

Article

Monsoon–Regulated Aerosol Variability and Radiative Effects over a Rural Receptor Site in Southeast India

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Abstract

This study aims to characterize the seasonal variability and optical properties of aerosols and to investigate their potential sources, transport pathways, and radiative impacts over a rural site in Southeast India. Ground–based MICROTUPS–II Sunphotometer observations during April 2021–December 2023 were integrated with trajectory–based source analysis and OPAC–SBDART radiative–transfer simulations to examine the links between aerosol characteristics, meteorological conditions, source regions, and radiative effects. The annual mean aerosol optical depth at 500 nm (AOD_{500}) was found to be 0.56 ± 0.22 , peaking during pre–monsoon (0.66 ± 0.19) and winter (0.64 ± 0.23), and lowering during the rainy monsoon (0.49 ± 0.21). Enhanced aerosol loading during the dry seasons was associated with local emissions and long–range continental transport, whereas monsoon conditions favored marine influence, atmospheric ventilation and wet scavenging, as supported by trajectory analyses using potential source contribution function (PSCF) and concentration weighted trajectory (CWT) models. Higher Ångström exponent (AE) values during winter and pre–monsoon (1.30 ± 0.24) indicated dominance of fine–mode continental aerosols, while the lower monsoon values (0.83 ± 0.37) reflected increased contribution of coarse particles. Negative values of spectral curvature further confirmed fine–mode dominance during dry seasons. The estimated precipitable water vapor increased markedly from winter (2.00 ± 0.37 cm) to monsoon (4.35 ± 0.35 cm), likely influencing aerosol optical properties through hygroscopic growth. Meteorological parameters significantly modulated aerosol loading and size distribution across seasons. AOD – AE relationships revealed predominance of fine anthropogenic aerosols in all seasons except monsoon, while aerosol classification indicated substantial fine–mode contributions under turbid atmospheric conditions. OPAC–SBDART simulations estimated significant aerosol–induced surface cooling (-41 to -42 W m⁻²) and atmospheric warming (38 – 41 W m⁻²) under high aerosol loading conditions, leading to atmospheric heating rates of 1.1 – 1.2 K day⁻¹. However, lower aerosol loading in monsoon reduced heating rates to 0.3 – 0.4 K day⁻¹. Current findings highlight the critical role of monsoon flow and meteorological dynamics in regulating aerosol characteristics and regional radiative forcing over Southeast India.



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Keywords: MICROTOPS II Sunphotometer; aerosol optical depth; aerosol classification; PSCF; CWT models; aerosol radiative forcing

1. Introduction

Atmospheric aerosols are among the most dynamic and influential constituents of the Earth's atmosphere, exerting profound impacts on air quality, radiation budget, hydrological cycle, large-scale atmospheric circulation, climate and human health [1–4]. Aerosols affect the climate system directly by scattering and absorbing solar and terrestrial radiation, and indirectly by altering cloud lifetime, optical and microphysical properties [5,6]. Additionally, through the semi-direct effect, absorbing aerosols heat the atmosphere, enabling it to modify cloud stability and coverage [7,8].

Since the pre-industrial era, the atmospheric burden of anthropogenic aerosols in India has more than doubled due to increased emissions from industrial, agricultural, commercial, and residential sectors [3,9–14]. In addition, aerosols from biomass burning, wildfires, and volcanic eruptions can be injected directly into the free troposphere, where their longer residence times enhance their climatic effects [15,16]. Aerosols emitted near the surface typically accumulate within the atmospheric boundary layer [17,18]; however, they can be transported to higher altitudes through convective activity, sea-breeze circulation, and synoptic-scale processes [19,20]. The uneven distribution of aerosol sources and sinks, combined with their relatively short atmospheric lifetimes, leads to substantial spatial and temporal heterogeneity, making the assessment of their regional climate impacts especially difficult [13,21–23].

Quantifying aerosol–climate interactions requires detailed knowledge of aerosol's physical, chemical, optical, and radiative properties [7,11,24,25]. Among these, aerosol optical depth (AOD) is a fundamental parameter that represents the column-integrated extinction of solar radiation by aerosols and serves as a direct indicator of aerosol loading. Ground-based Sunphotometers, particularly the portable, multiwavelength-based MICROTOPS II (Microprocessor-based Total Ozone Portable Spectrometer), have been extensively validated and deployed globally for this purpose [26–28]. Past studies [29,30] established its reliability, with AOD uncertainties typically ranging within ± 0.02 , making it a standard tool for field campaigns and long-term aerosol monitoring, especially useful for satellite validation [31–35]. In this context, Kharol et al. [31] demonstrated that MODIS-derived AOD over Hyderabad showed satisfactory agreement with ground measurements (better for Level 3 than Level 2), with an overall increasing trend driven by urbanization and local emissions. Srivastava et al. [36] highlighted the superior performance of the Sunphotometer under high-aerosol conditions in the western Himalayan foothills (Manora Peak, Nainital). On the other hand, the Ångström exponent (AE or α) expresses the wavelength dependence of AOD, providing insights into aerosol particle size and fine-to-coarse mode fractions, helping to distinguish between fine- and coarse-mode aerosol mixtures in the atmosphere [32,37–40].

South and East Asia, particularly India and China, experience persistently high aerosol loading due to rapid urbanization, population growth, industrialization, biomass burning, and increasing energy demands [3,9,41–43]. Within India, the Indo-Gangetic Plain (IGP) region has been recognized as a global aerosol hotspot [3,12,44,45], exhibiting strong seasonal-to-interannual aerosol heterogeneity associated with emission strength, seasonal agricultural burning and meteorological conditions [45–51]. Observational studies across different environments in India have highlighted strong regional contrasts in aerosol loading and optical characteristics. Ramachandran et al. [52] observed pronounced seasonal variability over Delhi, with summer AOD (~ 0.9) dominated by dust transport, and lower monsoon AOD (~ 0.4)

due to wet scavenging. Moorthy et al. [53] reported AOD ranging from ~ 0.2 under clean marine conditions to ~ 0.8 during polluted continental outflow over the Arabian Sea and Mumbai. They also observed pre-monsoon AOD between 0.4 and 0.7 over an eastern coastal city, Visakhapatnam, driven by dust and industrial emissions. In addition to local emissions, long-range and transboundary air mass transport plays a significant role in shaping aerosol characteristics over southern India. Pollutants from northern India can be transported towards the southern peninsula under favorable synoptic conditions, including strong convection and anticyclonic circulation patterns [54,55], leading to widespread pollution episodes over southern India [56–61]. In contrast, high-altitude and remote sites, especially in the Trans-Himalayan region, exhibit lower (~ 0.1 – 0.15) aerosol loading [40,62,63]. Over the east Indian coast, previous studies highlighted the dominant role of scattering aerosols in producing strong surface cooling, with atmospheric heating modulated by black carbon (BC) content [64]. Tiwari et al. [65] provided an overview of AOD and AE values from Sunphotometer observations at several sites across India. Furthermore, studies specifically employing radiative transfer models have advanced current understanding of aerosol radiative effects and efficiency [43,66–70]. Aruna et al. [71] showed that aerosol radiative forcing over the coastal Chennai city, close to current measuring site, varies significantly by season, and is enhanced under higher relative humidity (RH) conditions, while model estimates agreed satisfactorily with ground-based radiometric measurements.

Across peninsular India, aerosol characteristics exhibit strong spatial contrasts owing to differences in surface characteristics, emission sources, meteorology, and proximity to the coast. Semi-arid and inland regions are frequently influenced by mineral dust, resuspended soil particles, and continental anthropogenic emissions, whereas coastal urban environments are affected by a complex mixture of industrial, vehicular, construction, and marine aerosols, together with sea-breeze-driven transport [53,65,71]. In contrast, rural and agricultural environments can experience episodic increases in aerosol loading associated with crop-residue burning, domestic biomass combustion, soil dust, and the regional transport of anthropogenic pollutants. In southern rural India, aerosol properties are strongly modulated by long-range transport from northern India and the Arabian Sea, particularly during winter and pre-monsoon seasons [54,55,57]. Despite these regional contrasts, most intensive aerosol investigations in peninsular India have concentrated either on semi-arid/dust-dominated environments or densely populated coastal and metropolitan regions. Agricultural-rural environments located at the transition between rural, suburban, industrial, and transportation-dominated source regimes remain comparatively underrepresented. Such mixed-receptor locations are particularly important because the observed aerosol column may simultaneously reflect local biomass-burning emissions, regional anthropogenic transport, mineral dust, and marine influences, making their seasonal separation essential for understanding regional aerosol-climate interactions.

The present measurement site represents such a mixed-receptor environment in south-east India, situated within the Krishna River basin and surrounded by extensive croplands, suburban activities, a nearby thermal power plant, and a major National Highway (NH). These characteristics allow the site to capture the combined influence of local and regional aerosol sources rather than representing a single dominant source regime. In particular, the seasonal aerosol burden over this region can reflect contributions from local biomass burning, long-distance transport from the polluted Indo-Gangetic Plain (IGP), mineral dust transported from northwestern arid regions, and marine sea-salt intrusions from the Arabian Sea and Bay of Bengal. Therefore, the site provides a valuable natural receptor for disentangling the relative importance of competing aerosol sources and examining their influence on columnar aerosol properties and radiative forcing. Despite the importance of such mixed rural-suburban environments for regional climate and air-quality

assessment, a comprehensive coupling of seasonal aerosol loading, source–region analysis, aerosol–type discrimination, and radiative forcing has not yet been adequately documented over this agricultural–rural region of southeast India. The present study addresses this knowledge gap by providing an integrated assessment of aerosol optical characteristics, source influences, and radiative effects over a rural environment in Andhra Pradesh.

The present study provides a first year–long investigation of columnar aerosol properties using a MICROTOPS II Sunphotometer at Koneru Lakshmaiah Education Foundation (KLEF) University campus in southeast India during the study period (April 2021–December 2023). The key aspects of this work are the use of continuous and real–time ground–based Sunphotometer observations to analyze AOD, AE (or α), and precipitable water vapor (PWV). The study also focuses on the discrimination of key aerosol types and adopted the classification mechanism to examine the dominant aerosol contribution, which is especially important for aerosol radiative forcing (ARF) assessment, employing well–established radiative transfer models such as Optical Properties of Aerosols and Clouds (OPAC) and Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) to quantify atmospheric heating rates and forcing efficiency.

The scientific novelty of the work lies in three major aspects. First, it establishes a unique three–year, continuous columnar aerosol dataset at a mixed rural–suburban receptor site in the Krishna River basin, where extensive croplands coexist with nearby suburban activities, a thermal power plant, and a major National Highway. This observational setting differs substantially from the predominantly urban, metropolitan, coastal, or arid environments investigated in many previous South Indian aerosol studies [1,2,40,42,46,49,65]. Second, this study quantitatively examines the seasonal contributions of four major competing aerosol source influences, namely local biomass–burning emissions, long–distance transport of polluted air masses from the IGP, mineral dust transported from northwestern arid regions, and marine sea–salt intrusions. The combined application of aerosol optical characterization, air–mass trajectory analysis, potential source contribution function (PSCF), concentration–weighted trajectory (CWT), and aerosol–type discrimination provides a framework for separating these source influences and identifying their seasonal dominance. Third, the study provides site–specific quantification of aerosol–induced atmospheric heating, demonstrating the important role of absorbing aerosols in modifying the regional radiation balance, boundary–layer stability, vertical mixing, and monsoon dynamics at an underrepresented agricultural–rural receptor site. By integrating three years of continuous ground–based observations with source–region and transport analysis, aerosol–type discrimination, and radiative–transfer modeling, this study provides a comprehensive characterization of seasonal aerosol loading, competing source influences, and aerosol–induced atmospheric heating, aiming to establish an aerosol baseline in rural southeast India.

2. Study Region

2.1. Experimental Site

The measurement site at Koneru Lakshmaiah Education Foundation (KLEF) University campus (16.44° N, 80.66° E, 30 m a.m.s.l) is in a rural area on the banks of Krishna River near Vijayawada City (~7 km towards south) in Andhra Pradesh state, Southeast India (Figure 1a). The surrounding area is dominated by croplands (~59.5%), followed by tree cover (~22.8%), with the remaining area comprising grasslands and shrublands (~8%) (Figure 1b). The observational site is approximately 3.2 km from the National Highway (NH–16) in the west, indicating less influence by vehicular emissions. However, the highway may act as a potential source of particulate matter (PM), road dust, and gaseous pollutants transported towards the site under favorable meteorological conditions. A large thermal power plant

with a capacity of ~1760 MW is located in the suburban Vijayawada city to the north at a distance of approximately 20 km (Figure 1c). Owing to its geographical setting, the region is influenced by multiple anthropogenic aerosol sources, including emissions from large-scale transportation and thermal power generation, biomass burning, and domestic wood-burning activities [13,18,72]. Seasonal variations in agricultural practices, vegetation growth and associated biomass-burning activities can significantly modulate pollutant emissions from different land cover types. Therefore, continuous monitoring and analysis of aerosol characteristics over the KLEF site are essential for understanding the influence of land-use-driven seasonal variability on regional air quality, apart from transported polluted air masses. Such observations also support the development of regional environmental management strategies and mitigation of aerosol emissions and impacts.

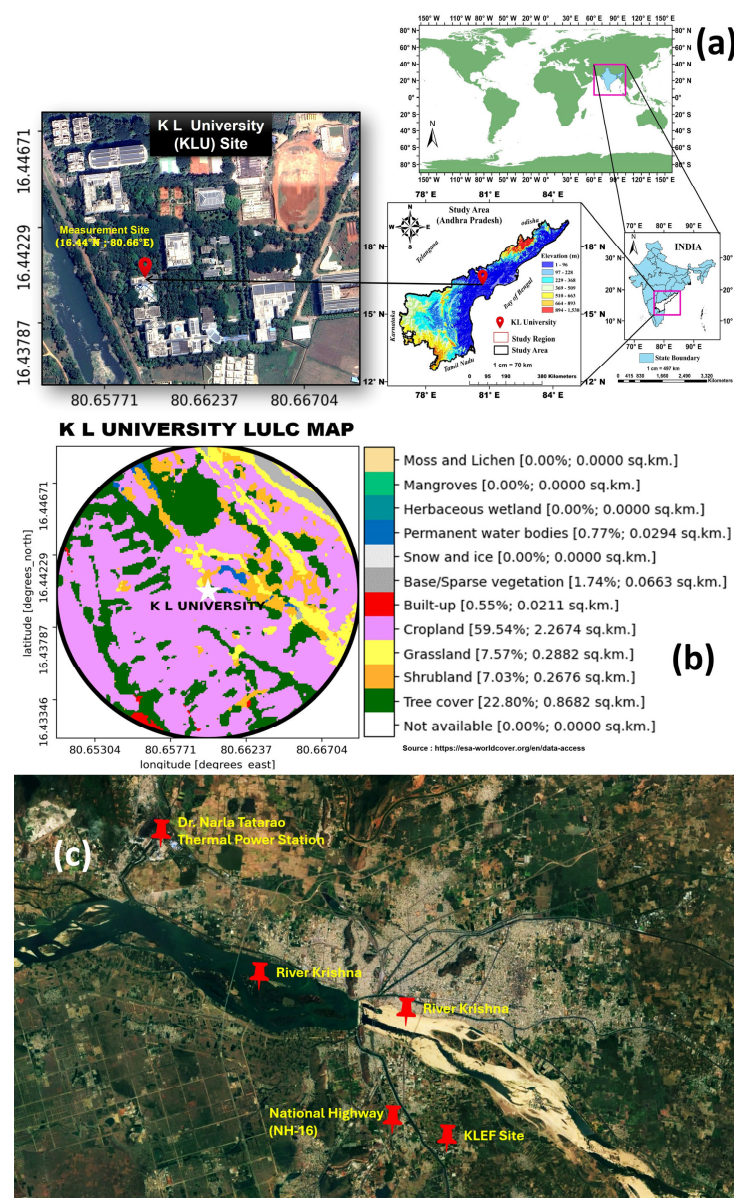


Figure 1. (a) Location of the study area depicting the elevation (top right) and pointing to the receptor site (KLEF) (top left) (10 × 10 km resolution accessed from <https://earthengine.google.com/>). (b) Land-use Land-Cover (LULC) map of the surrounding area (source: <https://esa-worldcover.org/en/data-access>; accesses on 10 August 2026) during the study period.

The topography is represented using the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), with a spatial resolution of $90\text{ m} \times 90\text{ m}$, downloaded from the U.S. Geological Survey (USGS) Earth Explorer portal. (c) The map (<https://earthengine.google.com/>) shows the location of the KLEF site (16.44° N , 80.66° E) in Andhra Pradesh, India, together with the nearby Dr. Narla Tatarao Thermal Power Station, National Highway (NH-16), and Krishna River that may influence aerosol loading at the receptor site.

2.2. Local Meteorology

The KLEF site experiences a tropical wet and dry climate under the Köppen–Geiger climate classification system, characterized by hot summers, moderate rainfall and high RH during the southwest monsoon season, as well as mild winters. Figure 2a,b show the monthly, seasonal and annual mean meteorological parameters, obtained from collocated ground-based meteorological station during the period 2021–2023. Based on prevailing meteorological conditions, the region is broadly divided into four distinct seasons: winter (January and February; JF), pre-monsoon or summer (March–April–May; MAM), monsoon (June–July–August–September; JJAS), and post-monsoon (October–November–December; OND) [13]. The highest (lowest) temperatures were recorded during the pre-monsoon (winter) season, with mean values of 37.5°C ($\sim 26.5^\circ\text{C}$). RH showed a pronounced seasonal cycle, with maximum (minimum) values during the post-monsoon (pre-monsoon) seasons of $\sim 70\%$ ($\sim 40\%$), respectively, while wind speed maximized during monsoon ($\sim 3.5\text{ m/s}$). Meteorological conditions strongly influence aerosol loading and optical characteristics in the atmosphere. Higher RH promotes hygroscopic growth of particles, increasing their size and enhancing scattering process and columnar AOD [73]. In contrast, higher temperatures favor stronger vertical mixing, which disperses pollutants and reduces surface concentrations, although this mixing can redistribute aerosols under favorable winds vertically within the column [74].

