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Long-Term Analysis of Aerosol Loading and Particle Size Distribution over Western and Central India (2016–2025)

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Abstract- — This study investigates the spatial and temporal variability of aerosols over Western and Central India using satellite-derived Aerosol Optical Depth (AOD) and Ångström Exponent (AE) for the period 2016–2025. AOD provides information on aerosol loading, while AE is used to infer particle size distribution. The analysis was carried out at monthly, seasonal, and annual scales using a zonal approach to distinguish regional characteristics. The results reveal significant seasonal variation in aerosol properties. AOD shows maximum values during the pre-monsoon season, particularly over Western India (~0.47), attributed to enhanced dust activity and dry atmospheric conditions. In contrast, AOD decreases during the monsoon season due to wet scavenging processes. AE exhibits an opposite trend, with higher values during monsoon and post-monsoon seasons (up to ~1.63 in Central India), indicating the dominance of fine-mode aerosols from anthropogenic emissions and biomass burning. Monthly analysis further confirms this inverse relationship between AOD and AE, reflecting the transition from coarse to fine particles across seasons. Interannual analysis indicates relatively stable aerosol patterns with noticeable fluctuations, including a decline in AOD during 2020, likely associated with reduced anthropogenic activities. A clear regional contrast is observed, where Western India is dominated by coarse-mode dust aerosols (high AOD, low AE), while Central India shows a higher influence of fine-mode anthropogenic aerosols (moderate AOD, high AE). Overall, the combined assessment of AOD and AE provides critical insights into aerosol behavior, sources, and seasonal dynamics. The findings are relevant for improving air quality management, understanding aerosol–climate interactions, and supporting environmental policy development in India

Keywords- Aerosol Optical Depth (AOD), Ångström Exponent (AE), MODIS, Aerosol variability, Spatio-temporal analysis, Western India, Central India, Air quality.

I. INTRODUCTION

Atmospheric aerosols constitute a critical component of the Earth's climate system due to their ability to influence radiative forcing, cloud microphysics, and atmospheric chemistry. They exert both direct effects, by scattering and absorbing solar radiation, and indirect effects, by acting as cloud condensation nuclei that modify cloud properties, lifetime, and precipitation processes (Intergovernmental Panel on Climate Change, 2021). These interactions introduce significant uncertainty in climate predictions, particularly over regions with high aerosol loading. Among the key parameters used to characterize aerosols, Aerosol Optical Depth (AOD) represents the total columnar burden of aerosols in the atmosphere, providing a measure of aerosol concentration, while the Ångström Exponent (AE) serves as an indicator of particle size distribution. Higher AE values typically correspond to fine-mode particles originating from anthropogenic activities such as combustion, whereas lower AE values indicate coarse-mode particles such as desert dust (Ångström, A., 1964; Holben et al., 1998). With advancements in satellite remote sensing, instruments like MODIS have enabled continuous, large-scale monitoring of these aerosol properties, facilitating long-term assessments of aerosol variability and their environmental impacts. India is recognized as one of the most aerosol-intensive regions globally due to the combined influence of natural and anthropogenic emission sources. Rapid urbanization, industrial growth, vehicular emissions, and widespread biomass burning contribute significantly to fine particulate pollution, while natural sources such as desert dust from the Thar Desert and long-range transport from arid regions further enhance aerosol loading (Dey & Di Girolamo, 2010). The spatial heterogeneity of aerosols across India is particularly pronounced, with Western India predominantly influenced by coarse dust aerosols and Central India exhibiting a complex mixture of fine and coarse particles. Seasonal meteorological conditions strongly regulate these patterns. During the pre-monsoon season, elevated temperatures and strong winds promote dust uplift and transport, leading to increased AOD. In contrast, the monsoon season is characterized by intense precipitation that removes aerosols through wet deposition processes, resulting in reduced aerosol concentrations. Winter conditions, marked by low boundary layer heights and temperature inversions, favor the accumulation of fine-mode aerosolsthereby increasing AE values (Babu et al., 2013; Kaskaoutis et al., 2012). These seasonal dynamics highlight the intricate relationship between atmospheric processes and aerosol characteristics.

