Aerosol Characteristics over India Based on Long-Term AERONET Measurements

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Abstract

This study presents a comprehensive long-term analysis of Aerosol Optical Depth (AOD) variability over Jaipur, Rajasthan, India, spanning the period 2009 to 2025. Multi-sensor satellite retrievals from the Ozone Monitoring Instrument (OMI/OMAERUV), Multi-angle Imaging SpectroRadiometer (MISR), and Moderate Resolution Imaging Spectroradiometer (MODIS) onboard both Aqua and Terra platforms are integrated with ground-based AERONET sun-photometer measurements to evaluate inter-sensor consistency, temporal aerosol trends, and spectral aerosol characteristics. The AERONET retrievals at Jaipur reveal persistent moderate-to-high aerosol loading (AOD500nm ~ 0.3–0.8) with considerable seasonal and inter-annual variability over the study period. A distinct spectral dependence of AOD, decreasing from 0.36 at 440 nm to 0.29 at 870 nm, points to the dominance of fine-mode anthropogenic aerosols, while a post-2020 shift in the fine-to-coarse mode ratio suggests a progressive transition in aerosol composition driven by urban growth and changing emission patterns. Satellite inter-comparison using Pearson correlation analysis reveals moderate to strong agreement among MODIS, MISR, and AERONET datasets (R = 0.42–0.66), with Terra MODIS achieving the strongest correlation with AERONET (R = 0.66). The systematically low correlations involving OMAERUV Absorbing AOD (R = 0.17–0.39) are consistent with its retrieval of the absorbing aerosol fraction only. These findings underscore the complementary nature of multi-sensor aerosol observations and provide a robust baseline for aerosol radiative forcing assessments and air quality monitoring over this rapidly urbanizing arid-zone city.

Keywords: Aerosol Optical Depth; AERONET; MODIS; MISR; OMAERUV; Jaipur; Rajasthan; Multi-sensor comparison; Fine mode aerosol; Urban aerosol variability

1. Introduction

Atmospheric aerosols are a critical component of the Earth's climate system, exerting significant influence on the radiation budget through direct scattering and absorption of solar radiation, and indirectly through their role as cloud condensation nuclei (Kaufman et al., 2002; IPCC, 2021). In South Asia, and particularly over the Indo-Gangetic Plain and Rajasthan desert fringe, aerosol loading is among the highest in the world due to a complex interplay of natural and anthropogenic sources including mineral dust from the Thar Desert, vehicular emissions, industrial pollution, biomass burning, and agricultural residue combustion (Satheesh and Moorthy, 2005; Prasad et al., 2007). These aerosols significantly degrade air quality, alter regional precipitation patterns, and pose serious public health risks, making their long-term monitoring a scientific and policy priority.

Aerosol Optical Depth (AOD) is the primary column-integrated metric used to quantify aerosol loading in the atmosphere. Over the past two decades, the proliferation of ground-based sun-photometer networks such as AERONET (Holben et al., 1998) and the availability of multiple satellite-based aerosol retrieval products have made it possible to characterize aerosol properties at unprecedented spatial and temporal scales. However, significant discrepancies between satellite-derived and ground-based AOD estimates persist over heterogeneous, high-albedo surfaces such as the arid and semi-arid landscapes of Rajasthan, posing a major challenge for regional aerosol studies (Tripathi et al., 2005; Kaskaoutis et al., 2009).

Jaipur, the capital of Rajasthan and one of India's fastest-growing metropolitan cities, presents a particularly challenging yet important environment for aerosol research. Located at the eastern margin of the Thar Desert, the city experiences a complex aerosol regime influenced by mineral dust intrusions during the pre-monsoon season, intense photochemical pollution during winter, and smoke from agricultural fires during post-harvest periods (Singh et al., 2006; Kumar et al., 2014). Despite its scientific importance, comprehensive multi-sensor analyses of long-term aerosol variability over Jaipur remain limited in the literature.

Several previous studies have validated MODIS and MISR AOD retrievals against AERONET over India, reporting variable agreement depending on season, surface type, and aerosol loading regime (Misra et al., 2015; Mehta et al., 2016). The OMAERUV product provides complementary information on the absorbing component of the aerosol column, which is particularly relevant for black carbon and iron-oxide-bearing dust aerosols prevalent over Rajasthan (Torres et al., 2007). However, simultaneous inter-comparison of all four major sensor systems against AERONET over a sustained 16-year record at Jaipur has not been undertaken previously.