Seasonal wind patterns further modulate aerosol transport and distribution at the study site. Radar plots of wind speed and direction indicate that stronger winds ($5\text{--}8\text{ m s}^{-1}$) predominantly originate from the southeast (SE) during the pre-monsoon season, shifting to stronger westerlies in monsoon and easterlies in the post-monsoon. In contrast, winter is characterized by weaker winds ($2\text{--}3\text{ m s}^{-1}$) mainly from the eastern direction (Figure 2c). These pronounced seasonal variations in meteorological conditions introduce significant heterogeneity in aerosol sources, transport pathways and transformation processes, thereby playing a critical role in shaping the observed aerosol characteristics over the site [72,75–77].

The seasonal meteorological cycle at the KLEF site also closely coincides with the agricultural calendar of the surrounding croplands and therefore contributes to the observed seasonal variability in aerosol loading. During the pre-monsoon (MAM) season, the region experiences high temperatures, relatively low RH, enhanced solar heating, and stronger winds, which favor the desiccation and mobilization of exposed agricultural soils and road dust. This period generally corresponds to the agricultural transition, when fields may remain relatively exposed following harvesting of winter crops and before the establishment of the subsequent monsoon-season crops. Consequently, enhanced surface dust emissions, together with local anthropogenic activities and regional transport, may contribute to elevated AOD during this period. The onset of the southwest monsoon substantially modifies these conditions through increased precipitation and RH, which promote wet scavenging and suppress the resuspension of soil and other coarse particles.

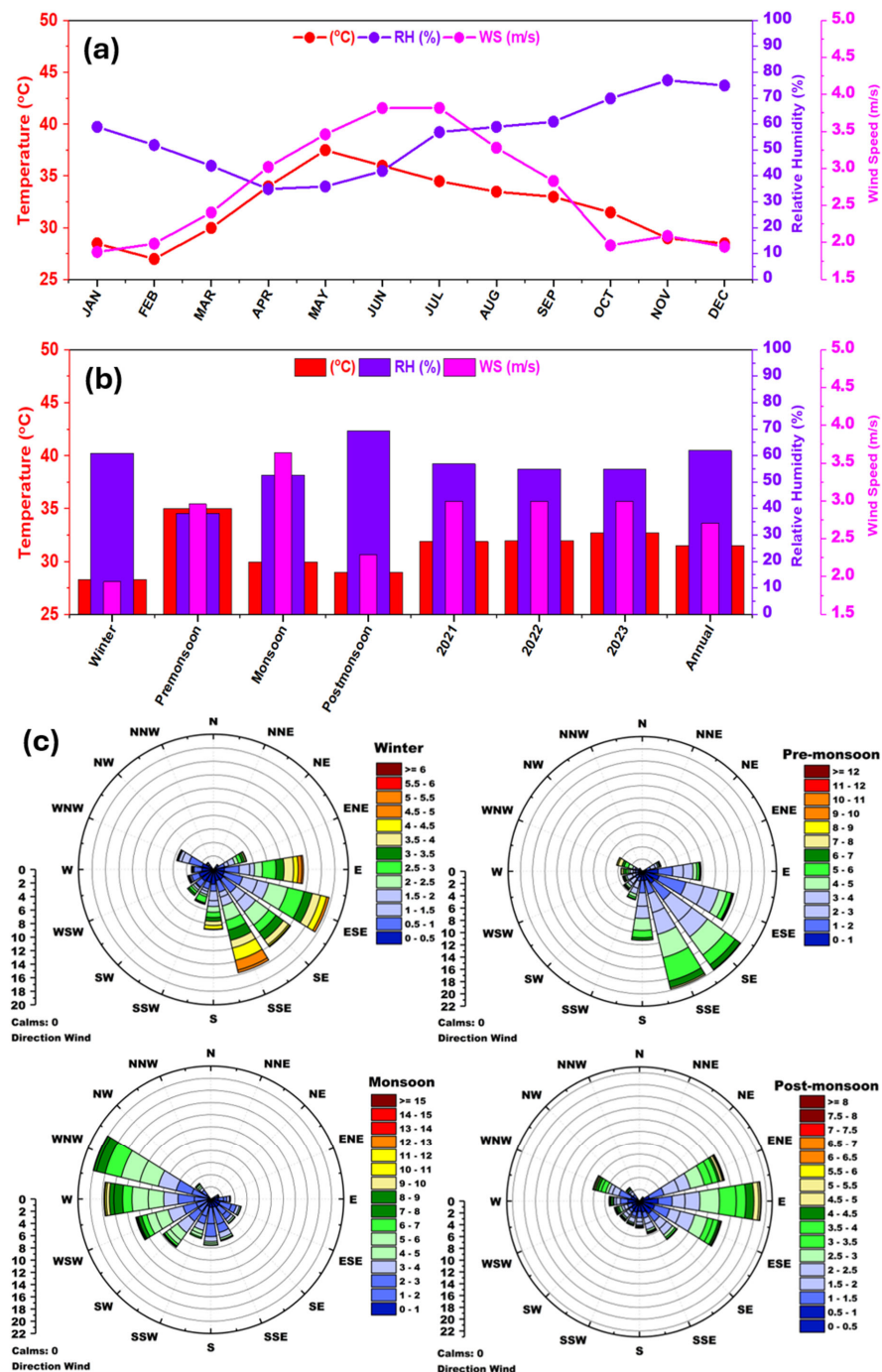


Figure 2. (a,b) Temporal variations in meteorological parameters, and (c) seasonal wind rose plots illustrating wind speed and wind direction during the study period at the KLEF site.

The post-monsoon (OND) season represents another important period in which agricultural activities can influence aerosol variability. Following the southwest monsoon harvest cycle, crop-residue management and open-field biomass burning in agricultural areas surrounding the site can provide an additional episodic source of fine-mode carbonaceous aerosols. The relatively dry conditions, decreasing rainfall, and changing wind patterns during this season favor the accumulation and regional transport of smoke plumes from agricultural burning, contributing to increased AOD. Therefore, the correspondence between seasonal meteorological conditions, agricultural activities, and aerosol loading suggests that the observed AOD variability at the site is governed not only by meteoro-

logical processes but also by the timing of agricultural operations and associated biomass-burning emissions.

2.3. Ground-Based Measurements

The columnar spectral AOD and precipitable water vapor (PWV; in cm) were measured using a MICROTOPS II Sunphotometer, a handheld and portable instrument widely used in several previous studies (e.g., [27,34,48,78,79], and references therein). The MICROTOPS-II is equipped with five spectral channels centered at 340, 500, 870, 936, and 1020 nm, enabling simultaneous multiwavelength measurements of AOD, with a total angular field of view of about 2.5°. The PWV is obtained in the water-vapor absorption channel at 936 nm. This measurement is important because water vapor, as a major greenhouse gas (GHG), regulates atmospheric radiative balance and modifies aerosol optical behavior through moisture uptake and hygroscopic particle growth [80].

The measurements were carried out at the KLEF site during the period 2021–2023 on all days, except cloudy and rainy conditions. The corresponding statistics of measured days and data availability in each month are presented in Table S1 of the Supplementary Material (SM). The Sunphotometer measurements were carried out in 15 min intervals, including weekends and holidays, within the forenoon (FN) and afternoon (AN) measurement sessions, normally from 08:00 to 16:00 h (Indian Standard Time (IST); GMT + 5:30 h), while extending the measuring period until 16:30 h in case of clear and sunshine conditions. More details about the measuring protocol, pre-processing and quality assurance of Sunphotometer measurements can be seen in the SM. The instrument was periodically calibrated, typically on an annual basis, either using the Langley plot technique or through intercomparison with a reference Sunphotometer at high-altitude clean air sites, ensuring reliable and consistent measurement accuracy. Furthermore, to maintain data quality, the front quartz window of the instrument was cleaned regularly throughout the observation period. The reliability of the Sunphotometer measurements was evaluated through comparisons with MODIS AOD products.

2.4. Methodology

The spectral dependence of AOD was quantified via the Ångström exponent (AE or α) in the 340–1020 nm wavelength range, which provides valuable information on aerosol particle size and fine-to-coarse mode ratio, as obtained via linear regression in an $\ln AOD_\lambda$ vs. $\ln \lambda$ plot. Determination of AOD at other wavelengths (i.e., 440 and 675 nm) was performed via interpolation using the AE values [81–83]. Furthermore, the variation in AE with wavelength can be effectively represented by a second-order polynomial fit, which accounts for deviations from a simple power-law dependence and provides additional insight into aerosol size distribution and mixing states [37,84,85].

$$\ln AOD = a_2 \ln^2 \lambda + a_1 \ln \lambda + a_0 \quad (1)$$

where a_2 represents the spectral curvature, a_1 is the spectral slope, and a_0 is a constant term. The AE is related to the first derivative of this expression, while the derivative of AE (α') is obtained from the second-order term, reflecting deviations from a simple power-law behavior:

$$AE = -\frac{d \ln(AOD_\lambda)}{d \ln(\lambda)} = -(a_1 + 2a_2 \ln \lambda) \quad (2)$$

$$\alpha' = \frac{d\alpha}{d \ln(\lambda)} = -2a_2 \quad (3)$$

The coefficients a_1 and a_2 are derived from the 2nd-order polynomial fit (Equation (1)) applied to AOD values at four wavelengths, namely 340, 500, 870, and 1020 nm. The AOD

measurements at 936 nm are excluded from the fitting procedure, as this channel is more susceptible to uncertainties arising from water vapor absorption, which can adversely affect the accuracy of the retrievals. Furthermore, computed $AE_{440-675}$ and $AE_{675-870}$ values were used to apply Gobbi's scheme (AE vs. $\delta AE: AE_{440-675} - AE_{675-870}$), aiming to assess changes in fine-mode radius and fine-mode fraction under increasing AODs [86].

2.5. Discrimination of Aerosol Types

This study employs a simple and commonly used method for aerosol type classification utilizing AOD_{500} and $AE_{340-1020}$, following previous works (e.g., [20,39,78,82,87–90]). These two parameters are sensitive to aerosol loading and particle size, respectively, and provide an effective means to distinguish between different aerosol regimes. Clean Maritime (CM) aerosols are identified by very low aerosol loading ($AOD_{500} < 0.15$) and low $AE_{340-1020}$ (< 0.7), indicating dominance of coarse marine (sea salt) particles. Polluted Continental (PC) aerosols are characterized by relatively low aerosol loading ($AOD_{500} < 0.1$) but a high Ångström exponent ($AE_{340-1020} > 1$), reflecting fine-mode particles of anthropogenic origin, under relatively clean conditions. Biomass Burning (BB) aerosols are characterized by high AOD_{500} (> 0.5) and $AE_{340-1020} > 1$, indicative of dense smoke plumes affecting the site, while Urban–Industrial (UI) aerosols fall within moderate AOD_{500} (0.35–0.5) and $AE_{340-1020} > 1$, representing urban effects. Finally, Desert Dust (DD) aerosols are identified by high AOD_{500} (> 0.6) and low $AE_{340-1020}$ (< 0.7), characteristic of coarse particles during transported dust events. The rest of the aerosols are considered as Mixed (MXD), which are indeterministic with varied composition.

2.6. HYSPLIT Air–Mass Trajectories

Using a 5-day isentropic air mass backward trajectory analysis, the long-range transport pathways of aerosols and the relative contribution of different geographical regions to the observed pollutant concentrations at the receptor site can be effectively identified. In this study, the backward trajectories were computed using the HYSPLIT model [91] at the arrival height of 500 m a.m.s.l. The KLEF site is located at approximately 30 m a.m.s.l.; therefore, the selected 500 m a.m.s.l. arrival height corresponds to approximately 470 m above ground level (a.g.l.), which is well within the boundary layer where the majority of aerosol exists. This arrival height was selected to represent the lower-tropospheric transport layer influencing the receptor site, while maintaining a consistent reference altitude for all seasons, despite the seasonal and diurnal evolution of the planetary boundary layer (PBL). The resulting trajectories for each season were then averaged to obtain seasonal mean transport pathways, which were further visualized to depict dominant airflow patterns.

The MeteoInfo software (Version: 3.2.5) TrajStat Plugin, demonstrated by Wang et al. [92], was used to calculate the potential source contribution function (PSCF) and perform concentration weighted trajectory (CWT) analysis, aiming to apportion possible sources (hotspot regions) that contribute to aerosol loading at the receptor site [65,93]. The PSCF model uses data from the HYSPLIT model to identify regional pollution sources (hotspot regions) associated with enhanced aerosol loading at the KLEF receptor. The $0.5^\circ \times 0.5^\circ$ trajectory grid was used to calculate the conditional probability of a grid cell being associated with elevated aerosol concentrations based on the number of trajectory endpoints passing through that cell. Grid cells with a small number of trajectory endpoints were given lower statistical weight to minimize the uncertainty associated with sparsely visited cells. Thus, the weighted PSCF analysis primarily serves to reduce the influence of statistically less robust grid cells and does not represent a direct quantitative contribution from individual emission sources. A high PSCF value indicates a greater probability that

air masses associated with enhanced AOD at KLEF passed through the corresponding geographical region, which acts as a pollution hotspot.

In addition, the CWT analysis was performed using the statistical formula given below:

$$C_{ij} = \frac{1}{\sum_{l=1}^M T_{ijl}} \sum_{i=0}^M C_l T_{ijl} \quad (4)$$

where C_{ij} is the average weighted concentration in the ij^{th} cell, l is the index of the trajectory, M is the total number of trajectories, C_l is the concentration observed on the departure of trajectory l and T_{ijl} is the time spent in the ij^{th} cell by trajectory l [94]. Physically, the CWT value represents the concentration associated with air masses spending time over a particular geographical region before reaching the KLEF receptor. A high CWT value indicates that trajectories residing over a specific grid cell were associated with enhanced aerosol concentrations at the receptor, thereby identifying that region as a potential hotspot source area. Therefore, CWT provides a spatially resolved indication of potential source influence rather than a direct quantitative emission contribution or formal source apportionment. The combination of PSCF and CWT allows both the probability and the concentration strength associated with potential source regions to be evaluated. Both PSCF and CWT approaches were applied for all days with AOD measurements, aiming to assess the source regions and transport pathways that favor accumulation of aerosol over the receptor site.

2.7. Assessment of Aerosol Radiative Forcing

To integrate measured AOD into radiative impacts, well-established radiative transfer models (RTMs) are used. The Optical Properties of Aerosols and Clouds (OPAC) model [95] is widely used to derive aerosol optical properties (like single scattering albedo (SSA) and asymmetry parameter (ASYM)) for defined mixtures of aerosol components (e.g., water-soluble, insoluble, soot, dust). These OPAC outputs are then used as inputs in the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model [96] to compute radiative fluxes and aerosol forcing in the shortwave spectrum (0.25–4.0 μm) under clear-sky conditions. For the OPAC–SBDART simulations, the aerosol optical properties were generated using a site-specific external mixture consisting of water-soluble, insoluble, mineral dust, soot (black carbon), and sea-salt components, representing the major aerosol types expected over the KLEF region. The component concentrations were adjusted for each observation/season by constraining the OPAC-derived AOD₅₀₀ to the corresponding MICROTOPS-II observations, while relative-humidity-dependent changes in hygroscopic aerosol properties were considered. The seasonal radiative-transfer calculations accounted for the dominant surface conditions surrounding the KLEF site, particularly cropland and exposed/bare soil, using their corresponding surface albedo characteristics. A standard tropical atmospheric profile was adopted for the atmospheric temperature and pressure structure, while column water vapor was constrained from MICROTOPS-II PWV observations. The aerosol vertical distribution was represented by an exponential profile with a 1 km scale height. The same atmospheric and geometric configurations were maintained between the aerosol-loaded and aerosol-free simulations, with only the aerosol optical properties being varied. Detailed information on the OPAC aerosol components, humidity levels, aerosol mixing procedure, surface characteristics, atmospheric profiles, ozone and water-vapor inputs, and aerosol vertical distribution is provided in the SM. The ARF was computed at top of atmosphere (TOA), surface (SUR) and within the atmosphere (ATM), while the heating rates were also estimated following previous works [94,97]. Furthermore, estimates of the radiative forcing efficiency, i.e., ARF per AOD unit, were computed at the final stage and the ARF estimates are presented on a monthly mean basis. More details

about the OPAC-generated outputs and the SBDART estimates of radiative forcing are given in the SM and in a series of previous studies [34,39,55,64,71,98–101].

3. Results and Discussion

3.1. Comparison of Ground and Satellite AOD

The Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor onboard Terra and Aqua satellites provides observations in 36 spectral bands ranging from 0.41 to 14.4 μm with spatial resolutions of 250 m, 500 m, and 1 km, enabling retrieval of aerosols, clouds, and atmospheric properties [3,30]. In this study, Terra-MODIS Collection 6.1 (C061) Level 3 monthly AOD₅₅₀ ($1^\circ \times 1^\circ$) values from DT, DB, and DTB products, downloaded from the NASA GIOVANNI portal over the KLEF site (<https://giovanni.gsfc.nasa.gov/giovanni/>; accessed on 22 February 2024), were used to validate with the Sunphotometer measurements of AOD₅₀₀ and to identify the uncertainties during the period 2021–2023.