Although numerous studies have examined aerosol climatology over India, most have focused on either national-scale assessments or specific regions such as the Indo-Gangetic Plain, often neglecting detailed inter- regional comparisons. In particular, the comparative analysis of aerosol characteristics between Western and Central India over extended temporal scales remains insufficiently explored. This represents a critical research gap, as these regions differ significantly in terms of emission sources, meteorological conditions, and dominant aerosol types. Addressing this gap is essential for improving regional air quality assessments and understanding aerosol–climate interactions. In this study, long-term satellite datasets spanning 2016–2025 are utilized to investigate the monthly, seasonal, and interannual variability of AOD and AE. The analysis reveals distinct regional patterns, with Central India consistently showing higher AE values indicative of fine- mode anthropogenic aerosols, while Western India exhibits stronger seasonal variability driven by dust transport. Additionally, AOD variations highlight enhanced aerosol loading during pre-monsoon periods and significant reductions during monsoon due to washout processes. The specific objectives of this study are:

- To analyze the temporal variability of AOD and AE at monthly, seasonal, and annual scales;
- To perform a comparative assessment of aerosol characteristics between Western and Central India; and
- To interpret the observed trends in relation to meteorological influences and emission sources, thereby contributing to improved understanding of regional aerosol dynamics and supporting effective air quality management strategies.

II. METHODOLOGY

1. Study Area

The present study focuses on two major aerosol-sensitive regions of India: Western India and Central India, selected based on their contrasting emission sources, meteorological conditions, and dominant aerosol types. These regions represent distinct atmospheric regimes, making them ideal for comparative aerosol analysis using satellite-derived parameters. Western India (20°–30°N, 68°–76°E) comprises predominantly arid and semi-arid landscapes, including parts of Rajasthan and Gujarat. This region is significantly influenced by the Thar Desert, which acts as a major source of mineral dust aerosols. Frequent dust storms during the pre-monsoon season, coupled with strong surface winds and low soil moisture, facilitate the uplift and long-range transport of coarse particles. In addition to local dust emissions, Western India is also affected by transboundary transport of aerosols from the Middle East and Southwest Asia, further enhancing aerosol loading. The atmospheric conditions in this region are characterized by high temperatures, low relative humidity, and strong boundary layer mixing during summer, which promote aerosol dispersion and variability. However, during winter, relatively stable atmospheric conditions can lead to moderate accumulation of fine particles in urban pockets. In contrast, Central India (18°–26°N, 76°–86°E) encompasses regions with dense population, rapid urbanization, and diverse land-use patterns, including industrial hubs and agricultural areas. Aerosols in this region are primarily influenced by anthropogenic emissions, such as vehicular exhaust, industrial activities, coal combustion, and residential biomass burning. Additionally, seasonal agricultural practices, particularly crop residue burning, contribute significantly to fine particulate matter. The region also experiences secondary aerosol formation due to chemical reactions involving precursor gases like SO_2, NO_x, and volatile organic compounds. Meteorologically, Central India is characterized by relatively higher humidity and lower wind speeds compared to Western India, which favor the accumulation and transformation of fine-mode aerosols. During winter, temperature inversions and reduced boundary layer height further enhance pollution levels, while the monsoon season leads to a substantial decrease in aerosol concentration due to intense rainfall and wet scavenging. The selection of these two regions allows for a comprehensive evaluation of coarse-mode dominated (dust-driven) versus fine-mode dominated (anthropogenic) aerosol regimes. Furthermore, the latitudinal overlap between the regions ensures comparable solar radiation and climatic forcing, enabling a more consistent comparison of aerosol characteristics. By analyzing these contrasting zones, the study aims to better understand the influence of emission sources, meteorology, and seasonal dynamics on aerosol behavior. Overall, the spatial delineation of Western and Central India provides a robust framework for investigating regional differences in aerosol loading, particle size distribution, and temporal variability, thereby contributing to improved insights into aerosol–climate interactions and air quality management strategies.

Data Source

The present study utilizes aerosol data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite. MODIS provides continuous, near-

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global observations of aerosol properties with high temporal frequency, making it highly suitable for long-term climatological and environmental studies (Levy et al., 2013). In this research, daily Aerosol Optical Depth (AOD) data spanning the period 2016–2025 were used to analyze aerosol variability over Western and Central India. The MODIS aerosol product is based on advanced retrieval algorithms that estimate aerosol properties over land and ocean surfaces by analyzing reflected solar radiation. These products are widely validated against ground-based observations such as AERONET and have been extensively used in aerosol research due to their reliability and spatial coverage.