The present study addresses this gap by conducting a rigorous multi-sensor evaluation of AOD over Jaipur using monthly mean data for the period January 2009 to December 2025. Specifically, this work aims to: (i) characterize long-term temporal and seasonal variability in AOD from multiple satellite and ground-based platforms; (ii) quantify spectral AOD characteristics and size-resolved aerosol partitioning using AERONET multi-wavelength retrievals; (iii) assess inter-sensor consistency through pairwise Pearson correlation analysis; and (iv) identify key drivers of aerosol variability including episodic dust events, urban emission growth, and potential COVID-19 lockdown effects on aerosol loading.

2. Study Area and Data

2.1 Study Area

Jaipur (26.91°N, 75.79°E; ~431 m above mean sea level) is the capital and largest city of Rajasthan, located in the northwestern part of India at the transitional zone between the semi-arid Thar Desert and the Aravalli mountain range. The city has a hot semi-arid climate (BSh under the Koppen classification) characterized by hot, dry summers (March–June), a monsoon season (July–September), and mild winters (November–February). The annual mean temperature ranges from approximately 15°C in January to 35°C in June, with mean annual rainfall of approximately 650 mm, predominantly concentrated in the monsoon months.

From an aerosol perspective, Jaipur is influenced by multiple source types operating at different temporal scales. During the pre-monsoon season (March–June), northwesterly winds transport mineral dust from the Thar Desert, leading to episodic AOD values exceeding 1.0. Winter months are characterized by low mixing layer heights, temperature inversions, and accumulation of vehicular and industrial pollutants. Post-harvest biomass burning in Punjab and Haryana during October–November contributes substantial carbonaceous aerosol loading through long-range transport. The city has experienced rapid urbanization over the study period, with its population growing from approximately 3 million to over 4.5 million, accompanied by significant increases in vehicular traffic, construction activity, and industrial expansion.

2.2 Data Sources

2.2.1 AERONET

Ground-based aerosol measurements were obtained from the AERONET station at Jaipur. AERONET employs Cimel sun-photometer instruments to measure direct solar irradiance at multiple wavelengths (340, 380, 440, 500, 675, 870, and 1020 nm), from which AOD is derived with an uncertainty of ±0.01–0.02 (Holben et al., 1998). Level 2.0 quality-assured data were used in this study, including cloud-screened AOD retrievals at 440, 500, 675, and 870 nm, along with size-resolved fine and coarse mode AOD derived using the spectral deconvolution algorithm (O'Neill et al., 2003). Monthly mean values were computed from all available cloud-free observations within each month.

2.2.2 MODIS (Aqua and Terra)

AOD at 550 nm was retrieved from the MODIS Deep Blue algorithm (Collection 6.1) for both Aqua (MYD08_M3) and Terra (MOD08_M3) platforms, providing monthly Level-3 gridded products at 1° × 1° spatial resolution. The Deep Blue algorithm is specifically designed for retrievals over bright desert surfaces and has been shown to perform well over arid and semi-arid regions such as Rajasthan (Hsu et al., 2013). Terra and Aqua overpass times are approximately 10:30 AM and 1:30 PM local time, respectively.

2.2.3 MISR

MISR AOD at 555 nm was obtained from the MISR Level 3 Component Global Aerosol product (MIL3MAE), providing monthly mean AOD at 0.5° × 0.5° spatial resolution. MISR employs nine cameras at different view angles to retrieve aerosol properties with reduced sensitivity to surface reflectance (Diner et al., 1998). The MISR data record shows some gaps in coverage after 2015, which should be considered when interpreting inter-sensor comparisons during the latter part of the study period.

2.2.4 OMAERUV

The Absorbing Aerosol Optical Depth (AAOD) at 500 nm was obtained from the OMAERUV Version 1.8.9.1 product derived from the Ozone Monitoring Instrument (OMI) aboard the NASA Aura satellite. Unlike total AOD products, OMAERUV retrieves only the absorbing component of the aerosol column, making it sensitive to black carbon and iron-oxide-bearing mineral dust aerosols (Torres et al., 2007). It must be emphasized that OMAERUV AAOD is not directly comparable in magnitude to total AOD products from MODIS, MISR, or AERONET.

2.3 Methodology

Monthly mean AOD values from all five datasets were compiled for January 2009 to December 2025 (192 months). Pearson correlation coefficients (R) were computed for all pairwise sensor combinations to quantify linear inter-sensor agreement. AERONET-derived spectral AOD values were used to estimate the mean Angstrom Exponent and characterize aerosol spectral dependence. Fine and coarse mode AOD time series from AERONET were analyzed to identify long-term shifts in aerosol size distribution. All analyses were conducted using Python 3.10 with NumPy, Pandas, SciPy, and Matplotlib libraries.