The comparative analysis between ground-based AOD₅₀₀ measurements and MODIS AOD₅₅₀ products reveals strong agreement, supporting the reliability of MODIS data over the study region (Figure 3). The combined DTB product shows the best overall performance with a correlation coefficient (r) of 0.80 and the lowest RMSE (0.121), indicating improved representativeness by leveraging the strengths of both DT and DB algorithms. The DT product also demonstrates good consistency ($r = 0.79$), but with slightly higher RMSE (0.126), likely due to its limitations over bright surfaces. The DB algorithm exhibits the highest correlation ($r = 0.81$) but also the highest RMSE (0.145), reflecting greater variability despite its design for bright-reflecting surfaces common in the region. All MODIS products tend to slightly overestimate low AODs and underestimate higher values, as indicated by regression slopes below unity. Nonetheless, the moderate RMSE and low mean bias errors across all comparisons confirm the applicability of MODIS AOD data, particularly the DTB product, for aerosol monitoring in regions with limited ground observations.

3.2. Seasonal Forenoon vs. Afternoon (FN–AN) Spectral AOD Dependence

Figure 4 illustrates the spectral variation in AOD for forenoon (FN) and afternoon (AN) observations across the four seasons, averaged over the entire study period. In all seasons, AOD decreases with wavelength, reflecting the wavelength-dependent nature of aerosol extinction and the predominance of fine-mode aerosols over the region. During winter, relatively higher AOD values are observed at shorter wavelengths (340–500 nm), with FN–AOD consistently exceeding AN–AOD. This behavior suggests enhanced accumulation of fine anthropogenic aerosols under stable atmospheric conditions in the morning hours, followed by partial dilution in the afternoon due to increased boundary-layer mixing. A similar pattern is evident in pre-monsoon, which exhibits the highest AOD levels among all seasons, particularly at shorter wavelengths. The elevated pre-monsoon AOD can be attributed to increased dust loading, stronger surface winds, and enhanced anthropogenic activity, while the FN–AN difference again reflects the influence of daytime dispersion processes.

The monsoon season shows the lowest spectral AOD values across all wavelengths, with a relatively smaller difference between FN and AN. This reduction is primarily associated with wet scavenging by precipitation, enhanced ventilation due to stronger winds, and increased atmospheric mixing, which together suppress aerosol accumulation. The flatter spectral slope during this season indicates a relatively greater contribution from coarse-mode aerosols. The post-monsoon season is characterized by a gradual increase in AOD, especially at shorter wavelengths, with FN values to be again slightly higher than AN values. This pattern is consistent with the resurgence of fine-mode aerosols from biomass burning, agricultural residue burning, and urban emissions following the monsoon [27]. Overall, the seasonal spectral behavior of FN and AN AOD highlights the

combined influence of aerosol sources, meteorological conditions, and diurnal boundary-layer dynamics. The systematic decrease in AOD from forenoon to afternoon across seasons underscores the role of daytime atmospheric mixing, while the distinct seasonal contrasts emphasize the importance of regional processes in controlling aerosol optical properties over the KLEF site.

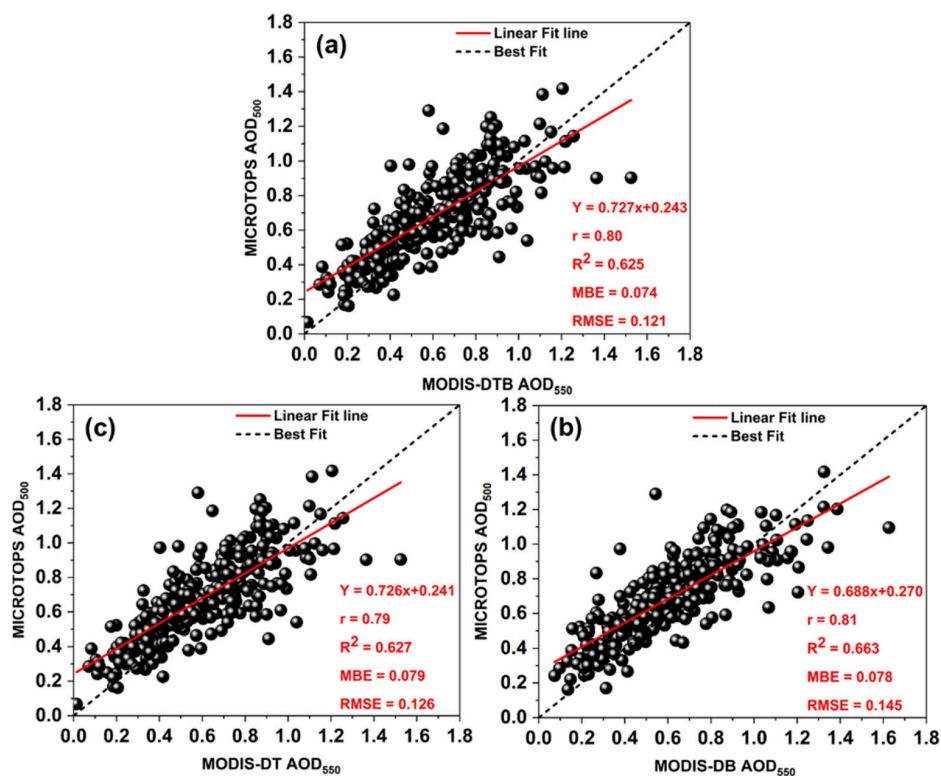


Figure 3. Scatter plots of validations between MODIS AOD₅₅₀ products (DTB, DT, and DB: (a–c)) with Sunphotometer AOD₅₀₀ for the entire study period at the KLEF site.

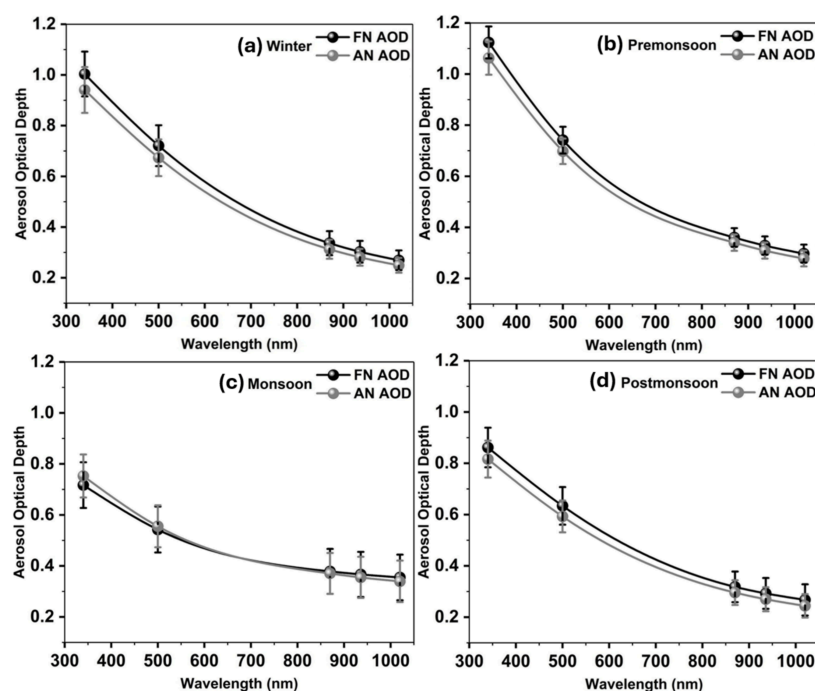


Figure 4. Spectral variation in forenoon (FN) and afternoon (AN) AODs for the four seasons—winter (a), pre-monsoon (b), monsoon (c), and post-monsoon (d)—at the KLEF site.

3.3. Spectral and Temporal Characteristics of AOD

The seasonal and monthly mean spectral variations in AOD at the KLEF site are presented in Figure 5. The analysis reveals a distinct spectral dependence of AOD in all seasons, characterized by higher values at shorter wavelengths that decrease progressively towards longer wavelengths (with lower decreasing rate in monsoon), indicating a typical signature with an abundance of fine-mode aerosols [35,78,84,102–106]. A pronounced seasonal spectral dependence is observed, driven by shifts in dominant aerosol size modes and composition under varying meteorological regimes [20,97,107,108]. In addition, the increase in RH during monsoon may enhance the moisture absorption capacity of aerosols, leading to their hygroscopic growth and consequently modifying the observed optical properties [59]. It is important to note that the power-law fitting (representing the Ångström's formula) on the seasonal and monthly mean AODs exhibits high accuracy ($R^2 > 0.98$), supporting the reliability of measurements and the low uncertainty in the spectral AOD retrievals.

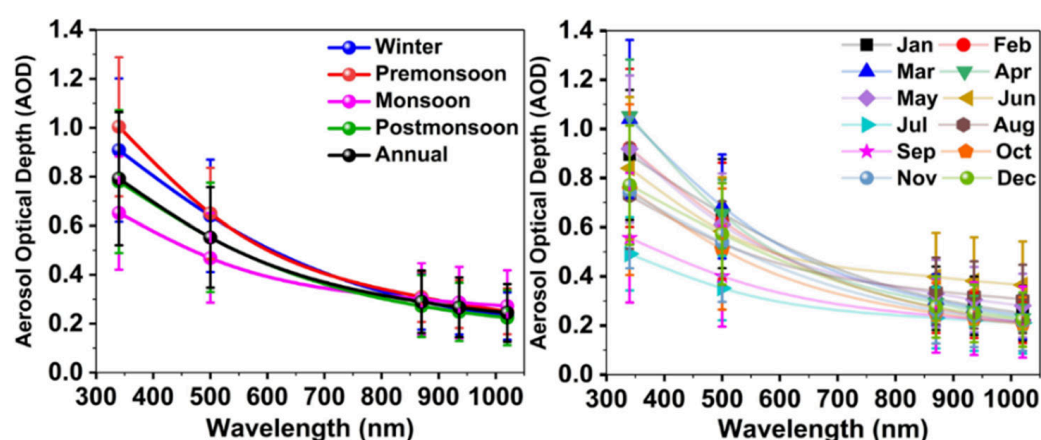


Figure 5. Seasonal ((left) panel) and monthly ((right) panel) mean spectral variations in AOD at five wavelengths (340, 500, 870, 936, and 1020 nm) at the KLEF site during 2021–2023. The vertical error bars represent ± 1 standard deviation (SD) of the corresponding AOD observations at each wavelength. The same error-bar convention is applied uniformly to all seasonal and monthly spectral measurements.

The temporal AOD variations reveal distinct monthly and seasonal patterns of aerosol optical properties influenced by changes in emission sources, atmospheric transport, and meteorological dynamics [65,97,108–110]. The annual mean AOD_{500} of 0.56 ± 0.22 observed at KLEF (Table 1) categorizes the station as a polluted rural site in southern India, which is strongly influenced by various nearby sources (natural and anthropogenic). The mean AOD_{500} peaks during the pre-monsoon season (0.66 ± 0.19), with monthly maxima reaching 0.69 in March and April (Table 1). Quantitatively, the pre-monsoon AOD_{500} was approximately 35% higher than the monsoon (0.49 ± 0.21), while winter AOD_{500} was about 31% higher than monsoon. This pronounced reduction during monsoon (minimum AOD in July: 0.35 ± 0.15) highlights the combined effects of precipitation-driven wet scavenging, coupled with enhanced RH, vertical mixing and stronger westerly winds that disperse accumulated aerosols [42,65,111]. On the contrary, the elevated pre-monsoon and winter AODs coincide with increased convective activity, accumulation of anthropogenic aerosols, and dry surface conditions, which promote both the resuspension of local soil dust and the long-range advection of coarse-mode mineral dust in southern India (e.g., [34,97,111–113]). AOD_{500} gradually recovers during the post-monsoon transition months by increasing to 0.52 ± 0.25 , as atmospheric stability returns and emission sources, notably agricultural residue burning in northern India, become active again [114]. The winter season sustains

moderate-to-high AOD₅₀₀ levels (0.64 ± 0.23 ; Table 1), reflecting the increased contribution from combustion aerosols, including black carbon (BC), organics and other species from vehicular emissions, industrial activities, and domestic biomass burning [115–117]. These pollutants accumulate due to stagnant meteorological conditions under a shallow boundary layer and frequent temperature inversions [11,101]. This seasonal variability is consistent with similar locations across peninsular India and the neighboring countries (see [65] and studies summarized in Table 2) due to undergoing rapid development and combined influences from nearby urban emissions and long-range transported aerosols [64].

Table 1. Monthly, seasonal, and annual averaged aerosol optical parameters observed at the KLEF site during the study period 2021–2023.

Parameters → Period ↓	AOD ₅₀₀ ± SD	AE _{340–1020} ± SD	PWV ± SD	a ₂	α'
January	0.65 ± 0.23	1.22 ± 0.22	1.96 ± 0.40	−0.47	0.95
February	0.63 ± 0.24	1.38 ± 0.18	2.04 ± 0.34	−0.43	0.87
March	0.69 ± 0.21	1.37 ± 0.24	2.22 ± 0.61	−0.34	0.67
April	0.68 ± 0.16	1.41 ± 0.15	2.99 ± 0.33	−0.23	0.46
May	0.61 ± 0.21	1.13 ± 0.33	3.83 ± 0.65	−0.09	0.18
June	0.58 ± 0.23	0.77 ± 0.32	4.00 ± 0.44	0.22	−0.43
July	0.35 ± 0.15	0.78 ± 0.34	4.61 ± 0.25	0.12	−0.24
August	0.59 ± 0.23	0.76 ± 0.39	4.38 ± 0.31	0.01	−0.03
September	0.40 ± 0.22	0.96 ± 0.39	4.40 ± 0.41	−0.06	0.12
October	0.49 ± 0.25	1.20 ± 0.35	3.59 ± 0.76	−0.18	0.36
November	0.52 ± 0.25	1.16 ± 0.33	3.37 ± 0.79	−0.29	0.57
December	0.57 ± 0.21	1.21 ± 0.23	2.47 ± 0.70	−0.46	0.92
Winter	0.64 ± 0.23	1.30 ± 0.20	2.00 ± 0.37	−0.45	0.91
Pre-monsoon	0.66 ± 0.19	1.30 ± 0.24	3.01 ± 0.53	−0.22	0.44
Monsoon	0.49 ± 0.21	0.83 ± 0.37	4.35 ± 0.35	0.05	−0.11
Post-monsoon	0.54 ± 0.23	1.18 ± 0.29	3.14 ± 0.67	−0.28	0.57
Annual	0.56 ± 0.22	1.10 ± 0.30	3.38 ± 0.52	−0.19	0.37

Table 2 reviews AOD₅₀₀ values from previous studies in India and abroad at sites with different topographic characteristics, while analytic comparison between AOD levels at several sites in India can be seen in Tiwari et al. [65]. Such a comparison revealed that the current site is ranked in the middle between highly polluted urban/industrial areas in the IGP, where AOD₅₀₀ frequently exceeds 1.0 [46,118], and low-polluted sites in remote and mountainous areas. Along with this, detailed monthly and annual statistics of AOD₅₀₀, AE_{340–1020}, and PWV, including their mean, median, minimum, and maximum values, further demonstrated the temporal variability and range of aerosol optical conditions observed during the study period mentioned in Table S2 of the SM. Furthermore, the KLEF site exhibits relatively higher aerosol loading compared to semiarid regions in southern India such as Anantapur [62,115] and Kadapa [34], except during the pre-monsoon season. Therefore, current AOD values and seasonality could be considered as a baseline climatology for rural southern India.

Table 2. Comparison of aerosol optical and radiative properties measured and estimated across various sites in India and abroad. The data is obtained from AERONET Sunphotometers for all sites, except a few stations (with S. No. 1–4) that utilized the MICROTOPS II Sunphotometer.

S. No.	Site Name with Citation	Region Type	AOD ₅₀₀	AE	TOAF	SURF	ATMF
1	KLEF, India (Present Study)	Rural, Suburban	0.56	1.10	−6.45	−37.91	31.46
2	Anantapur, India [115]	Semiarid	0.35	1.25	−6.75	31.65	24.92
3	Kadapa, India [34]	Semiarid	0.38	1.75	−6.6 to −2.4	−32.3 to −17.8	15.0 to 28.0
4	Chennai, India [71]	Coastal, Urban	0.43	0.84	−4.34 to −6.01	−32.26 to −38.43	27.92 to 40.70
5	Hyderabad, India [119]	Urban	0.52	1.08	−17	−65 to −80	48 to 63
6	Doon Valley, India [94]	Urban, Valley	0.41	0.54	−11.03	−46.20	35.17
5	Jaipur, India [35]	Urban	0.40 to 0.45	0.22 to 0.56	−11.40 to −5.60	−32.20 to −22.49	14.04 to 22.47
6	Malindi, Kenya [120]	Coastal	0.26	0.57	−5.96 to −10.26	−37.95 to −50.25	31.99 to 42.39
7	Mbita, Kenya [120]	Rural	0.27	1.01	−8.51 to −17.34	−37.38 to −56.14	28.31 to 47.27
8	Nairobi, Kenya [120]	Urban	0.19	0.89	−4.11 to −10.51	−30.47 to −40.87	19.96 to 32.24
9	Cairo, Egypt [121]	Urban	0.39 to 0.47	0.6 to 1.30	17 to 36	−46 to −81	29 to 45
10	Lanzhou, China [122]	Suburban	0.16 to 0.73	−0.01 to 1.15	0–4	−48 to −56	48–52
11	Pretoria, South Africa [67]	Urban	0.23	1.51	−7.52	−29.32	19.82
12	Skukuza, South Africa [68]	Rural	0.25	1.41	−13.62	−27.58	13.96
13	Lahore, Pakistan [88]	Urban	0.72	1.21	−17.25 to −59.37	−89.52 to −138.29	41.24 to 79.26
14	Lahore, Pakistan [66]	Urban	0.57 to 0.76	0.39 to 1.22	−22.5	−96	74.56
15	Karachi, Pakistan [66]	Coastal and Urban	0.33 to 0.63	0.29 to 0.95	−18	−60	41.85

The seasonal and monthly values of measured precipitable water vapor (PWV) content along with derived Ångström exponent (AE_{340–1020}) at the KLEF site are also presented in Table 1. The high AE_{340–1020} values during winter and pre-monsoon with seasonal means of 1.30 ± 0.20 and 1.30 ± 0.24 , respectively, indicate dominance of fine-mode aerosols (e.g., from urban/industrial emissions and biomass burning). The seasonal contrast is substantial, with the winter and pre-monsoon AE values being approximately 57% higher than the monsoon value (0.83 ± 0.37), indicating a marked transition from predominantly fine-mode conditions during the dry seasons toward a greater coarse-mode contribution during monsoon, suggesting a shift toward coarse-mode sea salt particles, possibly mixed with cloud-processed aerosols and long-range transported dust from the southern

Arabian Peninsula in certain cases [123]. This is also justified by (i) the high scattering efficiency of large-geometric-size marine aerosols and (ii) humidification-induced growth of fine particles, thereby reducing $AE_{340-1020}$ [124]. The $AE_{340-1020}$ values in post-monsoon (1.18 ± 0.29) revert to moderate levels, reflecting a return to mixed aerosol types, which are progressively shifted to fine mode as the season progresses.