The dataset includes the following key variables:

- Latitude (°): Geographic coordinate specifying the north–south position of each observation point
- Longitude (°): Geographic coordinate specifying the east–west position
- Date (YYYYDDD format): Temporal information representing year and Julian day
- AOD values: Column-integrated aerosol optical depth representing aerosol loading in the atmosphere

To ensure the quality and consistency of the dataset, several preprocessing steps were applied. First, the date variable in Julian format (YYYYDDD) was converted into standard calendar dates using appropriate date-time functions. This enabled extraction of temporal attributes such as month, season, and year, which are essential for multi-scale analysis. Quality control was implemented to remove erroneous and unrealistic observations. AOD values were filtered within a physically meaningful range of 0–5, as values outside this range typically represent retrieval errors or noise. Missing and invalid entries were excluded to maintain data integrity. Additionally, extreme outliers were minimized through statistical filtering to avoid bias in subsequent analysis. Spatial filtering was performed to restrict the dataset to the study regions defined by specific latitude and longitude bounds corresponding to Western and Central India. This ensured that only relevant data points were included for regional comparison. To facilitate spatial aggregation and reduce computational complexity, the data were further discretized into uniform grids using latitude–longitude binning. Each observation was assigned to a grid cell based on its coordinates, enabling efficient computation of mean aerosol values. Given the large volume of satellite data, a chunk-wise processing approach was adopted to optimize memory usage and prevent system overload. The dataset was processed in smaller subsets, and intermediate results were aggregated using cumulative sum and count techniques to compute mean AOD values without loading the entire dataset into memory. Furthermore, normalization techniques were applied in selected analyses to standardize AOD values between and 1, allowing better visualization and comparison across different time periods. Smoothing techniques, such as Gaussian filtering, were also used in spatial mapping to reduce noise and enhance pattern clarity. Overall, these preprocessing steps ensured that the dataset was accurate, consistent, and suitable for detailed spatio-temporal analysis of aerosol characteristics, forming a robust foundation for subsequent monthly, seasonal, and interannual assessments.

Data Preprocessing

Temporal Processing

The date variable was converted from Julian format (YYYYDDD) into standard datetime format using Python-based processing. From this, month and year attributes were extracted to facilitate temporal aggregation.

Spatial Filtering

- To reduce computational load and focus on the Indian region, data points were spatially filtered within:
- Latitude: 6°N to 38°N Longitude: 68°E to 98°E
- Further filtering was applied based on predefined bounding boxes for Western and Central India.
- Chunk-Based Processing (Memory Optimization)
- Due to the large size of MODIS datasets, a chunk-wise processing approach was implemented using Pandas (chunksize = 300,000). This ensured that the system did not exceed available RAM limits. Each chunk was processed independently, and intermediate statistics (sum and count) were stored in dictionaries, avoiding full dataset loading into memory.

Seasonal Classification

Table 1 Seasonal Classification and Meteorological Characteristics Used in the Study

Season	Months	Description
Winter (DJF)	December–February	Stable atmosphere, pollutant accumulation
Pre-Monsoon (MAM)	March–May	Dust transport and high temperatures
Monsoon (JJAS)	June–September	Wet deposition and aerosol washout
Post-Monsoon (ON)	October–November	Biomass burning and transition period

Each data point was assigned a season based on its month.

Zonal Aggregation Method
For each zone (West and Central India), AOD values were aggregated using the following procedure:

Spatial filtering based on latitude–longitude bounds Grouping by time scale (monthly, seasonal, yearly) Computation of mean AOD using:

$$\text{Mean AOD} = \frac{\sum AOD}{N}$$

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where:
N = number of observations
This approach ensures unbiased averaging even when data density varies spatially and temporally.

Temporal Analysis Monthly Analysis
Monthly mean AOD values were computed for each zone (January–December). This helped in identifying intra-annual variability and seasonal transitions.

Seasonal Analysis
Seasonal averages were calculated by combining monthly data within each defined season. This enabled the identification of dominant aerosol processes such as:

- Dust dominance (Pre-Monsoon)
- Washout effects (Monsoon)
- Pollution accumulation (Winter/Post-Monsoon)
- Annual Analysis

Yearly mean AOD values (2016–2025) were computed to assess long-term trends and interannual variability. Visualization Techniques

Bar charts were used for comparative visualization of AOD between Western and Central India. The following features were incorporated:

- Grouped bar plots for side-by-side comparison
- Seasonal and monthly labeling for clarity
- Numerical annotations on bars for precise interpretation
- High-resolution output (600 dpi) for thesis- quality figures

These visualizations effectively highlight spatial contrasts and temporal patterns in aerosol loading.

