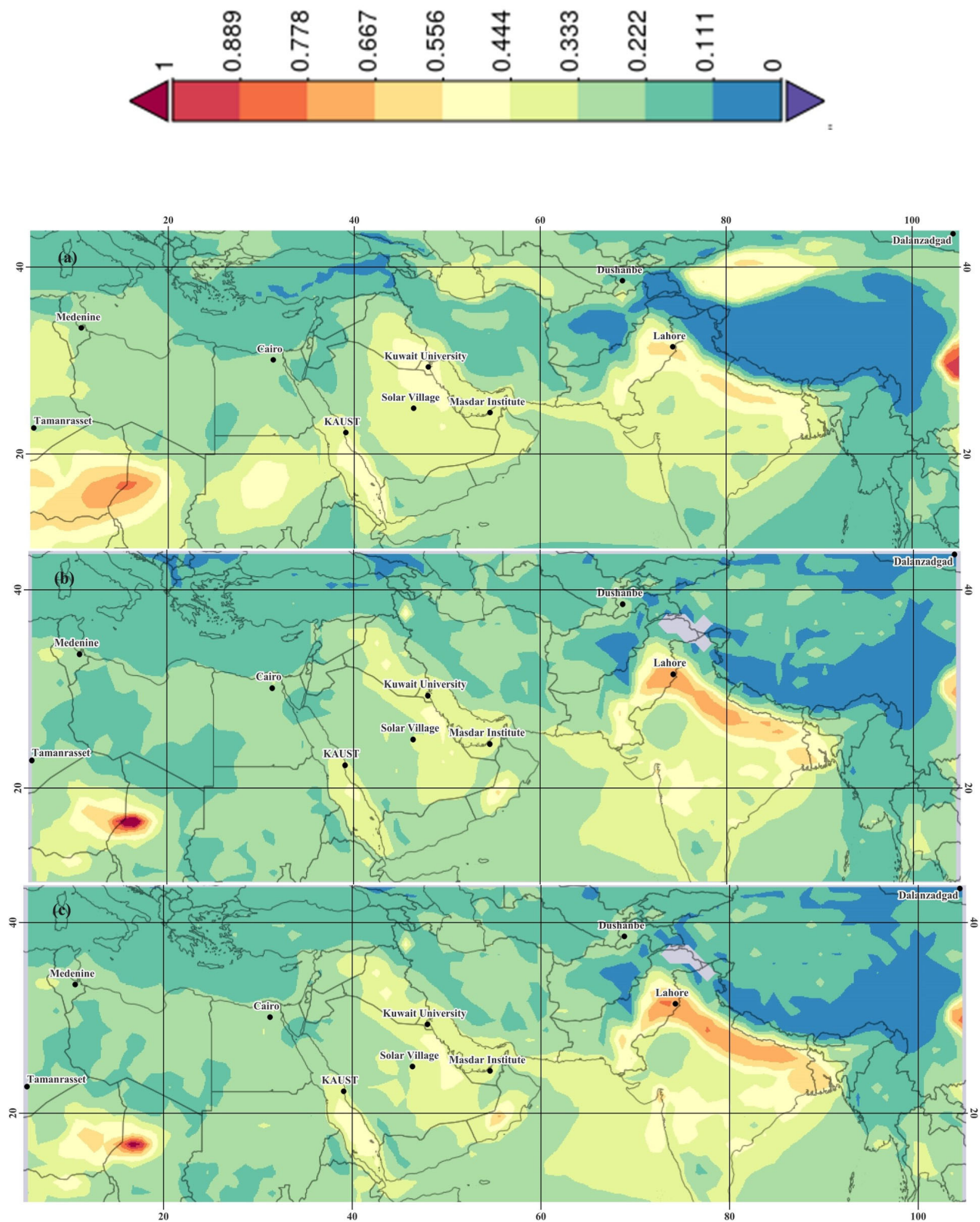


Figure 7. Mean seasonal aerosol spatial distribution over dust belt region for autumn season based on (a) MERRA-2, (b) MODIS Aqua, and (c) MODIS Terra.