3. Results and Discussion

3.1 Long-Term Temporal Variability of Multi-Sensor AOD (2009–2025)

Figure 1 presents the monthly average AOD time series from four satellite sensors over Jaipur for the period 2009–2025. The time series reveals pronounced seasonal oscillations in aerosol loading across all sensors, with recurring peak values during the pre-monsoon months (April–June) driven by intense dust activity from the Thar Desert. Secondary peaks are observed during the post-monsoon period (October–November), attributable to agricultural residue burning in Punjab and Haryana, whose smoke is advected southeastward toward Jaipur under prevailing meteorological conditions.

Terra/MODIS AOD consistently exhibited the highest monthly mean values among all satellite sensors throughout the study period, with episodic peaks frequently exceeding 0.8 and several extreme events surpassing 1.0, notably in 2012, 2014, 2016, and 2024. These extreme episodes are consistent with documented severe dust storms that periodically impact Rajasthan during the pre-monsoon season. The Terra overpass at approximately 10:30 AM local time coincides with the period of maximum dust activity, as daytime surface heating intensifies convective mixing and dust entrainment in the lower troposphere, potentially contributing to systematically higher AOD values compared to Aqua.

Aqua/MODIS Deep Blue AOD displayed a systematically lower magnitude than Terra MODIS, with monthly means predominantly in the range 0.1–0.4. The approximately three-hour difference in overpass time introduces a diurnal sampling asymmetry. By early afternoon, dust emission from the surface is partially suppressed by increased surface wind turbulence and boundary layer deepening, and increased cloud cover during monsoon transition months may disproportionately reduce Aqua data availability during high-AOD episodes, introducing a negative sampling bias.

MISR AOD at 555 nm showed generally good agreement with Terra MODIS in terms of seasonal phase, capturing the pre-monsoon peaks and post-monsoon secondary maxima throughout the 2009–2015 period when data coverage was most complete. The multi-angle retrieval approach of MISR provides robust aerosol retrievals over bright desert surfaces by effectively constraining the surface BRDF, thereby reducing retrieval uncertainty compared to single-view sensors (Diner et al., 1998; Kahn et al., 2010). After approximately 2015, MISR data availability becomes intermittent, limiting continuous inter-comparison during the latter half of the study period.

OMAERUV AAOD at 500 nm remained consistently low throughout the entire study period, with monthly mean values typically below 0.05. This is physically consistent and expected, as OMAERUV retrieves only the absorbing fraction of the aerosol column. An important feature in the multi-sensor time series is the elevated aerosol loading observed during 2020–2022, potentially associated with post-COVID recovery emissions, extreme dust events, or changing agricultural burning practices — a period warranting dedicated future investigation.