Software and Tools
The analysis was performed using:

- Python (Google Colab environment)
- Libraries:
- pandas (data handling)
- numpy (numerical operations)
- matplotlib (visualization)

This combination allowed efficient processing of large datasets and generation of publication-quality graphics.

Limitations

- Satellite-derived AOD may be affected by cloud cover and surface reflectance errors.
- Bounding box approach may not perfectly represent regional boundaries.
- Ground validation (e.g., AERONET) was not included in this study.
- Despite these limitations, the methodology provides a robust framework for large-scale aerosol analysis

III. RESULTS AND DISCUSSION

Seasonal Comparison of AOD and AE
The seasonal variation of Aerosol Optical Depth (AOD) and Ångström Exponent (AE) shows a clear contrast between aerosol loading and particle size characteristics across Western and Central India. AOD values peak during the pre-monsoon season, reaching 0.47 in Western India and 0.44 in Central India, indicating maximum aerosol loading. This increase is primarily driven by dust transport and dry atmospheric conditions, especially over Western India. During the monsoon season, AOD decreases to 0.43 (West) and 0.39 (Central) due to rainfall-induced wet deposition, which efficiently removes aerosols from the atmosphere. Lower AOD values are observed in winter and post- monsoon (~0.34–0.36), reflecting relatively cleaner atmospheric conditions.

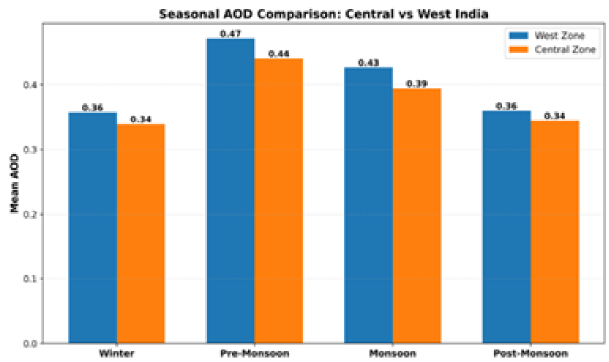

Figure 1 Seasonal AOD Comparison: West Zone and Central Zone

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In contrast, AE exhibits an opposite trend. The highest AE values occur during post-monsoon (1.63 in Central, 1.43 in West) and monsoon seasons (1.57 Central, 1.35 West), indicating the dominance of fine-mode aerosols. During pre-monsoon, AE decreases (1.30 West, 1.43 Central), reflecting the increased contribution of coarse dust particles. Central India consistently shows higher AE values across all seasons, indicating a stronger influence of anthropogenic aerosols, while Western India is dominated by coarse particles.

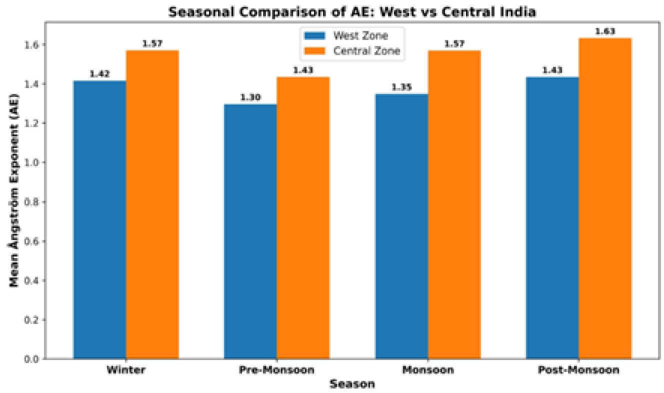

Figure 2 Seasonal Comparison of AE Central Zone and West Zone

Monthly Variation of AOD and AE

The monthly analysis provides detailed insight into aerosol dynamics throughout the year. AOD gradually increases from January (~0.36) to a peak in May (~0.50 in West and ~0.47 in Central India). This trend reflects enhanced dust uplift, high temperatures, and dry conditions during the pre-monsoon period. Following this peak, AOD decreases steadily from June (~0.49) to September (~0.36) due to monsoonal rainfall and aerosol washout processes. Post-monsoon months (October–November) show moderate AOD values (~0.34–0.38), influenced by biomass burning and urban emissions.