The progressive increase in PWV content from winter minimum to monsoon maximum (4.35 ± 0.35 cm) is associated with enhanced convective activity and moisture transport from the Arabian Sea and the Bay of Bengal during the monsoon period, which is well documented all over India [80]. The PWV content in monsoon is more than double that of winter (approximately 2.0 cm), leading to favorable conditions for hygroscopic growth of water-soluble and sea-salt aerosols, thereby contributing to the observed reduction in AE and modification of aerosol extinction characteristics. Kumar et al. [125] showed that enhanced PWVs in pre-monsoon season are associated with dust events over the IGP, revealing a positive correlation between PWV and dust due to its common origin from the west/southwest (Arabian Sea and SW desert Asia). In the current case, during months with $PWV > 3.5$ cm (May–September), the turbidity coefficient β derived from Ångström's formula was generally higher (≥ 0.23), indicating water uptake by hygroscopic aerosols that enhance scattering at longer wavelengths. Conversely, dry winter months exhibited lower β values (< 0.26), despite the high AODs, implying that aerosol loading is dominated by non-hygroscopic soot particles [126]. However, a detailed association between PWV content and aerosol characteristics, chemical composition and hygroscopic growth is beyond the scope of the current research.

3.4. Diurnal Variation in AOD

The diurnal variation in AOD at three representative wavelengths (near UV (340 nm), visible (500 nm), and NIR (1020 nm)) was analyzed on a seasonal basis, aiming to explore the temporal dynamics of aerosol loading on a diurnal scale and the impact of potential sources (Figure 6). These diurnal patterns range from morning to afternoon hours, i.e., 08:00 to 16:30 h Indian Standard Time (IST; GMT + 5:30 h). Overall, AOD_{500} shows relatively higher values during the morning (~08:00–10:00 h), associated with a shallower boundary layer, local emissions, enhanced relative humidity, and possible thin haze layers during the early-morning hours [111,127,128]. The persistence of higher morning AOD across the seasons, followed by a gradual decline toward the afternoon, indicates that the diurnal variability is primarily associated with boundary-layer evolution rather than a strong episodic local emission signal. The stronger morning enhancement can be physically associated with the early-morning boundary-layer structure. During winter, weak solar heating, lower temperatures, and relatively stable atmospheric conditions favor a shallow boundary layer and can promote the persistence of an early-morning temperature inversion. Under these conditions, aerosols emitted from nearby traffic, residential activities, and other combustion sources are confined within a relatively shallow layer, increasing the columnar aerosol loading observed during the early hours (AOD_{500} : ~0.65–0.75). The boundary layer progressively deepens toward noon and afternoon, enhancing vertical dilution and turbulent mixing, and thereby reducing AOD. The morning enhancement may also be supported by higher PWV and relative humidity, which promote hygroscopic growth of water-soluble aerosol particles and increase their light-extinction efficiency. The relatively small magnitude of the FN–AN contrast compared with the pronounced seasonal differences further supports the interpretation that regional transport and seasonal meteorology exert a stronger control on columnar aerosol loading than short-term local emissions [11,127,128].

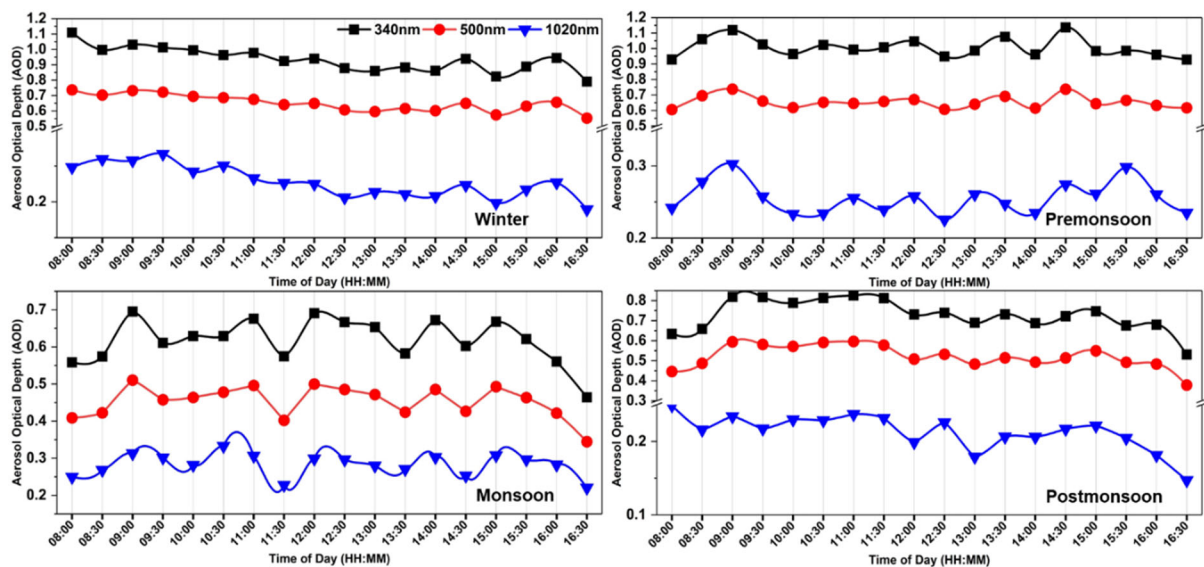


Figure 6. Diurnal variations in spectral AODs averaged in each season at the KLEF site.

During pre-monsoon, AOD_{500} varies between ~ 0.60 and 0.75 , with higher values in the morning ($\sim 08:00$ – $09:00$ h), a slight reduction around midday ($\sim 11:00$ – $13:00$ h), and a secondary increase in the afternoon ($\sim 14:00$ – $16:00$ h). This pattern slightly reflects the evolution of the boundary layer mechanism, where morning accumulation is diluted by convective mixing at noon, and later enhanced again by resuspension processes and afternoon/evening emissions.

The FN–AN contrast becomes weak and less systematic during monsoon. The frequent rainfall and efficient wet scavenging remove aerosol particles from the atmospheric column, while strong southwesterly flow and enhanced atmospheric ventilation promote horizontal transport and vertical mixing. Consequently, the boundary layer effect is less pronounced than during winter. Although the high ambient water-vapor content during monsoon may enhance hygroscopic particle growth and extinction, this effect is partly offset by precipitation removal and stronger atmospheric ventilation.

In post-monsoon, AOD_{500} remains moderate-to-high (~ 0.50 – 0.60), with higher values during morning ($\sim 08:00$ – $10:00$ h) followed by a gradual decrease toward afternoon ($\sim 14:00$ – $16:00$ h), likely due to increased solar heating and boundary layer expansion [128]. This corresponds to renewed continental transport from central/eastern India and the IGP, along with local anthropogenic and post-harvest biomass-burning emissions [58,128–130]. Current observations are consistent with diurnal patterns reported at other sites across Peninsular India, where interactions between local emission sources and mesoscale meteorological conditions control the daily aerosol variations [34,78,113].

To sum up, the FN–AN contrast is more evident during the winter and pre-monsoon seasons, when the local combustion processes maximize, reflecting the combined effects of early-morning atmospheric stability, boundary-layer growth, episodic anthropogenic emissions, and humidity-induced aerosol hygroscopic growth. The diurnal pattern becomes weaker in monsoon due to rainfall washout that weakens the effect of local emissions, stronger ventilation, and transition of air-mass transport. Further analysis revealed that similarly to AOD, PWV content was generally higher during the forenoon period compared to the afternoon. This feature suggests that enhanced morning moisture conditions may support hygroscopic growth of aerosol particles, thereby increasing aerosol scattering and AOD during FN hours. Overall, the AOD diurnal patterns did not reveal notable variability or specific peaks during the day that could be ascribed to intense local emission sources, i.e., traffic, cooking, residential heating, etc. The mostly neutral diurnal patterns in all seasons,

despite the progressive slight decreasing tendency towards afternoon hours, justify the rural and regional character of the measuring site that is not directly affected by local intense pollution sources.

3.5. Influence of Wind Regime on Aerosol Properties

The seasonal dependence of AOD and AE on wind speed and direction is examined via polar bivariate plots, highlighting the seasonally changing role of local and transported aerosols at the KLEF site (Figure 7). In winter, higher AOD values are mainly associated with easterly winds under low-to-moderate wind speeds (~ 1.5 – 2.5 m/s), which in the vast majority of the cases originate from the eastern IGP after crossing east India (see Figure 8). These air masses contribute to the dominance of fine-mode aerosols from regional anthropogenic emissions, residential combustion, and shallow boundary-layer conditions, while the highest AE values (1.0 – 1.4) are associated with east and southerly winds of similar characteristics. The southerlies may also transfer urban/anthropogenic aerosols from Chennai megacity, located south of the study site, thus enhancing AE values. In pre-monsoon, moderate to high AODs are observed under southerly winds, with moderate wind speeds (~ 4 m/s). Stronger westerly winds, reaching up to ~ 6 m/s, are associated with lower AODs, indicating cleaner air masses coming from the west, i.e., the Arabian Sea, although in some cases they may transfer dust aerosols from the Arabian Peninsula [131]. These westerly air masses are related to the lowest AE (<0.8), suggesting a presence of sea spray (likely mixed with dust) aerosols, under cleaner conditions (lower AODs). On the contrary, weak-to-calm winds are associated with higher AE values in pre-monsoon, reflecting a mixed aerosol regime, where transported sea spray, dust and locally resuspended particles coexist with fine anthropogenic aerosols from local origin. Similar characteristics with aerosol mixing and significant contributions from various sources were observed in urban Hyderabad, located north from the study site [78]. Lower AODs, along with the lowest AE (<0.8) in monsoon, are mainly linked with south-westerly winds under moderate to high wind speeds (~ 5 – 6 m/s), indicating the impact of marine air-mass and efficient wet removal processes. Similar to pre-monsoon, we noted the highest AE values for calm winds, indicating the effect of local pollution. Higher AE (~ 1.1 – 1.25) and AOD (0.6 – 0.75) values in the post-monsoon season are depicted for southerlies with moderate-to-low wind speeds (up to 3 m/s), indicating turbid conditions and dominance of fine-mode aerosols, mostly associated with local/regional sources, while transport from central and northern India may further escalate the aerosol loading. On the contrary, stronger easterlies in this season are associated with lower AODs and AE values, likely representing marine air masses from the Bay of Bengal that tend to clean the atmospheric conditions at the KLEF site.

Overall, the polar distributions indicate a clear dependence of aerosol loading on wind regime: the highest winter AOD values (~ 0.6 – 0.75) occur under weak-to-moderate easterly flow (~ 1.5 – 2.5 m s^{-1}), whereas monsoon AOD generally decreases to ~ 0.4 – 0.5 under stronger south-westerly winds (~ 5 – 6 m s^{-1}). This lower (by ~ 30 – 40%) monsoonal AOD is consistent with enhanced ventilation and wet removal, whereas the weaker winter winds favor aerosol accumulation and regional transport.

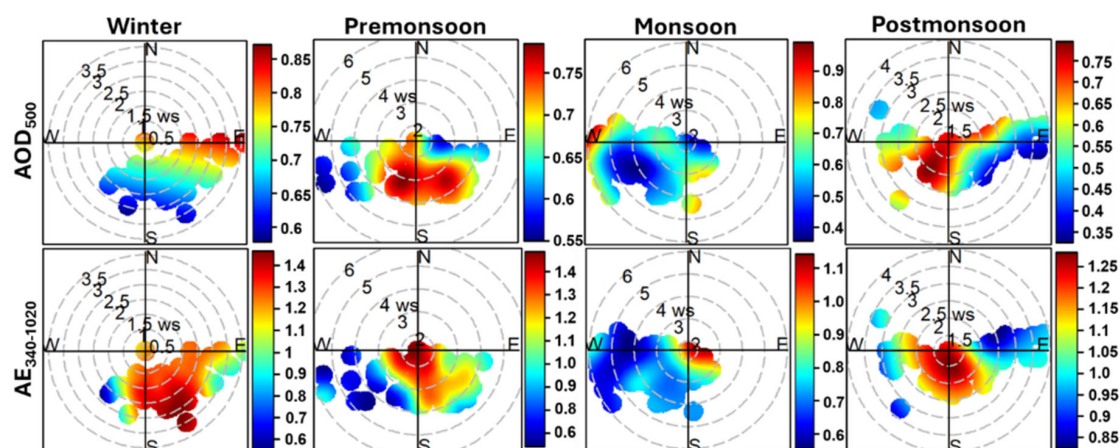


Figure 7. Bivariate polar plots of AOD_{500} and $AE_{340-1020}$ for different seasons observed at the KLEF site during the study period.

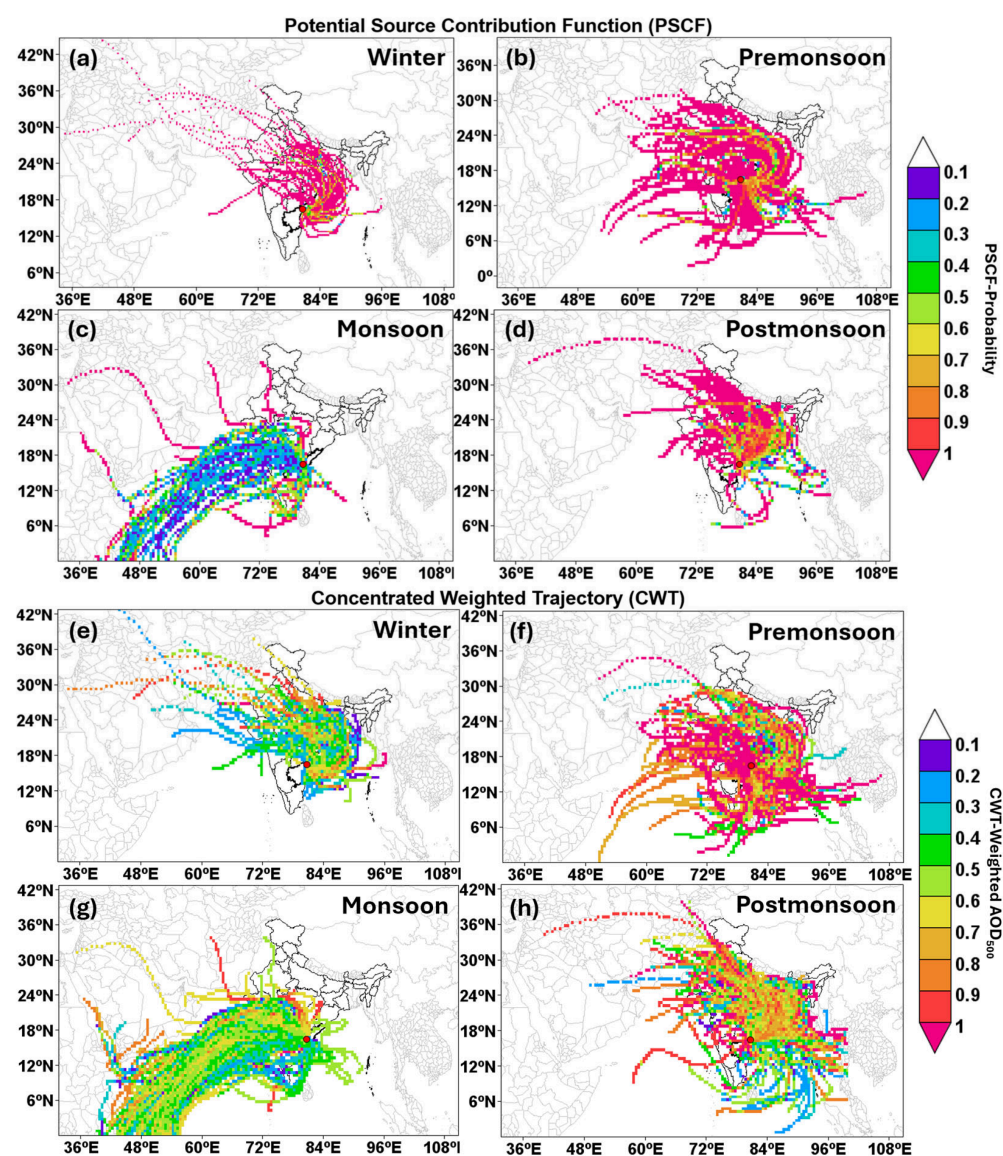


Figure 8. Trajectory analysis of AOD_{500} from PSCF (panels (a–d), color scale represents probability) and CWT (panels (e–h), color scale represents weighted AOD_{500} values) models for each season at the KLEF site during the study period.