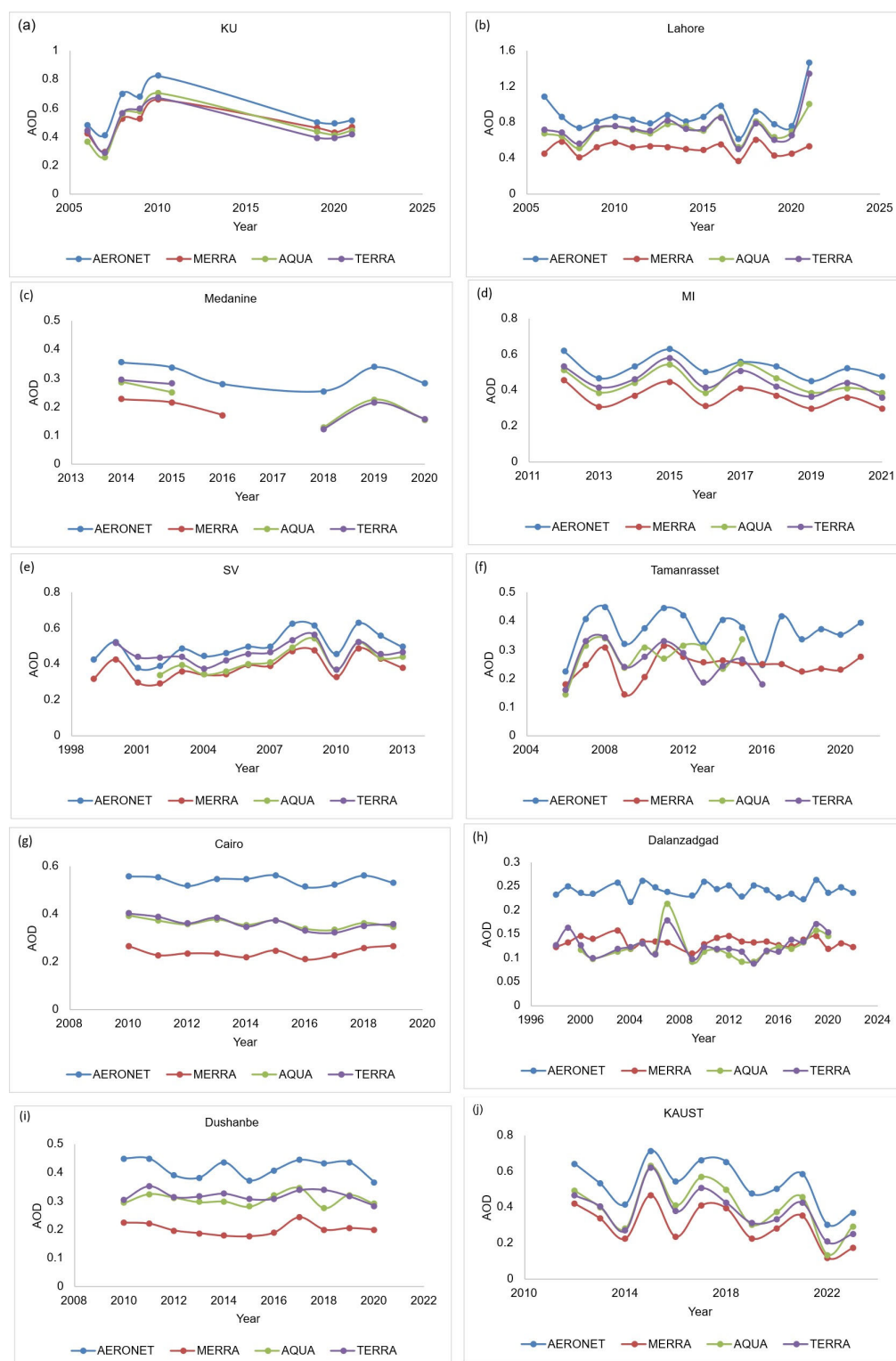


Figure 8. The average annual AOD for MERRA-2, MODIS Aqua, MODIS Terra, and AERONET stations (a) KU, (b) Lahore, (c) Medanine, (d) MI, (e) SV, (f) Tamanrasset, (g) Cairo, (h) Dalanzadgad, (i) Dushanbe, and (j) KAUST.