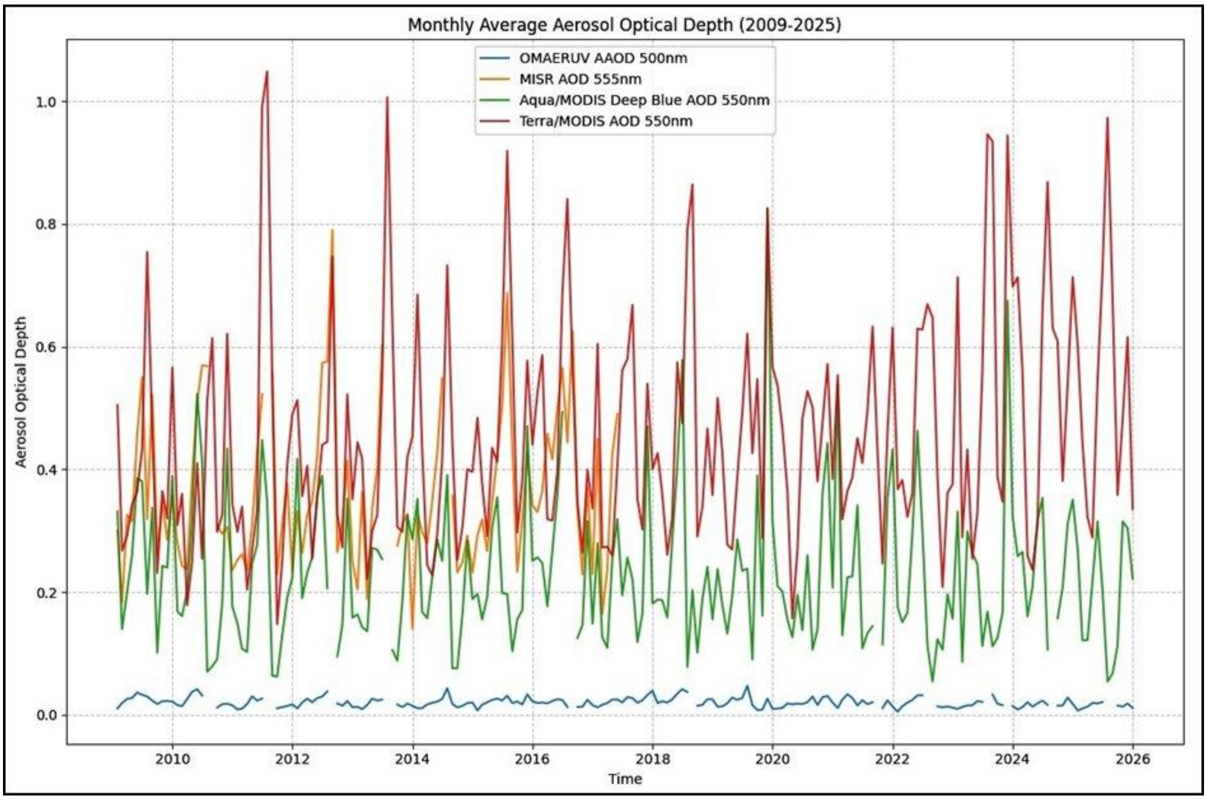

Figure 1. Monthly average Aerosol Optical Depth (AOD) from four satellite sensors over Jaipur, India (2009–2025). OMAERUV AAOD (blue), MISR AOD at 555 nm (orange), Aqua/MODIS Deep Blue AOD at 550 nm (green), and Terra/MODIS AOD at 550 nm (red) are shown. Note the consistent seasonal oscillations, episodic dust-driven peaks exceeding 1.0 in Terra/MODIS, and the systematically lower OMAERUV AAOD values reflecting the absorbing aerosol fraction only.

3.2 AERONET-Based Multi-Wavelength AOD Variability at Jaipur

3.2.1 Temporal Variability of Spectral AOD

Figure 2(A) presents the AERONET monthly mean AOD time series at four wavelengths (440, 500, 675, and 870 nm) for Jaipur over the study period. The four wavelength channels maintain a consistent hierarchical stratification throughout the record, with AOD at 440 nm exceeding that at 500 nm, which in turn exceeds AOD at 675 nm and 870 nm at virtually all times. This wavelength ordering — wherein shorter wavelengths experience greater aerosol extinction — is characteristic of size distributions dominated by sub-micron particles and is described quantitatively by the Angstrom Exponent relationship: $AOD(\lambda) = AOD(\lambda_0)(\lambda/\lambda_0)^{(-\alpha)}$, where $\alpha > 1$ indicates fine-mode dominance (Angstrom, 1929).

Over the entire 2009–2025 record, monthly mean AOD at 500 nm ranges from approximately 0.2 to 0.8 under normal conditions, with an extreme event in 2021 driving AOD at 440 nm above 1.2 — the highest value in the entire AERONET Jaipur record. The absence of data between approximately 2018 and 2020 in the AERONET record, attributable to instrument maintenance or data quality screening, creates a gap that limits direct comparison with the satellite record during this critical transition period.

The post-gap period (2020–2025) is distinguished by increased variability at all wavelengths and greater frequency of high-AOD events compared to the early years of the record, potentially reflecting the combined influence of urban growth, changing agricultural practices, and increasingly erratic pre-monsoon dust storm activity associated with regional climate variability.

3.2.2 Spectral AOD Characteristics and Angstrom Exponent

Figure 2(B) presents the climatological mean spectral AOD at Jaipur, showing a systematic and monotonic decrease from 0.36 at 440 nm to 0.33 at 500 nm, 0.30 at 675 nm, and 0.29 at 870 nm. This consistent negative spectral slope is a defining characteristic of aerosol populations dominated by fine-mode particles in the sub-micron size range (radius < 0.5 μm). The Angstrom Exponent (α) estimated from the spectral AOD at 440/870 nm yields $\alpha \approx 0.70–0.80$, indicating a mixed aerosol regime with contributions from both fine-mode anthropogenic particles and coarse-mode mineral dust (Eck et al., 1999). This intermediate α value is consistent with Jaipur's geographic setting at the interface between the dust-dominated Thar Desert and the anthropogenically influenced Indo-Gangetic Plain.