To further investigate the geographic origins, source regions and transport pathways of aerosols affecting the KLEF site, Potential Source Contribution Function (PSCF) and Concentration Weighted Trajectory (CWT) analyses were performed on a seasonal basis, using HYSPLIT-modeled air mass back trajectories along with concurrent AOD measurements at the receptor site. These complementary receptor models identify probable source regions and transport pathways, rather than direct quantitative source apportionment, and assess their potential influence on the observed aerosol loading based on trajectory residence time and receptor concentrations [93,132]. The results reveal a pronounced seasonal shift in dominant source regions, underscoring the role of synoptic meteorology in modulating long-range aerosol transport to this rural location (Figure 8). During the winter season, both PSCF and CWT analyses identify the IGP and central India as persistent high-probability source regions for the highest AODs at the KLEF site under prevailing northeasterly air masses. Elevated CWT values confirm that long-range transport of aerosols from these regions is a major driver of the high AOD₅₀₀ with a dominance of fine aerosols at the KLEF site. In the pre-monsoon season, the source footprint expands north-westward, with high PSCF and CWT values extending over arid and semi-arid regions of northwestern India, while trajectories from the west (Arabian Sea) also influence the receptor site. This spatial pattern reflects the growing influence of mineral dust, which is uplifted under hot, dry and windy conditions and transported over long distances [50,111]. At the same time, aerosols from north and central India continue to contribute significantly, along with local emissions under weak winds, leading to a mixed aerosol environment where dust particles combine with anthropogenic pollution [133].

The monsoon season presents a distinct reversal in transport patterns. The high-probability source regions shift to the Arabian Sea, the Bay of Bengal and the southern Indian peninsula. This reflects the dominance of cleaner, marine-influenced air masses carried by the strong south-westerly monsoon flow, which suppresses continental aerosol inflow over the measurement site. It is evident that these marine air masses bring relatively cleaner and moisture-rich air to the site (Figure 7). During the post-monsoon season, the influence of continental sources reemerges, coinciding with the reversal to northeasterly winds and the onset of widespread paddy residue burning, which emits large quantities of fine-mode absorbing aerosols [123,134,135]. Hence, the integrated PSCF and CWT analyses demonstrate that aerosol loading at the measurement site is not merely a function of local emissions but is profoundly influenced by seasonally varying long-range transport. These findings align with similar trajectory-based studies over southern India and highlight the interconnected nature of aerosol pollution across the Indian subcontinent [13,128]. Current results are subject to uncertainties associated with trajectory calculation, meteorological input resolution, trajectory length, receptor height, grid-cell size, and the spatio-temporal distribution of the observations. In addition, the relatively limited number of trajectories passing through some grid cells may increase the uncertainty of the corresponding PSCF/CWT values. Therefore, regions showing consistently high values in both PSCF and CWT, and known regional emission sources, are interpreted as more robust potential source influences rather than definitive emission contributions. The combined use of these independent indicators provides greater confidence in the inferred seasonal source patterns while acknowledging the inherent limitations of receptor-based trajectory analyses.

3.6. Insights into Spectral Variability of AOD

This section examines the spectral behavior of AOD and AE values, aiming to provide further insights about dominant aerosol features, types and mixing processes in the atmosphere. Figure 9 presents the seasonal relationships of AOD₅₀₀ (top panels) and AE_{340–1020} (bottom panels) values with several parameters (a_2 – a_1 , a_2 , α' , and a_1) obtained from the

spectral curvature of AOD and AE (Equations (1)–(3)). Together, these parameters provide insight into aerosol size distribution, mixing state, and the relative dominance of fine- and coarse-mode particles over the study region [37,84,86]. In this respect, $a_2 - a_1$, obtained from spectral curvature (second-order polynomial fit), equals Ångström's α for a linear equation [37], while its “1–1” association with α ($R^2 = 0.99$) confirms the high accuracy of sunphotometer measurements and the retrievals of all parameters related to spectral curvature [48,65,123].

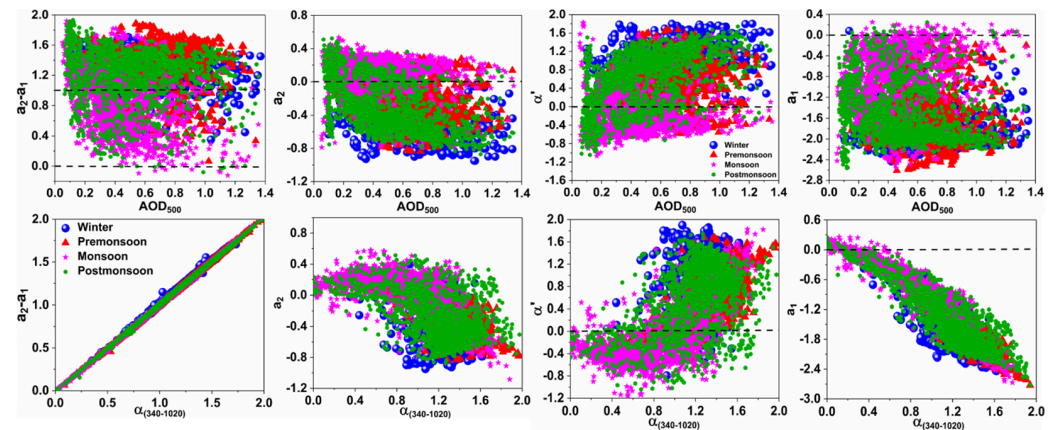


Figure 9. Seasonal correlations of the coefficients $a_2 - a_1$, a_2 , alpha derivative (α'), and a_1 versus AOD_{500} ((top) panels) and $\alpha_{340-1020}$ ((bottom) panels) at the KLEF site.

Higher $a_2 - a_1$ values during winter and post-monsoon ($AOD_{500} > 0.6$, $AE_{340-1020} > 1.2$) indicate stronger spectral curvature associated with fine-mode aerosols from anthropogenic and biomass-burning sources [127,128]. In contrast, much lower values during monsoon suggest a mixed aerosol regime influenced by coarse marine particles mixed with transported dust and pollution [62]. In general, $a_2 - a_1$ values present a large scatter with AOD_{500} throughout the year, indicating seasonally changing aerosol properties that are affected by various sources, mixing states and meteorological dynamics. The absence of a consistent monotonic relationship between spectral curvature and AOD indicates that increasing aerosol loading does not necessarily correspond to a systematic change in particle size. Instead, comparable AOD levels can arise from substantially different aerosol mixtures, suggesting that source composition and atmospheric processing are more important than aerosol abundance alone in determining the spectral shape.

The parameter a_2 remains predominantly negative, especially at higher AOD_{500} and $AE_{340-1020}$ values (>1.0 – 1.2), confirming fine-mode aerosol dominance [37,65]. Its increasingly negative magnitude during post-monsoon, pre-monsoon and winter for higher AODs reflects a higher presence of local or transported anthropogenic/soot fine aerosols under high aerosol loading conditions. Occasional near-zero or weakly positive a_2 values, mostly at lower $AE_{340-1020}$ (<0.8) values, indicate intermittent coarse-mode influence, particularly during monsoon, but also in cases of dust transport in pre-monsoon. The derivative α' exhibits more frequent positive values during winter and post-monsoon ($AE_{340-1020} > 1.2$), indicating stronger wavelength dependence of AOD and a greater influence from fine particles. In contrast, monsoon conditions show lower or near-zero α' values, consistent with coarse-mode aerosols and weaker spectral dependence [64]. Finally, a_1 is negative in the vast majority of the cases, since it is equal to $-\alpha$ in cases with negligible or zero curvature ($a_2 \approx 0$) and seems to be rather independent from AOD, without any notable tendency under highest AOD values, apart from the narrower range of a_1 . As expected from its definition, a_1 shows a strong inverse relationship with $AE_{340-1020}$, which becomes more scattered for increasing AE values, suggesting higher influence from the

spectral curvature on these cases. The most negative a_1 values occur during winter and post-monsoon, reflecting a sharper wavelength-dependent decrease in AOD associated with fine regional aerosols or transported over long distances [11]. During monsoon, weaker negative slopes confirm the presence of a mixed aerosol regime dominated by continental, marine and dusty air masses.

The seasonal variation in aerosol microphysical properties was further examined by adopting the Gobbi classification scheme [85,86,108,124], which relates the $AE_{440-870}$ to its difference ($dAE = AE_{440-675} - AE_{675-870}$). This framework (Figure 10a–d) enables the classification of aerosol size distribution characteristics, specifically the fine-mode fraction (FMF) and effective radius (R_{eff}) for various classes of AOD, providing further insights into aerosol aging and mixing processes [39,65,119,136]. During winter, data points cluster within $AE_{440-870}$ values of 0.7–1.8 and show slightly negative to near-zero spectral curvature ($dAE \approx -0.2$ to 0.0). This corresponds to moderate-to-high FMF (~50–70%) and small effective radius ($R_{eff} = 0.15 \pm 0.03 \mu\text{m}$), indicating dominance of accumulation-mode aerosols from urban-industrial and biomass-burning sources under stable atmospheric conditions [11,119,127]. In the pre-monsoon season, the distribution broadens ($AE_{440-870} \sim 0.4$ –2.0; $dAE -0.2$ to $+0.1$), revealing a large range of FMF (~20–80%) and fine R_{eff} values (~0.1–0.2 μm). This suggests a mixed aerosol regime where anthropogenic fine particles coexist with increasing coarse-mode contributions [86,119]. Note that in both seasons increasing AOD values do not modify the data scattering in the plot, since high AODs (aerosol episodes) occur for both high and low FMF and R_{eff} values, corresponding to urban haze and intense dust events, respectively.

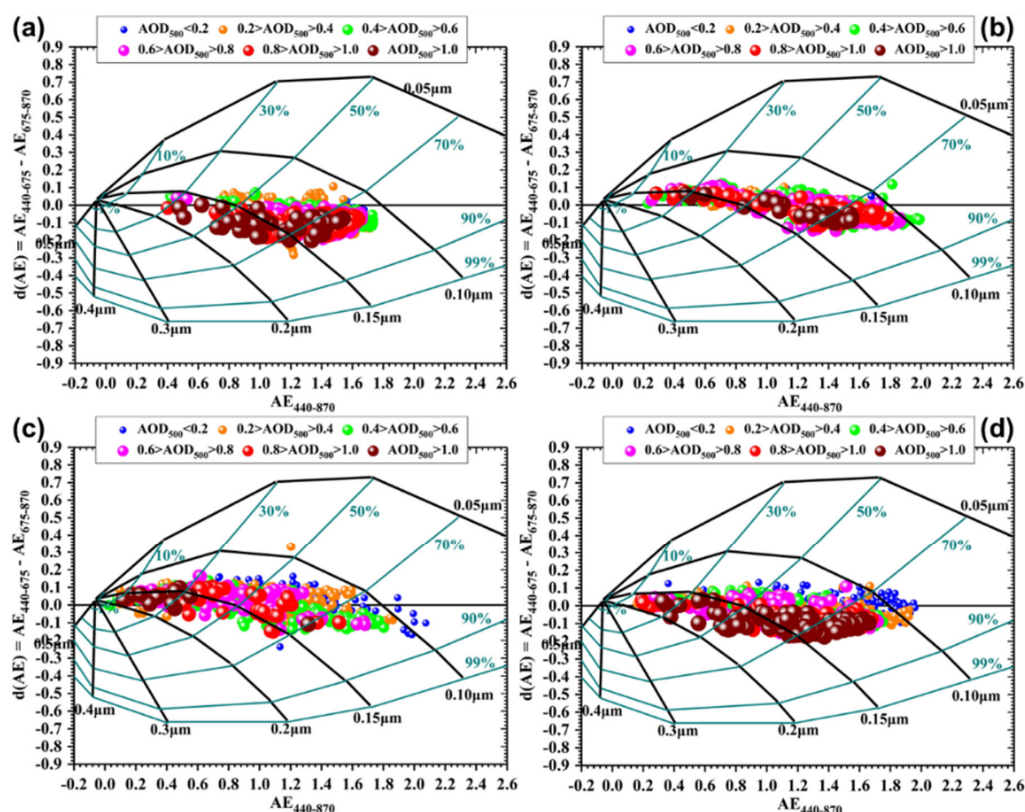


Figure 10. Gobbi scheme representing the relationship between dAE ($AE_{(440-675)} - AE_{(675-870)}$) and $AE_{(440-870)}$ for various AOD classes in (a) winter, (b) pre-monsoon, (c) monsoon, and (d) post-monsoon seasons at the KLEF site.

However, this feature is changed in monsoon, when the highest AODs present a shift towards the beginning of the scheme (zero point), indicating humidification and coagulation processes under higher turbid conditions [86,119]. For these high AOD cases (>1.0), AE values are below 0.4 and dAE is near zero, indicating low FMF values ($<30\%$) and higher R_{eff} ($0.15\text{--}0.2\ \mu\text{m}$). Therefore, the strong aerosol episodes during monsoon are associated with a large presence or even dominance of coarse-mode aerosols, likely representing dusty conditions. Monsoon shows the widest spread in the AE–dAE scatter plot, with AE_{440–870} ranging from 0.2 to 2.0 and dAE from -0.2 to $+0.2$. These conditions correspond to FMF values of 10 to 80% and R_{eff} ranging from 0.10 up to $0.3\ \mu\text{m}$. Positive dAE values indicate enhanced coarse-mode influence driven by strong winds and convective mixing [42]. Simultaneously, wet scavenging removes hydrophilic fine particles, enriching coarse aerosols and shifting the distribution toward lower AE and higher R_{eff} [137]. Long-range transport of marine air masses mixed with dust, as shown in Figure 8, verifies the findings extracted from this scheme regarding aerosol properties and mixtures.

During post-monsoon, the distribution shifts back toward higher AE_{440–870} values, especially for the highest AODs ($0.8\text{--}1.8$), which are also associated with negative dAE values, opposing the positive ones for the lowest AODs, and for FMF exceeding 50–70% (R_{eff} below $0.15\ \mu\text{m}$). The negative dAE and the lower R_{eff} and higher FMF values indicate an enhanced presence of fresh or aged fine-mode aerosols, reflecting the influence of long-range-transported soot particles from IGP agricultural burning [119,138]. Overall, the analysis of Gobbi et al.'s [86] scheme indicates year-round dominance of fine-mode aerosols at the measurement site, with FMF generally $>60\%$ and R_{eff} mostly $<0.15\ \mu\text{m}$ (Figure 10). These findings highlight the strong influence of seasonal meteorology, emission variability and atmospheric processing on aerosol size characteristics, confirming KLEF as a receptor site of both local anthropogenic emissions and regionally transported natural or biomass-burning aerosols.

3.7. Discrimination and Contribution of Aerosol Types

The seasonal variability of different aerosol types and their characteristics at the KLEF site was further investigated for the first time through an aerosol discrimination technique associating AOD and AE values (Figure 11a–d). This two-dimensional approach is widely used to discriminate aerosol types based on particle size and columnar loading [20,78,88,108,120]. The analysis was supported by the quantitative source contribution (as a percentage) derived from seasonal density clustering. During winter, the aerosol population is overwhelmingly dominated by fine-mode particles, with data points heavily concentrated in the regime of moderate-to-high AOD₅₀₀ ($0.4\text{--}0.8$) and high AE_{340–1020} ($1.4\text{--}1.6$), characteristic of urban-industrial (35.9%) and biomass burning (56.3%) aerosol types. This aerosol classification reflects the effect of local vehicular emissions, industrial activity, and domestic biomass burning under stable atmospheric conditions that suppress aerosol dispersion [130]. The pronounced fine-mode dominance aligns with observed spectral behavior (Figures 5 and 10) and underscores the important role of combustion sources during this season. The density plot shows a well-defined maximum and a progressive density decrease around it, similar to results observed over urban Hyderabad, located north from the KLEF site [78]. Note also the near absence of aerosol types like clean maritime and desert dust in this season.

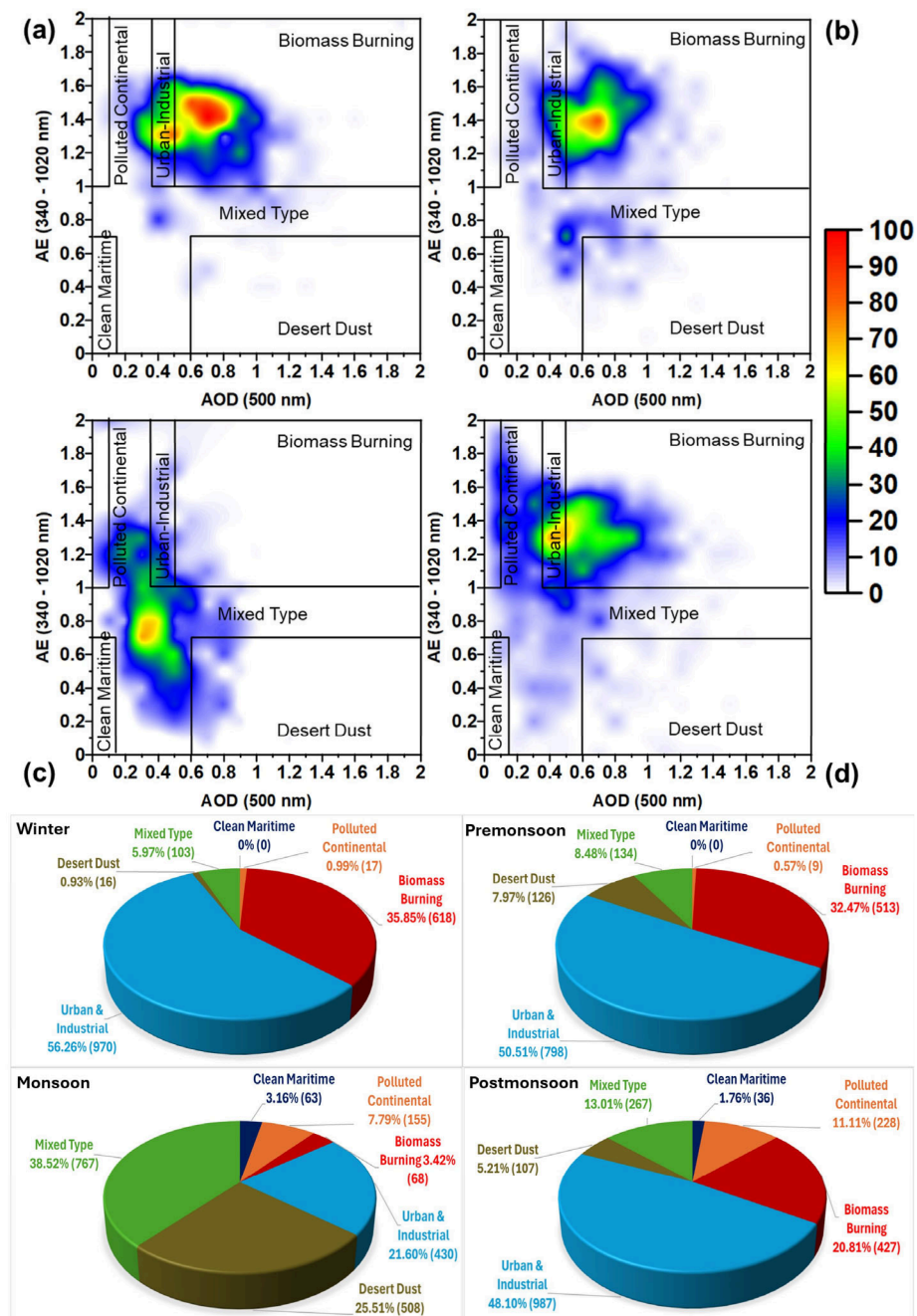


Figure 11. Contour density plots of the AOD_{500} and $AE_{340-1020}$ relationship to represent different aerosol types for (a) winter, (b) pre-monsoon, (c) monsoon, and (d) post-monsoon and its contributions (pie charts in %) observed at the KLEF site.