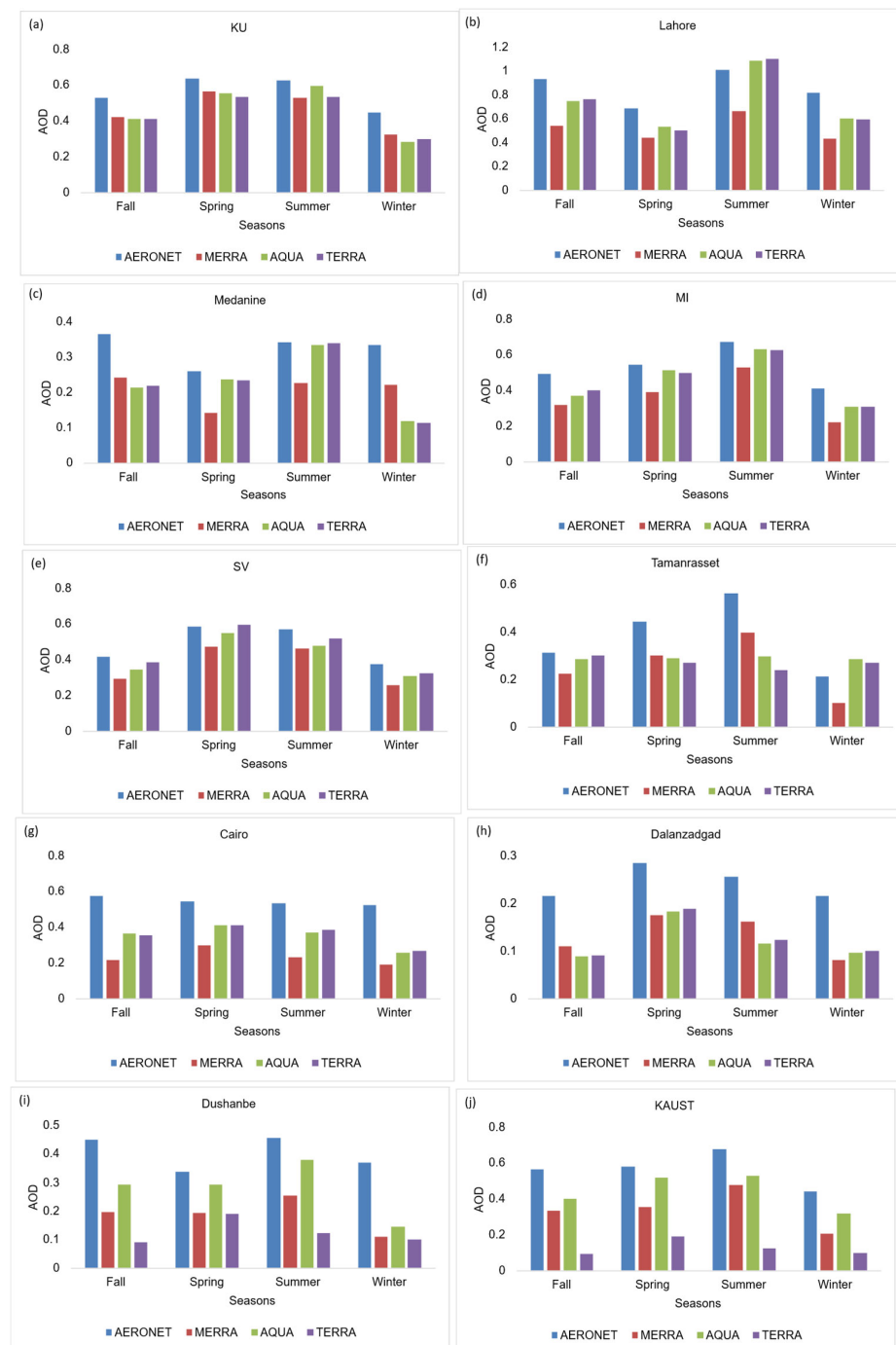


Figure 9. The average seasonal AOD for MERRA-2, MODIS Aqua, MODIS Terra, and AERONET stations (a) KU from 2006 to 2021, (b) Lahore from 2006 to 2021, (c) Medenine from 2014 to 2020, (d) MI from 2012 to 2021, (e) SV from 1999 to 2013, (f) Tamanrasset from 2006 to 2021, (g) Cairo from 2010 to 2019, (h) Dalanzadgad from 1998 to 2022, (i) Dushanbe from 2010 to 2020, and (j) KAUST from 2012 to 2023.