3.2.3 Fine and Coarse Mode AOD Partitioning

Figure 2(C) presents the time series of fine mode and coarse mode AOD derived from the AERONET spectral deconvolution algorithm. During 2009–2018, coarse mode AOD dominates or is broadly comparable to fine mode AOD for much of the year, with coarse mode values frequently exceeding 0.4 during the pre-monsoon season, consistent with the seasonal influx of mineral dust from the Thar Desert. A marked and sustained transition is evident after 2020, whereby fine mode AOD increasingly dominates over coarse mode AOD.

Fine mode AOD peaks above 1.0 in 2021 and maintains elevated values through 2024, suggesting a structural change in the aerosol emission environment of Jaipur driven by rapid post-COVID urbanization, increased vehicular traffic, and enhanced regional biomass burning activity.

The consistently low coarse mode AOD values observed during 2020 may partially reflect the reduced dust emission associated with decreased surface disturbance during the COVID-19 lockdown — a phenomenon reported for other Indian cities during this period (Mahato et al., 2020). The subsequent rebound and sustained elevation of both fine and coarse mode AOD in 2021–2025 further supports this interpretation and highlights the sensitivity of Jaipur's aerosol regime to anthropogenic emission controls and natural dust variability.

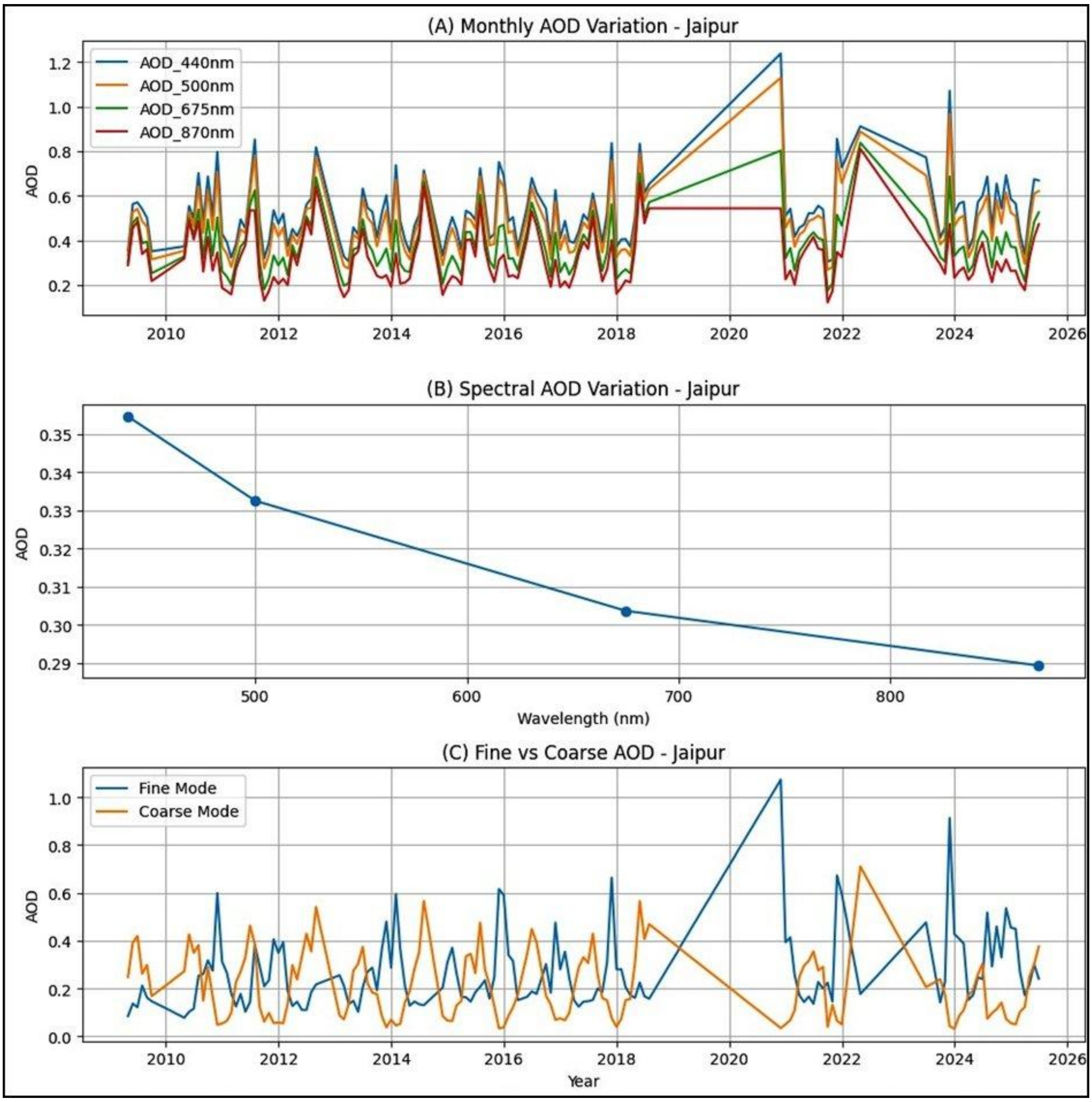

Figure 2. AERONET-based aerosol optical depth analysis at Jaipur, India (2009–2025). (A) Monthly AOD variation at four wavelengths: 440 nm (blue), 500 nm (orange), 675 nm (green), and 870 nm (red). Note the data gap (~2018–2020) and the extreme event exceeding AOD = 1.2 in 2021. (B) Climatological mean spectral AOD showing a monotonic decrease from 440 nm to 870 nm, indicating fine-mode aerosol dominance. (C) Fine mode (blue) versus coarse mode (orange) AOD time series, revealing a progressive shift toward fine-mode aerosol dominance after 2020.

3.3 Multi-Sensor Inter-Comparison and Correlation Analysis

3.3.1 Overview of Inter-Sensor Correlations

Figure 3 presents the pairwise Pearson correlation matrix for monthly mean AOD from five sensors — OMAERUV AAOD (500 nm), MISR AOD (555 nm), Aqua MODIS AOD (550 nm), Terra MODIS AOD (550 nm), and AERONET AOD (500 nm) — along with frequency histograms of each individual dataset on the diagonal. Correlation coefficients range from a minimum of R = 0.17 (OMAERUV vs. Terra MODIS) to a maximum of R = 0.66 (Terra MODIS vs. AERONET), indicating highly variable inter-sensor agreement depending on the physical nature of the retrieved aerosol quantity and the technical characteristics of each sensor.

3.3.2 OMAERUV AAOD Correlations