The pre-monsoon period exhibits increased compositional heterogeneity. The fine-mode aerosols remain prevalent, with urban-industrial (32.5%) and biomass-burning (50.5%) types still significant, while other types like desert dust (8.0%) and aerosol mixtures (8.5%) present lower fractions. In the density plot, note the secondary “cloud” denoting mixed and dust aerosols. A marked transformation occurs during the monsoon season, where the data points are clustered predominantly in the low $AE_{340-1020}$ (<1.0) and low-to-moderate AOD_{500} (<0.4) regions, with the mixed type (38.5%) followed by desert dust (25.5%) and urban-industrial (21.6%) to be the dominant key aerosol types. This seasonal shift reflects the efficient wet scavenging of anthropogenic aerosols with increased contribution of clean marine and dust particles [42,112]. In the post-monsoon season, the aerosol distribution reverts toward fine-mode dominance, though with a more diverse composition

than winter and more scattered data points, reflecting larger variability of the identified aerosol types. Urban–industrial aerosols reemerge as the dominant type (48.1%), accompanied by significant contributions from biomass–burning (20.8%), mixed (13.1%), polluted continental (11.1%) and desert dust aerosols (5.2%). This seasonal variation in aerosol types at KLEF is consistent with the overall aerosol patterns and contributions observed in urban Hyderabad [78] and other sites across Peninsular India [85,90,119,139,140]. The seasonal change in aerosol–type fractions is substantial. Biomass–burning aerosols decrease from 56.3% in winter to 50.5% in pre–monsoon and become only 3.4% during monsoon. The combined mixed and desert–dust contribution during monsoon reaches approximately 64%, compared with only a minor dust contribution during winter, quantitatively demonstrating the strong seasonal shift from predominantly fine anthropogenic/combustion aerosols toward a more heterogeneous coarse– and mixed–mode aerosol regime.

3.8. Shortwave Aerosol Radiative Forcing

The simulated shortwave aerosol radiative forcing (ARF), derived using observationally constrained OPAC and SBDART models, reveals a significant seasonal variability in aerosol radiative effects over the KLEF site. Figure 12 and Table 3 summarize the forcing values at the top of the atmosphere (TOAF), surface (SURF), and within the atmosphere (ATMF), along with atmospheric heating rates and radiative forcing efficiency (FE). The OPAC–simulated AOD₅₀₀ agrees well with MICROTOPS observations across all seasons. Black carbon (BC) concentrations also present a distinct seasonality, peaking in winter ($3.52 \mu\text{g m}^{-3}$) and lowering in monsoon ($1.19 \mu\text{g m}^{-3}$). Similarly, SSA remains low during winter (0.84) and pre–monsoon (0.83), indicating dominance of absorbing aerosols, whereas in monsoon SSA increases significantly (~ 0.97 – 0.98), reflecting predominance of scattering (sea salt, dust) aerosols [112].

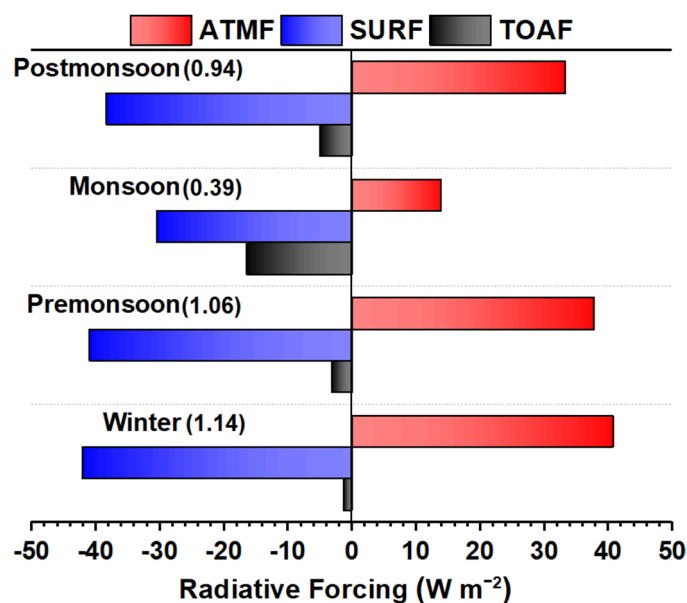


Figure 12. Seasonal–averaged variation in simulated aerosol radiative forcing (ARF in W m^{-2}) at top of atmosphere (TOAF), surface (SURF), and within the atmosphere (ATMF) along with the corresponding heating rates shown in the open brackets (K/day) estimated over the KLEF site for the entire study period.

Table 3. Estimated optical and radiative properties of aerosols obtained from OPAC and SBDART models at KLEF site.

Parameters → Period ↓	MCTPS AOD ₅₀₀	OPAC AOD ₅₀₀	BC ($\mu\text{g m}^{-3}$)	TOAF (W m^{-2})	SURF (W m^{-2})	ATMF (W m^{-2})	Heating Rate (K day^{-1})	Forcing Efficiency ($\text{W m}^{-2} \tau^{-1}$)
January	0.655	0.626	3.83	−1.23	−41.49	40.25	1.13	61.46
February	0.628	0.612	3.41	−1.32	−42.57	41.25	1.16	65.68
March	0.686	0.634	2.95	−1.75	−37.49	35.74	1.00	52.10
April	0.680	0.654	2.15	−1.74	−38.46	36.72	1.03	54.00
May	0.610	0.603	1.63	−5.95	−46.85	40.90	1.15	67.05
June	0.583	0.521	0.82	−15.75	−28.03	12.28	0.34	21.07
July	0.353	0.351	0.56	−14.96	−26.29	11.33	0.32	32.09
August	0.592	0.582	0.38	−13.87	−38.70	24.83	0.70	41.94
September	0.402	0.412	0.82	−21.16	−28.58	7.41	0.21	18.44
October	0.493	0.482	2.42	−7.25	−38.53	31.27	0.88	63.44
November	0.516	0.523	3.04	−3.19	−35.68	32.49	0.91	62.96
December	0.572	0.543	3.48	−4.35	−40.64	36.29	1.02	63.44
Winter	0.641	0.619	3.52	−1.28	−42.03	40.75	1.14	63.57
Pre-monsoon	0.659	0.630	2.54	−3.15	−40.93	37.79	1.06	57.72
Monsoon	0.482	0.467	0.69	−16.43	−30.40	13.96	0.39	28.39
Post-monsoon	0.527	0.516	3.33	−4.93	−38.28	33.35	0.94	63.28
Annual	0.577	0.558	2.52	−6.45	−37.91	31.46	0.88	53.24

Aerosols over the KLEF site cause substantial surface cooling throughout the year, with the strongest negative SURF forcing during winter and pre-monsoon (≈ -41 to -42 W m^{-2}), suggesting efficient attenuation of incoming solar radiation by aerosols [34,49,141]. In contrast, monsoon exhibits the weakest surface forcing (-30 W m^{-2}), consistent with lower aerosol loading (0.45) and dominance of scattering aerosols (SSA of 0.93) caused by the marine influence [112]. TOAF remains negative in all seasons, indicating net planetary cooling over southern rural India. The strongest TOAF cooling occurs during monsoon (-16 W m^{-2}), when enhanced aerosol scattering increases solar irradiance reflection back to space. During winter and pre-monsoon, TOAF is comparatively less negative (-1 to -5 W m^{-2}), reflecting partial compensation between scattering-induced cooling and atmospheric warming from absorbing aerosols such as BC [62,94,97,139].

The difference between TOAF and SURF defines the atmospheric forcing (ATMF), which remains positive throughout the year, indicating aerosol-induced atmospheric warming. ATMF peaks during winter (41 W m^{-2}) and pre-monsoon (38 W m^{-2}), corresponding to elevated concentrations of absorbing aerosols and BC under dry atmospheric conditions [127]. The winter atmospheric forcing of 41 W m^{-2} is nearly three times the monsoon value of 14 W m^{-2} , while the corresponding heating rate decreases from 1.1–1.2 to 0.3–0.4 K day^{-1} . This ~65–70% reduction in atmospheric heating during monsoon is consistent with the simultaneous decrease in aerosol loading and increase in SSA, demonstrating that both aerosol abundance and absorption characteristics jointly regulate the atmospheric radiative response, potentially affecting atmospheric stability, cloud evaporation, and regional circulation patterns [59]. Post-monsoon conditions show recovery in ATMF (33 W m^{-2}) and heating rate (0.8 K day^{-1}), associated with increased fine-mode absorbing aerosols from biomass burning and urban emissions under more stable atmospheric conditions [58].

The Forcing Efficiency (FE) also exhibits pronounced seasonal variability, with higher values in winter and post-monsoon, and lower ones in monsoon. This highlights the importance of aerosol chemical composition and optical properties, particularly SSA and asymmetry parameter (0.68–0.73), in determining the aerosol radiative efficiency [94,142]. Overall, aerosols over the KLEF site play a dual climatic role by simultaneously cooling the surface and warming the atmosphere. This radiative perturbation is strongest during the dry seasons and may significantly influence boundary-layer dynamics, cloud processes, and regional hydrological cycles [1,3]. The pronounced seasonal variability in forcing and

heating rates emphasizes the need for seasonally resolved aerosol optical properties in regional climate models to improve assessments of aerosol–climate interactions in south-east India. Overall, the quantitative seasonal contrasts demonstrate a coherent coupling between aerosol loading, particle size, transport regime, and radiative response at the KLEF site. The approximately 35% enhancement of AOD_{500} during pre-monsoon relative to monsoon, the ~57% higher AE during winter and pre-monsoon than monsoon, and the ~65–70% reduction in atmospheric heating during monsoon collectively indicate that seasonal meteorology and source composition exert strong controls on both aerosol optical characteristics and radiative effects. The consistency among AOD, AE, aerosol-type fractions, trajectory patterns, and radiative parameters provides converging evidence for the proposed seasonal aerosol regimes.

The radiative effects at KLEF also show an intermediate behavior compared with the sites listed in Table 2. The annual mean surface cooling at KLEF (-37.91 W m^{-2}), reaching approximately -41 to -42 W m^{-2} during winter and pre-monsoon, is stronger than that reported for relatively lower-aerosol semi-arid sites such as Anantapur and Kadapa. This stronger cooling is consistent with the comparatively higher aerosol loading at KLEF and the combined influence of fine-mode anthropogenic aerosols, absorbing carbonaceous particles, mineral dust, and regional aerosol transport. However, the surface cooling remains weaker than that reported for heavily polluted urban environments in the IGP, such as Lahore, where substantially higher aerosol loading and stronger absorbing particles contribute to enhanced radiative perturbation. These differences demonstrate that aerosol radiative effects are controlled not only by AOD, but also by aerosol size distribution, absorption characteristics, atmospheric moisture, and the prevailing topographic characteristics and albedo. The corresponding atmospheric forcing at KLEF (31.46 W m^{-2} annually), together with the seasonal atmospheric heating rates of approximately 1.1 – 1.2 K day^{-1} during winter and pre-monsoon, indicate that absorbing aerosols can substantially modify the atmospheric energy balance. Such aerosol-induced heating may influence boundary-layer stability, vertical mixing, convective development, and cloud formation, with potential implications for regional monsoon dynamics and precipitation. However, the present radiative-transfer simulations alone cannot establish a direct causal relationship between aerosol heating and precipitation; such relationships require further investigation using coupled regional atmospheric and climate models.

4. Limitations and Future Work

Despite the comprehensive observational and modeling framework adopted in this study, several limitations should be acknowledged. First, the observations were obtained from a single rural-suburban receptor site, which limits the spatial representativeness of the results for the broader southeast Indian region. Second, the MICROTOPS-II Sunphotometer provides column-integrated aerosol optical properties and therefore does not directly resolve the vertical distribution of aerosols. The assumed aerosol vertical profile used in the OPAC-SBDART simulations may consequently introduce uncertainty into the estimated radiative forcing and atmospheric heating rates. Third, the present study lacks direct in situ measurements of carbonaceous aerosol components, particularly black carbon and other carbonaceous species, which limits the ability to independently constrain the absorbing aerosol contribution and its source characteristics. In addition, PSCF and CWT provide potential source regions rather than direct quantitative chemical source apportionment, while the radiative-transfer estimates are subject to uncertainties associated with aerosol mixing state, vertical distribution, surface characteristics, and atmospheric profiles.

Future investigations should therefore extend observations through multi-site field campaigns covering rural, agricultural, urban, and coastal environments across southeast

India to better resolve regional aerosol gradients and transport pathways. The integration of ground-based Sunphotometer observations with vertically resolved lidar measurements and aircraft-based aerosol observations would provide improved information on aerosol layering, transport, and vertical optical properties. Concurrent in situ measurements of black carbon, organic carbon, and other chemical components would further strengthen source attribution and aerosol absorption estimates. Combining these observations with satellite products, high-resolution chemical transport models, and aerosol–cloud interaction measurements would provide a more comprehensive assessment of aerosol–radiation–cloud interactions and their potential influence on boundary-layer dynamics and monsoon variability over southeast India.

5. Conclusions

This study provides a comprehensive assessment of atmospheric aerosols over the rural environment of Koneru Lakshmaiah Education Foundation (KLEF), Andhra Pradesh, South India, using multi-year MICROTOPS-II Sunphotometer observations during 2021–2023. The results demonstrate that aerosol variability at this mixed rural–suburban receptor site is governed by the combined influence of local emissions, agricultural activities, regional and long-range transport, seasonal meteorology, and marine inflow. Beyond characterizing seasonal aerosol optical and radiative properties, current findings highlight the importance of such underrepresented rural environments for understanding regional aerosol transport, atmospheric heating, and aerosol–climate interactions over southeast India. The main findings are summarized as follows:

1. Aerosol loading peaked during the pre-monsoon season ($\text{AOD}_{500} \sim 0.65\text{--}0.70$) due to dust transport and local emissions, and remained elevated in winter ($\sim 0.55\text{--}0.65$) because of accumulated fine-mode anthropogenic pollution composed of the highest BC concentrations from various combustion activities. The lowest values occurred during monsoon ($\text{AOD}_{500} \sim 0.35\text{--}0.40$ in July) owing to efficient wet scavenging by precipitation.
2. $\text{AE}_{340\text{--}1020}$, PWV, and spectral curvature parameters showed distinct seasonal variations in aerosol particle size and mixing state. Winter and pre-monsoon exhibited higher AE values (1.30 ± 0.20 and 1.30 ± 0.24 , respectively) with negative a_2 (-0.45 and -0.22 , respectively), indicating fine-mode aerosol dominance. In contrast, lower AE (0.83 ± 0.37) was found in monsoon, associated with higher PWV content (4.35 ± 0.35 cm), near-zero to positive a_2 (0.05), and negative α' (-0.11), suggesting mixed/coarse-mode aerosols influenced by marine sea salt inflow, desert dust and hygroscopic growth.
3. Combined PSCF–CWT analysis revealed seasonally varying transport pathways, with continental and biomass-burning influences during winter and post-monsoon, dust transport in pre-monsoon, and moisture-rich marine air masses mixed with dust during monsoon.
4. Aerosol classification based on AOD_{500} and $\text{AE}_{340\text{--}1020}$ values indicated dominance of urban-industrial aerosols during winter (56.3%), pre-monsoon (50.5%), and post-monsoon (48.1%), whereas monsoon was characterized mainly by mixed-type aerosols (38.5%) and desert dust (25.5%).
5. Light attenuation by aerosols produced strong surface cooling (SURF) during winter and pre-monsoon (-41 to -42 W m^{-2}), along with pronounced atmospheric heating (ATMF) (38 to 41 W m^{-2} ; heating rate $\approx 1.1\text{--}1.2$ K day^{-1}) due to higher aerosol loading ($0.6\text{--}0.65$) and absorbing particles. During monsoon, weaker radiative effects ($\text{SURF} \approx -30$ W m^{-2} ; $\text{ATMF} \approx 14$ W m^{-2}) dominated due to lower aerosol loading and dominance of scattering aerosols.