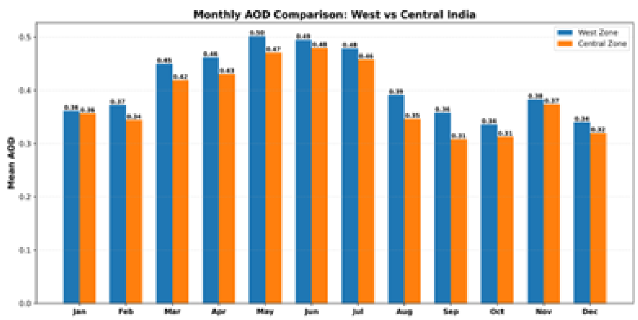

Figure 3 Monthly AOD Comparison West Zone and Central Zone

AE shows a contrasting pattern. It decreases from~1.41 in January to ~1.18–1.21 during May–June in Western India, indicating increasing dominance of coarse particles. However, AE increases sharply during the monsoon, reaching peak values of ~1.70 in Central India(September) and ~1.52 in

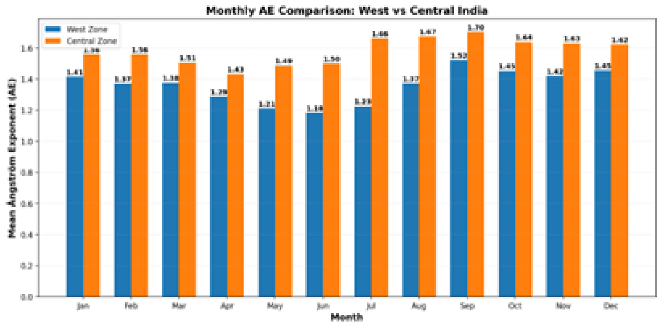

Figure 4 Monthly AE Comparison West zone and Central Zone

Western India, reflecting the dominance of fine aerosols after dust removal. High AE values persist during post-monsoon months due to biomass burning and secondary aerosol formation.

A consistent observation across all months is:

- Western India → Higher AOD, Lower AE
- Central India → Lower AOD, Higher AE

This confirms the contrasting aerosol regimes:

- Dust-dominated Western region
- Anthropogenic-dominated Central region

Interannual (Yearly) Variation of AOD and AE (2016–2025)

The interannual analysis indicates relatively stable trends with moderate variability over the study period.

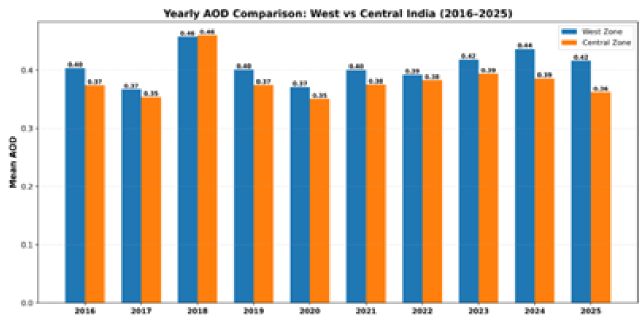

Figure 5 Yearly AE Comparison West zone and Central Zone

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For AOD, Western India consistently shows higher values ranging from 0.37 to 0.46, compared to Central India (0.35 to 0.46). The highest AOD values are observed in 2018 (~0.46 in both regions), suggesting intensified aerosol loading, likely due to increased dust activity or meteorological anomalies. A slight reduction in AOD is observed around 2020 (~0.37 West, ~0.35 Central), which may be associated with reduced anthropogenic emissions during the COVID-19 lockdown period. Post-2020, AOD values show gradual recovery. AE exhibits a clear dominance of fine par ticles in Central India, with values ranging from ~1.31 to 1.58,

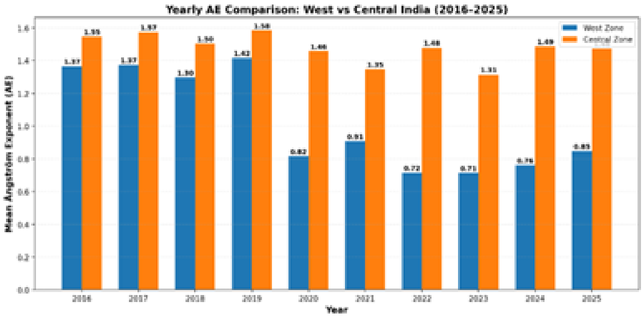

Figure 6 Yearly AE Comparison West Zone and Central Zone

Consistently higher than Western India (~0.71 to 1.42). A sharp drop in AE is observed in Western India during 2020–2023 (as low as ~0.71–0.82), indicating strong dominance of coarse aerosols during these years. In contrast, Central India maintains relatively stable AE values, confirming persistent anthropogenic influence.