OMAERUV AAOD at 500 nm showed moderate positive correlations with MISR AOD (R = 0.62) and Aqua MODIS AOD (R = 0.58), suggesting that the absorbing aerosol fraction tracked by OMI captures a meaningful proportion of the variance in total column aerosol loading during episodes of intense absorbing aerosol events, such as dust storms bearing iron-oxide-rich mineral particles or smoke from large-scale biomass burning. However, the correlation between OMAERUV AAOD and Terra MODIS AOD was notably weak (R = 0.17) — the lowest value in the entire matrix. Terra MODIS frequently retrieves very high AOD values during coarse-mode dust events when the absorbing fraction (AAOD/AOD ratio) is relatively small, and differences in spatial resolution, cloud screening algorithms, and surface reflectance models may contribute systematic noise to this correlation. The weak OMAERUV–AERONET correlation (R = 0.39) is also physically consistent, reflecting the fundamental difference between absorbing and total AOD as physical quantities.

3.3.3 MISR AOD Correlations

MISR AOD at 555 nm demonstrated consistent moderate-to-strong correlations with all other sensors, with values of R = 0.62 (OMAERUV), R = 0.56 (Aqua MODIS), R = 0.46 (Terra MODIS), and R = 0.59 (AERONET). The MISR-AERONET correlation of R = 0.59 is in line with published validation studies for this region, which report R values of 0.55–0.75 depending on season and aerosol type (Kahn et al., 2010; Mehta et al., 2016). The somewhat lower MISR-Terra MODIS correlation (R = 0.46) compared to MISR-Aqua MODIS (R = 0.56) likely reflects the higher dynamic range and more extreme monthly mean values of

Terra MODIS during dust events, introducing nonlinearity in the correlation not fully captured by MISR's constrained multi-angle retrieval.

3.3.4 MODIS Aqua and Terra Inter-Comparison

The correlation between Aqua MODIS and Terra MODIS AOD was $R = 0.42$, a value that is considerably lower than expected a priori given their identical sensor design and retrieval algorithm. This moderate agreement is consistent with published inter-comparisons over South Asia (Misra et al., 2015) and points to the significant influence of diurnal aerosol variability on monthly correlation statistics. The ~3-hour difference between Terra (~10:30 AM) and Aqua (~1:30 PM) overpass times allows substantial evolution of the boundary layer aerosol population, particularly during the summer dust season. Despite their moderate mutual correlation, both Aqua and Terra MODIS show considerably stronger correlations with AERONET ($R = 0.59$ and $R = 0.66$, respectively), confirming that each provides reliable monthly-scale aerosol information when independently evaluated against ground truth.