The annual average AOD values at KU derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.57, 0.47, 0.46, and 0.46, respectively. The annual trend analysis (Figure 8a) reveals that all datasets consistently indicate the highest AOD levels in 2010 and the lowest in 2007. Seasonal trends (Figure 9a) further show elevated AOD concentrations during spring and summer. Aerosol variability in Kuwait City is influenced by a combination of meteorological, climatic, and localized factors typical of urban settings in arid regions. For example, spring (March to May) is often characterized by sand and

dust storms, while summer (June to August) sees increased aerosol concentrations due to intensified surface heating, which lifts fine dust particles. Frequent dust events, such as the Shamal winds originating from the Arabian Desert, also contribute to elevated summer AOD levels. In autumn (September to November), temperatures begin to moderate and aerosol concentrations decline, although occasional dust events may still occur, particularly in early autumn. Winter (December to February) conditions are generally mild to cool, resulting in lower aerosol levels [1]. These findings are consistent with previous research [44,51].

For Lahore, the annual average AOD values derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.88, 0.50, 0.72, and 0.74, respectively. The annual trend analysis (Figure 8b) reveals that the highest AOD levels for AERONET occurred in 2021 while lowest is observed in 2017. Similarly, for MERRA-2 datasets the highest value occurred in 2018 and lowest in 2017. MODIS Aqua indicates highest AOD values in 2021 and lowest in 2008, while MODIS Terra shows highest values in 2021 and lowest in 2017. Seasonal trends (Figure 9b) indicate that the highest AOD levels are observed during summer and autumn followed by winter and spring. Located in the Punjab province of Pakistan, Lahore experiences pronounced seasonal fluctuations in aerosol concentrations, shaped by its climate, topography, and pollution sources. In spring, aerosol levels begin to rise due to sporadic dust events. During summer, elevated dust and fine particle concentration result from arid conditions and regional wind activity. Autumn serves as a transitional phase, generally exhibiting lower aerosol levels than summer. However, agricultural practices such as crop residue burning in nearby rural areas can cause localized spikes in aerosols concentration during winter. In addition to crop burning, frequent fog and smog events, and vehicular emissions contribute significantly to atmospheric pollution. The persistence of inversion layers further exacerbates aerosol buildup by limiting vertical mixing and hindering the dispersion of high AOD concentrations, which tend to peak in winter. While northwestern China is identified as a likely external source influencing AOD levels in Lahore, industrial emissions in that region are largely confined to basins, where surrounding topography restricts pollutant dispersion. In contrast, mineral dust exhibits relatively stable long-range transport capacity, with the most pronounced episodes typically occurring in spring. These findings are consistent with prior research [52,53].

The annual average AOD values at Medenine derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.32, 0.20, 0.21, and 0.22, respectively. Analysis of the annual trends (Figure 8c) reveals that the highest and lowest AOD values for AERONET occurred in 2014 and 2016, respectively. Similarly, MERRA-2 data show peak AOD in 2014 and the lowest in 2016, while MODIS Aqua and Terra indicate maximum values in 2014 and minimum values in 2018. Seasonal trend analysis (Figure 9c) indicates that the highest AOD values are observed during fall, summer, and winter whereas spring consistently exhibits the lowest AOD levels. These seasonal fluctuations in aerosol concentrations at the Medenine station are influenced by a combination of meteorological conditions, aerosol sources, and the broader regional climate. During spring, relatively stable and mild weather conditions are typically associated with reduced aerosol levels. In contrast, summer is characterized by hot and arid conditions, which, combined with elevated temperatures and prolonged dryness, lead to increased aerosol concentrations. This rise is further amplified by the transport of dust and sand from nearby desert regions, particularly the Sahara, with occasional dust storms contributing to pronounced spikes in aerosol levels. Autumn serves as a transitional period marked by shifting weather systems. Aerosol concentrations may remain elevated during this season, especially when residual dust from summer events persists in the atmosphere. In winter, cooler temperatures and periodic rainfall

helps cleanse the atmosphere thereby reducing aerosol presence [1,54]. These findings are consistent with previous research [55,56].