The present observations provide localized aerosol optical constraints that can improve the representation of aerosol properties in regional climate and atmospheric chemistry models over southeast India. The pronounced seasonal differences in AOD, AE, SSA, and aerosol radiative forcing demonstrate that applying spatially uniform aerosol optical properties may not adequately represent the radiative influence of aerosols over rural–suburban environments. The site-specific aerosol optical characteristics derived in this study can therefore serve as observational benchmarks for model evaluation and parameterization, particularly for simulations of aerosol radiative effects, atmospheric heating, and aerosol–meteorology interactions during contrasting monsoon and dry-season conditions.

The seasonal source characteristics identified in this study also have implications for regional air-quality management. The coexistence of agricultural biomass-burning emissions with suburban industrial, transportation, and other anthropogenic sources indicates that effective mitigation cannot rely exclusively on urban emission-control strategies. Coordinated measures targeting crop-residue burning in surrounding agricultural areas together with industrial and transportation emissions in the suburban environment could provide greater benefits for reducing regional aerosol loading. Such co-control strategies are particularly important during the dry and post-monsoon seasons, when stable atmospheric conditions and regional transport can facilitate the accumulation and redistribution of fine-mode absorbing aerosols across rural areas.

The present study aligns with several United Nations Sustainable Development Goals (SDGs) by improving the understanding of aerosol characteristics, source regions, transport pathways, and their implications for air quality and climate. More specifically, the study contributes to SDG 3 (Good Health and Well-being) and SDG 11 (Sustainable Cities and Communities) by providing scientific evidence useful for air-quality management and air pollution-control strategies in urban and regional environments. The assessment of aerosol optical properties and estimation of radiative forcing further supports SDG 13 (Climate Action), as aerosols play a significant role in atmospheric radiation balance, climate forcing, and regional climate variability.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17090876/s1>, Table S1: Summary of quality-controlled MICROTOPS-II Sunphotometer observations at the KLEF site during 2021–2023, showing the total number of valid observation days and corresponding retained data counts for different months, seasons, and years. The statistics represent observations remaining after excluding cloudy, rainy, partly cloudy, and otherwise unsuitable measurements, providing an assessment of the temporal availability and completeness of the final aerosol dataset.; Table S2: Monthly and annual statistical summary of aerosol optical parameters (AOD₅₀₀, AE_{340–1020}, and PWV), showing mean, median, minimum, and maximum values during the study period at the KLEF site [29,30,95,96,102].

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AE	Ångström Exponent
AE–33	Aethalometer Model AE–33
AN	Afternoon
AOD	Aerosol Optical Depth
AOD500	Aerosol Optical Depth at 500 nm
ARF	Aerosol Radiative Forcing
ASYM	Asymmetry Parameter
ATM	Atmosphere
BC	Black Carbon
BB	Biomass Burning
CM	Clean Maritime
CWT	Concentration Weighted Trajectory
DB	Deep Blue
DD	Desert Dust
DEM	Digital Elevation Model
DISORT	Discrete Ordinate Radiative Transfer
DT	Dark Target
DTB	Dark Target and Deep Blue
FN	Forenoon
FMF	Fine Mode Fraction
GHG	Greenhouse Gas
GMT	Greenwich Mean Time
HYSPLIT	Hybrid Single–Particle Lagrangian Integrated Trajectory Model
IGP	Indo–Gangetic Plain
IST	Indian Standard Time
JF	January–February
JJAS	June–July–August–September
KLEF	Koneru Lakshmaiah Education Foundation
LPM	Liters Per Minute
LULC	Land Use Land Cover
MAM	March–April–May
MISR	Multi–angle Imaging SpectroRadiometer

MODIS	Moderate Resolution Imaging Spectroradiometer
MW	Megawatt
MXD	Mixed Aerosols
NH	National Highway
OND	October–November–December
OPAC	Optical Properties of Aerosols and Clouds
PC	Polluted Continental
PM	Particulate Matter
PSCF	Potential Source Contribution Function
PWV	Precipitable Water Vapor
RH	Relative Humidity
RTM	Radiative Transfer Model
SBDART	Santa Barbara DISORT Atmospheric Radiative Transfer
SD	Standard Deviation
SE	Southeast
SM	Supplementary Material
SRTM	Shuttle Radar Topography Mission
SSA	Single Scattering Albedo
SUR	Surface
TOA	Top of Atmosphere
UI	Urban–Industrial
USGS	United States Geological Survey
UV	Ultraviolet

References

1. Satheesh, S.K.; Ramanathan, V. Large Differences in Tropical Aerosol Forcing at the Top of the Atmosphere and Earth's Surface. *Nature* **2000**, *405*, 60–63. [CrossRef] [PubMed]
2. Satheesh, S.K.; Ramanathan, V.; Holben, B.N.; Moorthy, K.K.; Loeb, N.G.; Maring, H.; Prospero, J.M.; Savoie, D. Chemical, Microphysical, and Radiative Effects of Indian Ocean Aerosols. *J. Geophys. Res. Atmos.* **2002**, *107*, AAC 20–1–AAC 20–13. [CrossRef]
3. Ramachandran, S.; Ansari, K.; Cherian, R. Air Pollution to Atmospheric Warming: Effects of Increasing Anthropogenic Aerosols on South Asia's Climate. *Earth Syst. Environ.* **2026**, *10*, 2047–2072. [CrossRef]
4. Krishnaveni, A.S.; Madhavan, B.L.; Ratnam, M.V. Advancing Global Aerosol Classification: Source–Compositional Typology and Variability from 30 Years (1993–2024) of AERONET Observations. *Sci. Total Environ.* **2025**, *1007*, 180918. [CrossRef] [PubMed]
5. Kaufman, Y.; Tanré, D.; Gordon, H.; Nakajima, T.; Lenoble, J.; Frouin, R.; Grassl, H.; Herman, B.; King, M.; Teillet, P. Passive Remote Sensing of Tropospheric Aerosol and Atmospheric Correction for the Aerosol Effect. *J. Geophys. Res. Atmos.* **1997**, *102*, 16815–16830. [CrossRef]
6. Li, J.; He, Q.; Ge, X. Spatiotemporal Distribution of Aerosols over the Tibet Plateau and Tarim Basin (1980–2020). *J. Clean. Prod.* **2022**, *374*, 133958. [CrossRef]
7. Rosenfeld, D.; Andreae, M.O.; Asmi, A.; Chin, M.; De Leeuw, G.; Donovan, D.P.; Kahn, R.; Kinne, S.; Kivekäs, N.; Kulmala, M. Global Observations of Aerosol–cloud–precipitation–climate Interactions. *Rev. Geophys.* **2014**, *52*, 750–808. [CrossRef]
8. Seinfeld, J.H.; Bretherton, C.; Carslaw, K.S.; Coe, H.; DeMott, P.J.; Dunlea, E.J.; Feingold, G.; Ghan, S.; Guenther, A.B.; Kahn, R.; et al. Improving Our Fundamental Understanding of the Role of Aerosol–cloud Interactions in the Climate System. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 5781–5790. [CrossRef] [PubMed]
9. Dey, S.; Di Girolamo, L. A Decade of Change in Aerosol Properties over the Indian Subcontinent. *Geophys. Res. Lett.* **2011**, *38*, L14811, Correction in *Geophys. Res. Lett.* **2021** *11*, L16899, <https://doi.org/10.1029/2011GL049191>. [CrossRef]
10. Kumar, K.R.; Kang, N.; Yin, Y. Classification of Key Aerosol Types and Their Frequency Distributions Based on Satellite Remote Sensing Data at an Industrially Polluted City in the Yangtze River Delta, China. *Int. J. Climatol.* **2018**, *38*, 320–336. [CrossRef]
11. Ansari, K.; Ramachandran, S. Radiative Effects of Absorbing Aerosol Types over South Asia. *Sci. Total Environ.* **2023**, *858*, 159969. [CrossRef] [PubMed]
12. Althaf, P.; Kannamadugu, H.B.S.; Kumar, K.R. Hotspot Analysis and Long–Term Trends of Absorbing Aerosol Index from Dust Emissions Measured by the Ozone Monitoring Instrument at Different Urban Locations in India during 2005–2018. *Atmos. Environ.* **2022**, *272*, 118933. [CrossRef]

13. Althaf, P.; Kumar, K.R.; Kannemadugu, H.B.S. Aerosol Optical Depth over the Andhra Pradesh State in South India from Reanalysis Data: Spatiotemporal Variabilities and Machine Learning Approach. *Earth Syst. Environ.* **2025**, *9*, 2797–2821. [\[CrossRef\]](#)
14. Althaf, P.; Devi, N.S.M.P.L.; Kumar, K.R. Spatiotemporal Changes of Pollutant Concentrations in South India during COVID–19 Lockdown Using Ground and Satellite–Based Data: A Comparative Analysis from the Machine Learning Model. *Water. Air. Soil Pollut.* **2025**, *236*, 189. [\[CrossRef\]](#)
15. Khamala, G.W.; Makokha, J.W.; Boiyo, R.; Kumar, K.R. Spatiotemporal Analysis of Absorbing Aerosols and Radiative Forcing over Environmentally Distinct Stations in East Africa during 2001–2018. *Sci. Total Environ.* **2023**, *864*, 161041. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Berhane, S.A.; Althaf, P.; Kumar, K.R.; Bu, L.; Yao, M. A Comprehensive Analysis of AOD and Its Species from Reanalysis Data over the Middle East and North Africa Regions: Evaluation of Model Performance Using Machine Learning Techniques. *Earth Syst. Environ.* **2024**, *9*, 3683–3708. [\[CrossRef\]](#)
17. Moorthy, K.K.; Sunilkumar, S.V.; Pillai, P.S.; Parameswaran, K.; Nair, P.R.; Ahmed, Y.N.; Ramgopal, K.; Narasimhulu, K.; Reddy, R.R.; Vinoj, V.; et al. Wintertime Spatial Characteristics of Boundary Layer Aerosols over Peninsular India. *J. Geophys. Res. Atmos.* **2005**, *110*, D08207. [\[CrossRef\]](#)
18. Sridhar, H.S.; Devi, N.S.M.P.L.; Uma, G.; Saha, A.; Chu, Y.-H.; Brahmanandam, P.S. Spatiotemporal Dynamics of Fine Particulate Matter (PM_{2.5}) over Different Locations of Andhra Pradesh, India. *Sustainability* **2026**, *18*, 4338. [\[CrossRef\]](#)
19. Verma, S.; Venkataraman, C.; Boucher, O.; Ramachandran, S. Source Evaluation of Aerosols Measured during the Indian Ocean Experiment Using Combined Chemical Transport and Back Trajectory Modeling. *J. Geophys. Res. Atmos.* **2007**, *112*, D11210. [\[CrossRef\]](#)
20. Mukhopadhyay, S.; Ningombam, S.S.; Amoghavarsha, A.V.; Madhavan, B.L.; Eck, T.F.; Dumka, U.C.; Khatri, P.; Gupta, P. Classification of Global Aerosol Types and Its Radiative Effects Using Aerosol Robotic Network (AERONET) Data. *Atmos. Environ.* **2025**, *362*, 121530. [\[CrossRef\]](#)
21. Bellouin, N.; Davies, W.; Shine, K.P.; Quaas, J.; Mülmenstädt, J.; Forster, P.M.; Smith, C.; Lee, L.; Regayre, L.; Brasseur, G.; et al. Radiative Forcing of Climate Change from the Copernicus Reanalysis of Atmospheric Composition. *Earth Syst. Sci. Data* **2020**, *12*, 1649–1677. [\[CrossRef\]](#)
22. Nyasulu, M.; Thulu, F.G.D.; Alexander, F. An Assessment of Four Decades Atmospheric PM_{2.5} Trends in Urban Locations over Southern Africa Using MERRA–2 Reanalysis. *Air Qual. Atmos. Health* **2023**, *16*, 2063–2084. [\[CrossRef\]](#)
23. Khamala, G.W.; Makokha, J.W.; Wanyera, C.; Kumar, K.R.; Almazroui, M.; Althaf, P.; Tariq, A. Vertical Distribution of Cloud Area Fraction and Associated Cloud Radiative Effects over East Africa Using MERRA–2 Reanalysis and CERES (2000–2025) Data. *Earth Syst. Environ.* **2026**. Available online: <https://link.springer.com/article/10.1007/s41748-026-01266-5> (accessed on 30 August 2026).
24. Collaud Coen, M.; Andrews, E.; Alastuey, A.; Arsov, T.P.; Backman, J.; Brem, B.T.; Bukowiecki, N.; Couret, C.; Eleftheriadis, K.; Flentje, H.; et al. Multidecadal Trend Analysis of in Situ Aerosol Radiative Properties around the World. *Atmos. Chem. Phys.* **2020**, *20*, 8867–8908. [\[CrossRef\]](#)
25. Kok, J.F.; Storelvmo, T.; Karydis, V.A.; Adebisi, A.A.; Mahowald, N.M.; Evan, A.T.; He, C.; Leung, D.M. Mineral Dust Aerosol Impacts on Global Climate and Climate Change. *Nat. Rev. Earth Environ.* **2023**, *4*, 71–86. [\[CrossRef\]](#)
26. Suresh Babu, S.; Krishna Moorthy, K.; Satheesh, S. *Temporal Heterogeneity in Aerosol Characteristics and the Resulting Radiative Impacts at a Tropical Coastal Station–Part 2: Direct Short Wave Radiative Forcing*; Copernicus Publications: Göttingen, Germany, 2007; Volume 25, pp. 2309–2320.
27. Kumar, K.R.; Narasimhulu, K.; Balakrishnaiah, G.; Reddy, B.S.K.; Gopal, K.R.; Reddy, R.R.; Satheesh, S.K.; Moorthy, K.K.; Babu, S.S. Characterization of Aerosol Black Carbon over a Tropical Semi–Arid Region of Anantapur, India. *Atmos. Res.* **2011**, *100*, 12–27. [\[CrossRef\]](#)
28. Akkiraju, B.; Kalluri, R.O.R.; Gugamsetty, B.; Kotalo, R.G.; Thotli, L.R.; Virupakshappa, U.K.; Lingala, S.S.R.; Kuncham, N. Measurements of Aerosol Optical Depth and Equivalent Black Carbon Aerosols over a Semi–Arid Station in Southern India. *Environ. Dev. Sustain.* **2023**, *25*, 7903–7925. [\[CrossRef\]](#)
29. Morys, M.; Mims, F.M., III; Hagerup, S.; Anderson, S.E.; Baker, A.; Kia, J.; Walkup, T. Design, Calibration, and Performance of MICROTOS II Handheld Ozone Monitor and Sun Photometer. *J. Geophys. Res. Atmos.* **2001**, *106*, 14573–14582. [\[CrossRef\]](#)
30. Ichoku, C.; Remer, L.A.; Kaufman, Y.J.; Levy, R.; Chu, D.A.; Tanré, D.; Holben, B.N. MODIS Observation of Aerosols and Estimation of Aerosol Radiative Forcing over Southern Africa during SAFARI 2000. *J. Geophys. Res. Atmos.* **2003**, *108*. [\[CrossRef\]](#)
31. Kharol, S.K.; Badarinath, K.V.S.; Sharma, A.R.; Kaskaoutis, D.G.; Kambezidis, H.D. Multiyear Analysis of Terra/Aqua MODIS Aerosol Optical Depth and Ground Observations over Tropical Urban Region of Hyderabad, India. *Atmos. Environ.* **2011**, *45*, 1532–1542. [\[CrossRef\]](#)
32. More, S.; Kumar, P.P.; Gupta, P.; Devara, P.C.S.; Aher, G.R. Comparison of Aerosol Products Retrieved from AERONET, MICROTOS and MODIS over a Tropical Urban City, Pune, India. *Aerosol Air Qual. Res.* **2013**, *13*, 107–121. [\[CrossRef\]](#)
33. Bilal, M.; Nazeer, M.; Nichol, J.E. Validation of MODIS and VIIRS Derived Aerosol Optical Depth over Complex Coastal Waters. *Atmos. Res.* **2017**, *186*, 43–50. [\[CrossRef\]](#)