3.3.5 AERONET as Ground Truth Reference

AERONET AOD at 500 nm achieved its strongest satellite correlations with Terra MODIS ($R = 0.66$) and MISR ($R = 0.59$), with comparable agreement with Aqua MODIS ($R = 0.59$). These values are broadly consistent with regional validation studies over northwestern India, though somewhat lower than $R > 0.80$ values reported for sites in more homogeneous terrain (Ichoku et al., 2002). The relatively moderate correlations likely reflect: (i) spatial sampling mismatch between the point AERONET measurement and the $1° \times 1°$ satellite grid cell; (ii) temporal sampling differences between instantaneous AERONET retrievals and the satellite overpass; and (iii) algorithmic uncertainties in satellite retrievals over the complex bright desert surface of Rajasthan.

3.3.6 AOD Frequency Distributions

The diagonal histograms in Figure 3 reveal important distributional characteristics. OMAERUV AAOD is tightly confined to a narrow range of 0.010–0.040, consistent with the near-invariant contribution of absorbing aerosols to the total column. MISR AOD follows a right-skewed distribution spanning 0.1–0.65, with the mode at approximately 0.3–0.4. Aqua MODIS AOD shows a peaked distribution in the range 0.1–0.4 with a mode around 0.2. Terra MODIS AOD exhibits a highly right-skewed distribution with a long tail extending to values approaching 1.0, reflecting frequent extreme dust events captured at its morning overpass. AERONET AOD at Jaipur exhibits a near-normal distribution centered at approximately 0.4–0.5, consistent with the moderately high mean aerosol loading characteristic of this urban desert-fringe environment.