The annual average AOD values at MI derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.52, 0.36, 0.45, and 0.45, respectively. Analysis of the annual trends (Figure 8d) reveals that the highest and lowest AOD values for AERONET occurred in 2015 and 2019, respectively. For MERRA-2 the peak was observed in 2012 and the minimum in 2021. MODIS Aqua recorded its highest value in 2017 and lowest in 2019, while MODIS Terra showed maximum AOD in 2015 and minimum in 2021. Seasonal trend (Figure 9d) analysis indicates that the highest AOD values are observed during summer, followed by spring and autumn with winter consistently showing the lowest levels. Located in the United Arab Emirates, MI exhibits seasonal aerosol patterns that closely resemble those observed in Kuwait City. During spring, aerosol concentrations begin to rise, primarily due to intermittent sand and dust events. This upward trend intensifies in summer, driven by strong surface heating, the influence of Shamal winds, and limited atmospheric circulation, all of which contribute to aerosols accumulation. As the region transitions into autumn and winter, aerosol concentrations tend to decline. Cooler temperatures and shifting wind dynamics during these seasons promote atmospheric cleansing [1]. These findings are consistent with previous research [57].

The annual average AOD values at SV derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.50, 0.38, 0.42, and 0.46, respectively. Analysis of the annual trends (Figure 8e) reveals that the highest and lowest AOD values for AERONET occurred in 2011 and 2001, respectively. For MERRA-2, the peak was observed in 2011 and the minimum in 2002. MODIS Aqua recorded its highest value in 2009 and lowest in 2002, while MODIS Terra showed maximum AOD in 2009 and minimum in 2010. Seasonal trend (Figure 9e) analysis indicates that the highest AOD values are observed during spring and summer followed by autumn and winter. Located in a desert environment, the SV station experiences seasonal aerosol variations that are strongly influenced by local climatic conditions. During spring, mild to warm temperatures combined with low humidity create favorable conditions for sand and dust storms. This upward trend in aerosols concentrations continues into the summer months, which are characterized by extremely hot and arid conditions. In contrast, aerosol levels begin to decline during autumn and winter, as temperatures drop, rainfall becomes more frequent, and the occurrence of sand and dust storms diminishes [1,13]. These findings are consistent with previous research [17,58].

The annual average AOD values at Tamanrasset derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.36, 0.23, 0.28, and 0.26, respectively. Analysis of the annual trends (Figure 8f) reveals that the highest and lowest AOD values for both AERONET and MERRA-2 occurred in 2011 and 2009, respectively. For MODIS Aqua and Terra, the highest values were recorded in 2008 and the lowest in 2006. Seasonal trend (Figure 9f) analysis indicates that the highest AOD values are observed during summer and spring, while autumn and winter consistently show lower concentrations. Tamanrasset, located in a desert region, frequently experiences elevated aerosol levels between March and August, primarily due to recurring desert dust events, a defining feature of the area. This period coincides with the Saharan dust season, which is particularly active from March to June. During this time, strong winds—commonly referred to as Harmattan winds—originate from the Sahara Desert and transport substantial quantities of mineral dust and sand into the atmosphere [1,59]. These findings are consistent with previous studies that report similar aerosol pattern in the region [55,60].

The annual average AOD values at Cairo derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.54, 0.24, 0.36, and 0.36, respectively. Analysis of the annual

trends (Figure 8g) reveals that the highest and lowest AOD values for AERONET occurred in 2015 and 2012, respectively. For MERRA-2 the peak was observed in 2019 and the minimum in 2016. MODIS Aqua and Terra recorded their highest values in 2010 and lowest in 2017. Seasonal trend analysis (Figure 9g) indicates that AOD values remain relatively consistent across the seasons, with autumn exhibiting the highest concentration. Among the North African cities analyzed in this study, Cairo stands out with the highest average AOD values, which also shows relatively limited temporal variability. This persistent elevation in aerosol levels is primarily attributed to continuous anthropogenic emission resulting from extensive urbanization and industrial activity. Seasonal variability in aerosol concentrations over Cairo is influenced by a combination of meteorological conditions, local emission sources, and broader regional climate dynamics. During spring, moderate temperatures and low humidity are accompanied by frequent dust intrusions from the nearby Sahara Desert, contributing to elevated coarse-mode aerosol levels. In summer, intense heat and arid conditions promote the formation of secondary aerosols. As autumn arrives, cooler temperatures and reduced dust activity lead to a gradual decline in aerosol concentration, a trend that continues into winter, aided by occasional rainfall that helps remove atmospheric particles [1,61]. These findings are consistent with results from previous studies [55,62].