This analysis highlights that:

- AOD variability is influenced by both natural and anthropogenic sources
- AE clearly differentiates aerosol type (coarse vs fine)

Integrated AOD–AE Relationship

The combined analysis of AOD and AE across seasonal, monthly, and yearly scales reveals key aerosol behavior patterns:

Inverse Relationship

- High AOD + Low AE → Dust-dominated conditions (coarse particles)
- Low/Moderate AOD + High AE → Fine aerosol dominance (pollution, biomass burning)

Regional Contrast

Western India

- oHigher AOD throughout the year
- oLower AE values
- Dominated by desert dust transport

Central India

- Lower AOD values
- Higher AE values
- Dominated by anthropogenic emissions and fine particles

Seasonal Control

- Pre-monsoon → Dust dominance
- Monsoon → Washout + fine particle dominance
- Post-monsoon → Biomass burning
- Winter → Pollution accumulation

Implications

The observed variations in AOD and AE have significant implications:

Air Quality

High AE in Central India indicates higher concentrations of fine particulate matter ($PM_{2.5}$), which poses greater health risks.

Climate Impact

Coarse aerosols (dust) in Western India influence radiative forcing, while fine aerosols affect cloud formation and atmospheric chemistry.

Policy Relevance

- Western India → Focus on dust
- mitigation and land management
- Central India → Focus on emission control and biomass burning regulation

IV. CONCLUSION

This Study Provides A Comprehensive Assessment Of Aerosol Characteristics Over Western And Central India Using Aerosol Optical Depth (AOD) And Ångström Exponent (AE) Across Monthly, Seasonal, And Interannual Scales (2016–2025). The Results Reveal Strong Spatial And Temporal Variability In Aerosol Loading And Particle Size Distribution, Highlighting The Influence Of Both Natural And Anthropogenic Sources. Seasonal Analysis Indicates That AOD Peaks During The Pre-Monsoon Period, With Maximum Values Observed In Western India (~0.47), Driven Primarily By Dust Transport And Dry Atmospheric Conditions. In Contrast, AOD Decreases During The Monsoon Due To Wet Deposition Processes, Followed By Moderate Levels In Post-Monsoon And Winter. Conversely, AE Exhibits Higher Values During Monsoon And Post-

Monsoon Seasons, Particularly In Central India (~1.63), Indicating A Dominance Of Fine-Mode Aerosols Associated With Anthropogenic Emissions And Biomass Burning. This Confirms A Clear Inverse Relationship Between AOD And AE, Reflecting The Transition Between Coarse And Fine Aerosol Regimes. Monthly Variations Further Reinforce These Findings, Showing A Gradual Increase In AOD From Winter To Pre-Monsoon, Followed By A Decline During Monsoon Months. AE Demonstrates An Opposite Pattern, Decreasing During Dust-Dominated Periods And Increasing During Fine Aerosol-Dominated Seasons. Interannual Trends Suggest Relatively Stable Aerosol Behavior With Noticeable Fluctuations, Including Reduced AOD During 2020, Likely Linked To Decreased Anthropogenic Activities.

Key Outcome Of This Study Is The Distinct Regional Contrast

Western India Is Characterized By Higher AOD And Lower AE, Indicating Dominance Of Coarse Dust Aerosols.

Central India Exhibits Lower AOD But Consistently Higher AE, Reflecting Fine Particulate Pollution From Anthropogenic Sources.

These Findings Have Important Implications For Air Quality Management And Climate Studies. Fine Aerosols Prevalent In Central India Pose Greater Health Risks Due To Their Ability To Penetrate Deep Into The Respiratory System, While Coarse Aerosols In Western India Significantly Influence Radiative Forcing And Regional Climate Dynamics. Overall, This Study Demonstrates That The Combined Use Of AOD And AE Provides A Robust Framework For Understanding Aerosol Behavior Across Different Regions And Seasons. The Insights Generated Can Support Policy Formulation, Emission Control Strategies, And Climate Impact Assessments, Particularly In Highly Polluted And Climatically Sensitive Regions Like India.

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