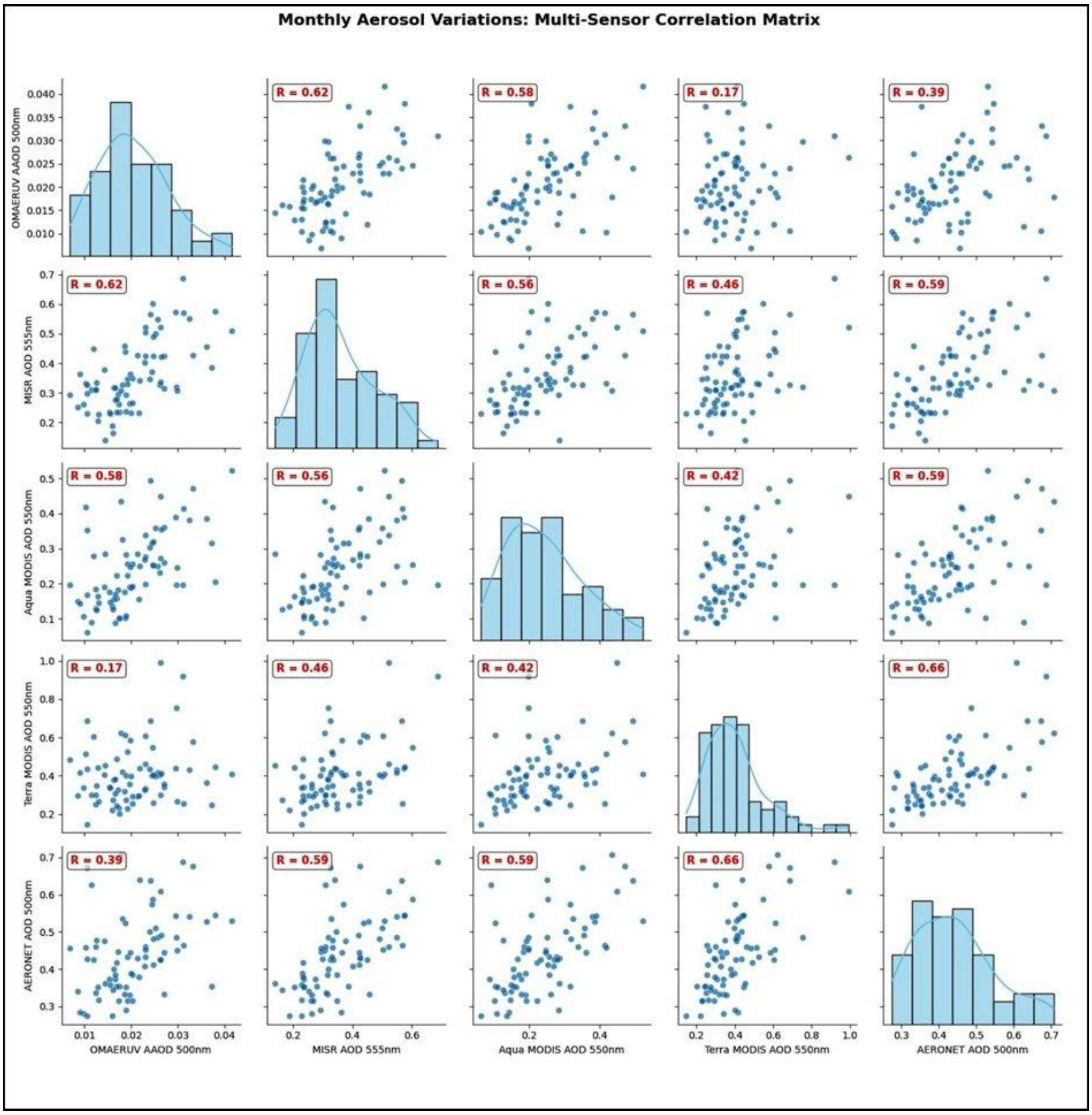

Figure 3. Monthly Aerosol Variations: Multi-Sensor Pearson Correlation Matrix for Jaipur, India. Off-diagonal panels show scatter plots of monthly mean AOD between each sensor pair with Pearson correlation coefficient (R) indicated in red. Diagonal panels show frequency histograms of each sensor's AOD distribution. Sensors: OMAERUV AAOD (500 nm), MISR AOD (555 nm), Aqua MODIS AOD (550 nm), Terra MODIS AOD (550 nm), and AERONET AOD (500 nm).

4. Conclusion

This study has presented a comprehensive multi-sensor analysis of Aerosol Optical Depth variability over Jaipur, Rajasthan, India, for the extended period 2009–2025, integrating monthly data from OMAERUV, MISR, MODIS Aqua, MODIS Terra, and AERONET. The key findings and conclusions are as follows:

The long-term multi-sensor AOD time series (Figure 1) reveals strong seasonal variability dominated by pre-monsoon dust activity and post-monsoon biomass burning events, with Terra MODIS consistently recording the highest AOD values due to its morning overpass timing coinciding with peak dust emission. OMAERUV AAOD remained consistently low throughout the record, reflecting its sensitivity to only the absorbing aerosol fraction. A notable period of elevated aerosol loading during 2020–2022 was identified, with potential contributions from post-COVID recovery emissions and extreme dust events, warranting detailed future investigation using chemical transport models and emission inventory analysis.

AERONET multi-wavelength analysis (Figure 2) reveals a climatological mean spectral AOD decreasing from 0.36 at 440 nm to 0.29 at 870 nm, corresponding to an Angstrom Exponent of approximately 0.70–0.80 indicative of a mixed fine-coarse aerosol regime. The fine versus coarse mode AOD partitioning analysis identifies a significant post-2020 transition characterized by increasing dominance of fine-mode aerosols, consistent with accelerated urbanization and growing anthropogenic emission sources in Jaipur superimposed on persistent coarse-mode mineral dust contributions from the Thar Desert. This compositional shift has direct implications for aerosol radiative forcing calculations and air quality management.

The inter-sensor Pearson correlation matrix (Figure 3) demonstrates moderate to strong agreement among the total AOD datasets, with Terra MODIS achieving the best agreement with AERONET (R = 0.66) and MISR showing consistent moderate correlations across all sensors (R = 0.46–0.62). The moderate Aqua-Terra MODIS correlation (R = 0.42) highlights the significant role of diurnal aerosol dynamics in determining monthly-scale inter-sensor agreement. OMAERUV AAOD correlations with total AOD sensors range from 0.17 to 0.62, reflecting the physical distinction between absorbing and total AOD rather than retrieval errors.

Collectively, these results validate the complementary nature of multi-sensor aerosol observations over complex arid urban environments and support the use of a combined satellite-AERONET ensemble approach for robust long-term aerosol trend analysis over Jaipur. Future work should incorporate chemical transport model simulations, satellite-derived aerosol absorption optical depth validation against AERONET inversion products, and trajectory-based source attribution analysis to mechanistically explain the observed post-2020 compositional transition in Jaipur's aerosol regime.

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