The annual average AOD values at Dalanzadgad derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.24, 0.13, 0.12, and 0.13, respectively. Analysis of the annual trend (Figure 8h) reveals that the highest and lowest AOD values for AERONET occurred in 2019 and 2004, respectively. For MERRA-2 the peak was observed in 2003 and the minimum in 2009. MODIS Aqua recorded its highest value in 2010 and lowest in 2015, while MODIS Terra showed maximum AOD in 2010 and minimum in 2016. Seasonal trend (Figure 9h) analysis indicates that AOD values remain consistent across all seasons with spring exhibiting the highest concentrations. Dalanzadgad, located in Mongolia's South Gobi Desert, displays distinct seasonal patterns in aerosol concentrations shaped by its arid climate and geographical features. The region is particularly susceptible to dust activity during spring and early summer, resulting in noticeable increases in aerosol levels. As snow and ice begin to melt in spring, exposed surfaces become sources of airborne dust and particulates. Local agricultural practices, such as plowing and tilling, further contribute to aerosol emissions during this period. In summer, aerosol levels remain elevated due to sporadic dust storms and wildfires in nearby areas, which inject smoke and fine particulate matter into the atmosphere. By autumn, aerosol concentrations generally decline, although occasional fluctuations may occur due to regional influences, land use changes, and vegetation cycles. Winter typically brings the lowest aerosol levels of the year, as snow cover and frozen soils suppress dust resuspension. Nevertheless, occasional dust transport from surrounding desert regions, including the Gobi Desert, can cause temporary spikes in aerosol concentrations [1]. These findings are consistent with previous research [63].

The annual average AOD values at Dushanbe derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.42, 0.20, 0.30, and 0.31, respectively. Analysis of the annual trends (Figure 8i) reveals that the highest and lowest AOD values for AERONET occurred in 2018 and 2015, respectively. For MERRA-2, the peak was observed in 2017 and the minimum in 2015. MODIS Aqua recorded its highest value in 2017 and lowest in 2018, while MODIS Terra showed maximum AOD in 2011 and minimum in 2020. Seasonal trend analysis (Figure 9i) indicates that the highest AOD values are observed during summer and autumn, while spring consistently shows the lowest concentrations. Dushanbe exhibits notable seasonal variation in aerosol concentrations, shaped by its geographical setting and regional climate. In spring, the city typically experiences relatively low aerosol levels due to milder weather and limited dust activity. As the region transitions into summer

and autumn, aerosol concentrations begin to rise. This increase is driven by several factors, including dry weather conditions, occasional wind events that transport dust and particulates from both local and surrounding areas, forest fires, and a potential increase in industrial emissions. In contrast, winter months tend to bring a reduction in aerosol levels, primarily due to diminished dust generation and enhanced atmospheric stability, which limits vertical mixing [1]. These findings are consistent with previous research [52].

The annual average AOD values at KAUST derived from AERONET, MERRA-2, MODIS Aqua, and MODIS Terra are 0.53, 0.30, 0.40, and 0.38, respectively. Analysis of the annual trend (Figure 8j) reveals that the highest and lowest AOD values across all datasets were observed in 2015 and 2022, respectively. Seasonal trend analysis (Figure 9j) indicates that the highest AOD values occur during summer followed by spring and autumn, while winter consistently exhibits the lowest concentrations. Situated along the Red Sea coast of Saudi Arabia, the KAUST station displays distinct seasonal patterns in aerosol concentrations, shaped by its unique coastal environment, regional climate, and a combination of natural and anthropogenic emission sources. In spring, the weather is generally warm and pleasant, with gradually rising temperatures. This season also experiences occasional sand and dust storms, particularly in the early months, contributing to a modest increase in aerosol levels. Summer brings extreme heat and dry conditions, which, combined with low humidity, favor the generation of secondary aerosols. These fine particulate aerosols originate from both natural processes and anthropogenic activities, resulting in elevated atmospheric concentrations. During autumn, temperatures begin to cool, the frequency of dust events declines, and aerosol levels exhibit a gradual decrease. Winter is typically mild and features occasional rainfall, which helps clean the atmosphere and further reduces aerosol presence [1,13]. These findings are consistent with previous research [14,58].

6. Conclusions

This study focused on analyzing the optical properties of aerosols using data from MERRA-2, MODIS Aqua, and Terra across the dust belt region, where aerosol characteristics are influenced by a range of factors including sand and dust storms, anthropogenic activities, geographic diversity, and varying aerosol types. To capture these complexities, data from ten AERONET stations were utilized, encompassing a spectrum of environments such as deserts, coastal zones, urban centers, and regions affected by biomass burning. For example, the Dalanzadgad station provided insights into naturally occurring desert aerosols, while urban locations like Lahore and Dushanbe reflected the impact of human-induced emissions. Stations in the Middle East such as SV, KAUST, KU, and MI captured the region's broad climatic and geographic variability. Meanwhile, North African sites including Cairo, Medenine, and Tamanrasset illustrated aerosol behavior across urban, coastal, and desert settings. Collectively, these diverse observational sites enabled a comprehensive assessment of aerosol patterns shaped by climatic, geographical, and anthropogenic influences.

The analysis revealed distinctive aerosol concentration trends across the North African AERONET sites, including Tamanrasset, Medenine, and Cairo. Tamanrasset exhibited elevated turbidity levels from March through August, corresponding to the peak period of Saharan dust activity. In Medenine, aerosol concentrations showed clear seasonal variability, primarily driven by shifting weather patterns and intermittent dust events. Cairo, by contrast, consistently reported high aerosol levels throughout the year, largely due to persistent urbanization and industrial emissions. Seasonal patterns were evident across three sites, with aerosol concentrations generally higher during spring and summer and lower during autumn and winter. Similar seasonal behavior was observed at the

Middle Eastern stations. SV and MI recorded heightened aerosol levels during spring and summer, followed by a decline during the cooler months. Meanwhile, KAUST and KU exhibited peak AOD values in summer, influenced by extreme temperatures, dry atmospheric conditions, frequent dust storms, and reduced atmospheric circulation.

The Asian AERONET stations exhibited clear seasonal trends in AOD values. At Dushanbe, aerosol concentrations were relatively low during spring but increased through summer and autumn, driven by dry weather conditions, wind-driven dust transport, and industrial emissions, before declining in winter. Lahore showed pronounced seasonal variability, with aerosol levels rising in spring due to dust storms, peaking in summer from both local and regional dust sources, stabilizing during autumn, and increasing again in winter, primarily due to temperature inversions and transboundary pollution. Dalanzadgad also demonstrated significant seasonal variation. Aerosol concentrations increased in spring as a result of snowmelt, agricultural activities, and dust events, remained elevated throughout summer due to dust storms and wildfire contributions, leveled off during autumn, and declined in winter, except for occasional dust transport events.

Across most stations, AOD values exhibit clear interannual variability, influenced by regional meteorology, geography, and anthropogenic activity. Aerosols such as black carbon and organic matter typically remain near the surface, making them difficult to detect from space. MERRA-2 shows generally good agreement with AERONET observations but tends to underestimate AOD. These discrepancies are largely due to the model's limitations in capturing fine-mode aerosols and surface-level pollution. MODIS Aqua demonstrates strong performance in tracking seasonal dust trends, closely aligning with AERONET data. However, it tends to underestimate AOD except at Lahore, where it overestimates values during the winter season. MODIS Terra mirrors many of the performance patterns observed with MODIS Aqua, showing good agreement in seasonal dust trends but underestimating AOD, with the same exception at Lahore during winter. These trends highlight the need for improved satellite algorithms, particularly in regions with mixed aerosol types. Nonetheless, MODIS Aqua and Terra generally outperform MERRA-2 in capturing seasonal dynamics across most stations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/earth6040115/s1>, Figure S1: Validation of AOD from MERRA-2 with AERONET at (a) KU, (b) Lahore, (c) Medenine, (d) MI, (e) SV, (f) Tamanrasset, (g) Cairo, (h) Dalanzadgad, (i) Dushanbe, and (j) KAUST; Figure S2: Validation of AOD from MODIS Aqua with AERONET at (a) KU, (b) Lahore, (c) Medenine, (d) MI, (e) SV, (f) Tamanrasset, (g) Cairo, (h) Dalanzadgad, (i) Dushanbe, and (j) KAUST. Figure S3: Validation of AOD from MODIS Terra with AERONET at (a) KU, (b) Lahore, (c) Medenine, (d) MI, (e) SV, (f) Tamanrasset, (g) Cairo, (h) Dalanzadgad, (i) Dushanbe, and (j) KAUST.

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