34. Viswanatha Vachaspati, C.; Reshma Begam, G.; Nazeer Ahammed, Y.; Raghavendra Kumar, K.; Reddy, R.R. Characterization of Aerosol Optical Properties and Model Computed Radiative Forcing over a Semi-Arid Region, Kadapa in India. *Atmos. Res.* **2018**, *209*, 36–49. [\[CrossRef\]](#)
35. Verma, S.; Prakash, D.; Soni, M.; Ram, K. Atmospheric Aerosols Monitoring: Ground and Satellite-Based Instruments. In *Advances in Environmental Monitoring and Assessment*; IntechOpen: London, UK, 2019; ISBN 978-1-83881-010-8.
36. Srivastava, A.K.; Ram, K.; Singh, S.; Kumar, S.; Tiwari, S. Aerosol Optical Properties and Radiative Effects over Manora Peak in the Himalayan Foothills: Seasonal Variability and Role of Transported Aerosols. *Sci. Total Environ.* **2015**, *502*, 287–295. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Schuster, G.L.; Dubovik, O.; Holben, B.N. Angstrom Exponent and Bimodal Aerosol Size Distributions. *J. Geophys. Res. Atmos.* **2006**, *111*. [\[CrossRef\]](#)
38. Kaskaoutis, D.G.; Kambezidis, H.D. The Diffuse-to-Global and Diffuse-to-Direct-Beam Spectral Irradiance Ratios as Turbidity Indexes in an Urban Environment. *J. Atmos. Sol.-Terr. Phys.* **2009**, *71*, 246–256. [\[CrossRef\]](#)
39. Kumar, K.R.; Boiyi, R.; Khan, R.; Kang, N.; Yu, X.; Sivakumar, V.; Griffith, D.; Devi, N.L. Multi-Year Analysis of Aerosol Optical Properties and Implications to Radiative Forcing over Urban Pretoria, South Africa. *Theor. Appl. Climatol.* **2020**, *141*, 343–357. [\[CrossRef\]](#)
40. Ramachandran, S.; Rupakheti, M. Aerosol Pollution across the Indo-Gangetic Plain and the Himalayas: Seasonal Patterns and Implications for Air Quality and Climate. *Air Qual. Atmos. Health* **2026**, *19*, 42. [\[CrossRef\]](#)
41. Lawrence, M.G.; Lelieveld, J. Atmospheric Pollutant Outflow from Southern Asia: A Review. *Atmos. Chem. Phys.* **2010**, *10*, 11017–11096. [\[CrossRef\]](#)
42. Krishna Moorthy, K.; Suresh Babu, S.; Manoj, M.R.; Satheesh, S.K. Buildup of Aerosols over the Indian Region. *Geophys. Res. Lett.* **2013**, *40*, 1011–1014. [\[CrossRef\]](#)
43. Khan, R.; Kumar, K.R.; Zhao, T. The Climatology of Aerosol Optical Thickness and Radiative Effects in Southeast Asia from 18-Years of Ground-Based Observations. *Environ. Pollut.* **2019**, *254*, 113025. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Srivastava, A.; Bisht, D.; Singh, S.; Kishore, N.; Soni, V.; Singh, S.; Tiwari, S. Scattering and Absorption Characteristics of Aerosols at an Urban Megacity over IGB: Implications to Radiative Forcing. *Atmos. Res.* **2018**, *205*, 107–117. [\[CrossRef\]](#)
45. Raul, S.; Dutta, M.; Mukherjee, S.; Chatterjee, A. Decadal Shifts in Aerosol Hotspots and Source Attribution over IGP, North-East India and Himalayas: A 25-Year (2000–2024) Study. *Atmos. Environ.* **2026**, *369*, 121810. [\[CrossRef\]](#)
46. Singh, R.P.; Dey, S.; Tripathi, S.N.; Tare, V.; Holben, B. Variability of Aerosol Parameters over Kanpur, Northern India. *J. Geophys. Res. Atmos.* **2004**, *109*. [\[CrossRef\]](#)
47. Lodhi, N.K.; Beegum, S.N.; Singh, S.; Kumar, K. Aerosol Climatology at Delhi in the Western Indo-Gangetic Plain: Microphysics, Long-term Trends, and Source Strengths. *J. Geophys. Res. Atmos.* **2013**, *118*, 1361–1375. [\[CrossRef\]](#)
48. Sharma, M.; Kaskaoutis, D.G.; Singh, R.P.; Singh, S. Seasonal Variability of Atmospheric Aerosol Parameters over Greater Noida Using Ground Sunphotometer Observations. *Aerosol Air Qual. Res.* **2014**, *14*, 608–622. [\[CrossRef\]](#)
49. Tiwari, S.; Dumka, U.C.; Hopke, P.K.; Tunved, P.; Srivastava, A.K.; Bisht, D.S.; Chakrabarty, R.K. Atmospheric Heating Due to Black Carbon Aerosol during the Summer Monsoon Period over Ballia: A Rural Environment over Indo-Gangetic Plain. *Atmos. Res.* **2016**, *178–179*, 393–400. [\[CrossRef\]](#)
50. Pandey, S.K.; Bakshi, H.; Vinoj, V. Recent Changes in Dust and Its Impact on Aerosol Trends over the Indo-Gangetic Plain (IGP). In *Proceedings of the Remote Sensing of the Atmosphere, Clouds, and Precipitation VI*; Im, E., Kumar, R., Yang, S., Eds.; SPIE: Bellingham, WA, USA, 2016; Volume 9876, p. 98761Z.
51. Shrestha, S.; Peel, M.C.; Moore, G.A. Development of a Regression Model for Estimating Daily Radiative Forcing Due to Atmospheric Aerosols from Moderate Resolution Imaging Spectrometers (MODIS) Data in the Indo Gangetic Plain (IGP). *Atmosphere* **2018**, *9*, 405. [\[CrossRef\]](#)
52. Ramachandran, S.; Kedia, S.; Srivastava, R. Aerosol Optical Depth Trends over Different Regions of India. *Atmos. Environ.* **2012**, *49*, 338–347. [\[CrossRef\]](#)
53. Moorthy, K.K.; Satheesh, S.; Babu, S.S.; Dutt, C. Integrated Campaign for Aerosols, Gases and Radiation Budget (ICARB): An Overview. *J. Earth Syst. Sci.* **2008**, *117*, 243–262. [\[CrossRef\]](#)
54. Priji, S.S.; Suresh Babu, S.; Lakshmi, N.B.; Satheesh, S.K.; Krishna Moorthy, K. Meridional Gradients in Aerosol Vertical Distribution over Indian Mainland: Observations and Model Simulations. *Atmos. Environ.* **2016**, *125*, 337–345. [\[CrossRef\]](#)
55. Kuttippurath, J.; Patel, V.K.; Roy, R.; Kumar, P. Sources, Variability, Long-Term Trends, and Radiative Forcing of Aerosols in the Arctic: Implications for Arctic Amplification. *Environ. Sci. Pollut. Res.* **2024**, *31*, 1621–1636. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Badarinath, K.V.S.; Kharol, S.K.; Sharma, A.R.; Prasad, V.K. Analysis of Aerosol and Carbon Monoxide Characteristics over Arabian Sea during Crop Residue Burning Period in the Indo-Gangetic Plains Using Multi-Satellite Remote Sensing Datasets. *J. Atmos. Sol.-Terr. Phys.* **2009**, *71*, 1267–1276. [\[CrossRef\]](#)

57. Ratnam, M.V.; Prasad, P.; Raman, M.R.; Ravikiran, V.; Rao, S.V.B.; Murthy, B.K.; Jayaraman, A. Role of Dynamics on the Formation and Maintenance of the Elevated Aerosol Layer during Monsoon Season over South–East Peninsular India. *Atmos. Environ.* **2018**, *188*, 43–49. [\[CrossRef\]](#)
58. Singh, P.; Vaishya, A.; Rastogi, S.; Babu, S.S. Seasonal Heterogeneity in Aerosol Optical Properties over the Subtropical Humid Region of Northern India. *J. Atmos. Sol.–Terr. Phys.* **2020**, *201*, 105246. [\[CrossRef\]](#)
59. Thomas, A.; Sarangi, C.; Kanawade, V.P. Recent Increase in Winter Hazy Days over Central India and the Arabian Sea. *Sci. Rep.* **2019**, *9*, 17406. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Kant, S.; Sarangi, C.; Wilcox, E.M. Aerosol Processes Perturb Cloud Trends over Bay of Bengal: Observational Evidence. *npj Clim. Atmos. Sci.* **2023**, *6*, 132. [\[CrossRef\]](#)
61. Mohandoss, R.; Jain, C.D.; Madhavan, B.; Ratnam, M.V. Spectroscopic and Chemical Compositional Analysis of the Atmospheric Aerosols in Urban and Rural Tropical Environment of Southern India. *Atmos. Environ.* **2025**, *360*, 121431. [\[CrossRef\]](#)
62. Babu, S.S.; Manoj, M.R.; Moorthy, K.K.; Gogoi, M.M.; Nair, V.S.; Kompalli, S.K.; Satheesh, S.K.; Niranjana, K.; Ramagopal, K.; Bhuyan, P.K.; et al. Trends in Aerosol Optical Depth over Indian Region: Potential Causes and Impact Indicators. *J. Geophys. Res. Atmos.* **2013**, *118*, 11,794–11,806. [\[CrossRef\]](#)
63. Joshi, H.; Naja, M.; Srivastava, P.; Gupta, T.; Gogoi, M.M.; Suresh Babu, S. Long–Term Trends in Black Carbon and Aerosol Optical Depth Over the Central Himalayas: Potential Causes and Implications. *Front. Earth Sci.* **2022**, *10*. [\[CrossRef\]](#)
64. Niranjana, K.; Sreekanth, V.; Madhavan, B.; Krishna Moorthy, K. Aerosol Physical Properties and Radiative Forcing at the Outflow Region from the Indo–Gangetic Plains during Typical Clear and Hazy Periods of Wintertime. *Geophys. Res. Lett.* **2007**, *34*. [\[CrossRef\]](#)
65. Tiwari, S.; Kaskaoutis, D.; Soni, V.K.; Dev Attri, S.; Singh, A.K. Aerosol Columnar Characteristics and Their Heterogeneous Nature over Varanasi, in the Central Ganges Valley. *Environ. Sci. Pollut. Res.* **2018**, *25*, 24726–24745. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Alam, K.; Trautmann, T.; Blaschke, T.; Majid, H. Aerosol Optical and Radiative Properties during Summer and Winter Seasons over Lahore and Karachi. *Atmos. Environ.* **2012**, *50*, 234–245. [\[CrossRef\]](#)
67. Kumar, K.R.; Kang, N.; Sivakumar, V.; Griffith, D. Temporal Characteristics of Columnar Aerosol Optical Properties and Radiative Forcing (2011–2015) Measured at AERONET’s Pretoria_CSIR_DPSS Site in South Africa. *Atmos. Environ.* **2017**, *165*, 274–289. [\[CrossRef\]](#)
68. Adesina, A.J.; Piketh, S.; Kanike, R.K.; Venkataraman, S. Characteristics of Columnar Aerosol Optical and Microphysical Properties Retrieved from the Sun Photometer and Its Impact on Radiative Forcing over Skukuza (South Africa) during 1999–2010. *Environ. Sci. Pollut. Res.* **2017**, *24*, 16160–16171. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Boiyo, R.; Kumar, K.R.; Zhao, T.; Guo, J. A 10–year Record of Aerosol Optical Properties and Radiative Forcing over Three Environmentally Distinct AERONET Sites in Kenya, East Africa. *J. Geophys. Res. Atmos.* **2019**, *124*, 1596–1617. [\[CrossRef\]](#)
70. Sangura, M.T.; Althaf, P.; Makokha, J.W.; Boiyo, R.; Kumar, K.R. Estimation and Model Performance of Aerosol Radiative Forcing from Radiative Transfer Models Using the AERONET Data over Kenya, East Africa. *Adv. Space Res.* **2025**, *75*, 481–496. [\[CrossRef\]](#)
71. Aruna, K.; Lakshmi Kumar, T.V.; Krishna Murthy, B.V.; Babu, S.S.; Ratnam, M.V.; Rao, D.N. Short Wave Aerosol Radiative Forcing Estimates over a Semi Urban Coastal Environment in South–East India and Validation with Surface Flux Measurements. *Atmos. Environ.* **2016**, *125*, 418–428. [\[CrossRef\]](#)
72. Prasad, P.; Roja Raman, M.; Venkat Ratnam, M.; Chen, W.–N.; Vijaya Bhaskara Rao, S.; Gogoi, M.M.; Kompalli, S.K.; Sarat Kumar, K.; Suresh Babu, S. Characterization of Atmospheric Black Carbon over a Semi–Urban Site of Southeast India: Local Sources and Long–Range Transport. *Atmos. Res.* **2018**, *213*, 411–421. [\[CrossRef\]](#)
73. Dumka, U.; Kaskaoutis, D.; Sagar, R.; Chen, J.; Singh, N.; Tiwari, S. First Results from Light Scattering Enhancement Factor over Central Indian Himalayas during GVAX Campaign. *Sci. Total Environ.* **2017**, *605*, 124–138. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Sinha, P.; Manchanda, R.; Kaskaoutis, D.; Kumar, Y.; Sreenivasan, S. Seasonal Variation of Surface and Vertical Profile of Aerosol Properties over a Tropical Urban Station Hyderabad, India. *J. Geophys. Res. Atmos.* **2013**, *118*, 749–768. [\[CrossRef\]](#)
75. Begam, G.R.; Vachaspati, C.V.; Ahammed, Y.N.; Kumar, K.R.; Reddy, R.R.; Sharma, S.K.; Saxena, M.; Mandal, T.K. Seasonal Characteristics of Water–Soluble Inorganic Ions and Carbonaceous Aerosols in Total Suspended Particulate Matter at a Rural Semi–Arid Site, Kadapa (India). *Environ. Sci. Pollut. Res.* **2017**, *24*, 1719–1734. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Varaprasad, V.; Kanawade, V.P.; Narayana, A.C. Spatio–Temporal Variability of near–Surface Air Pollutants at Four Distinct Geographical Locations in Andhra Pradesh State of India. *Environ. Pollut.* **2021**, *268*, 115899. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Gokul, P.R.; Mathew, A.; Bhosale, A.; Nair, A.T. Spatio–Temporal Air Quality Analysis and PM_{2.5} Prediction over Hyderabad City, India Using Artificial Intelligence Techniques. *Ecol. Inform.* **2023**, *76*, 102067. [\[CrossRef\]](#)
78. Kaskaoutis, D.; Badarinath, K.; Kumar Kharol, S.; Rani Sharma, A.; Kambezidis, H. Variations in the Aerosol Optical Properties and Types over the Tropical Urban Site of Hyderabad, India. *J. Geophys. Res. Atmos.* **2009**, *114*. [\[CrossRef\]](#)
79. Panda, U.; Boopathy, R.; Gadhavi, H.S.; Renuka, K.; Gunthe, S.S.; Das, T. Metals in Coarse Ambient Aerosol as Markers for Source Apportionment and Their Health Risk Assessment over an Eastern Coastal Urban Atmosphere in India. *Environ. Monit. Assess.* **2021**, *193*, 311. [\[CrossRef\]](#) [\[PubMed\]](#)

80. Dumka, U.C.; Kaskaoutis, D.G.; Khatrri, P.; Ningombam, S.S.; Sheoran, R.; Jade, S.; Shrungeshwara, T.S.; Rupakheti, M. Water Vapour Characteristics and Radiative Effects at High–Altitude Himalayan Sites. *Atmos. Pollut. Res.* **2022**, *13*, 101303. [\[CrossRef\]](#)
81. Kaskaoutis, D.; Kosmopoulos, P.; Kambezidis, H.; Nastos, P. Aerosol Climatology and Discrimination of Different Types over Athens, Greece, Based on MODIS Data. *Atmos. Environ.* **2007**, *41*, 7315–7329. [\[CrossRef\]](#)
82. Kumar, K.R.; Sivakumar, V.; Reddy, R.R.; Gopal, K.R.; Adesina, A.J. Inferring Wavelength Dependence of AOD and Ångström Exponent over a Sub–Tropical Station in South Africa Using AERONET Data: Influence of Meteorology, Long–Range Transport and Curvature Effect. *Sci. Total Environ.* **2013**, *461–462*, 397–408. [\[CrossRef\]](#) [\[PubMed\]](#)
83. Kalluri, R.O.R.; Kotalo, R.G. Identification of Different Aerosol Types over a Semi–Arid Location in Southern Peninsular India Retrieved from the CALIPSO. In *Atmospheric Remote Sensing*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 139–156.
84. Eck, T.F.; Holben, B.; Reid, J.; Dubovik, O.; Smirnov, A.; O’neill, N.; Slutsker, I.; Kinne, S. Wavelength Dependence of the Optical Depth of Biomass Burning, Urban, and Desert Dust Aerosols. *J. Geophys. Res. Atmos.* **1999**, *104*, 31333–31349. [\[CrossRef\]](#)
85. Kumar, K.R.; Sivakumar, V.; Reddy, R.R.; Gopal, K.R.; Adesina, A.J. Identification and Classification of Different Aerosol Types over a Subtropical Rural Site in Mpumalanga, South Africa: Seasonal Variations as Retrieved from the AERONET Sunphotometer. *Aerosol Air Qual. Res.* **2014**, *14*, 108–123. [\[CrossRef\]](#)
86. Gobbi, G.P.; Kaufman, Y.J.; Koren, I.; Eck, T.F. Classification of Aerosol Properties Derived from AERONET Direct Sun Data. *Atmos. Chem. Phys.* **2007**, *7*, 453–458. [\[CrossRef\]](#)
87. Alam, K.; Shaheen, K.; Blaschke, T.; Chishtie, F.; Khan, H.U.; Haq, B.S. Classification of Aerosols in an Urban Environment on the Basis of Optical Measurements. *Aerosol Air Qual. Res.* **2016**, *16*, 2535–2549. [\[CrossRef\]](#)
88. Khan, R.; Kumar, K.R.; Zhao, T.; Ali, G. The Contribution of Different Aerosol Types to Direct Radiative Forcing over Distinct Environments of Pakistan Inferred from the AERONET Data. *Environ. Res. Lett.* **2020**, *15*, 114062. [\[CrossRef\]](#)
89. Kolhe, A.R.; Aher, G.R.; Soyam, P.S.; Ralegankar, S.D.; Kedia, S.; Chaudhari, L.M.; Antad, V.V.; Ghude, S.D.; Safai, P.D.; Chakane, S.D.; et al. Aerosol Opto–Physical Properties: Temporal Variation, Aerosol Type Discrimination and Source Identification. *Aerosol Air Qual. Res.* **2022**, *22*, 220104. [\[CrossRef\]](#)
90. Vadde, S.; Kalluri, R.O.R.; Gugamsetty, B.; Kotalo, R.G.; Kajjer Virupakshappa, U.; Akkiraju, B.; Thotli, L.R.; Lingala, S.S.R.; Rapole, J.K. Classifying Aerosol Type Using in Situ and Satellite Observations over a Semi–Arid Station, Anantapur, from Southern Peninsular India. *Adv. Space Res.* **2023**, *72*, 1109–1122. [\[CrossRef\]](#)
91. Stein, A.F.; Draxler, R.R.; Rolph, G.D.; Stunder, B.J.B.; Cohen, M.D.; Ngan, F. NOAA’s HYSPLIT Atmospheric Transport and Dispersion Modeling System. *Bull. Am. Meteorol. Soc.* **2015**, *96*, 2059–2077. [\[CrossRef\]](#)
92. Wang, Y.Q.; Zhang, X.Y.; Draxler, R.R. TrajStat: GIS–Based Software That Uses Various Trajectory Statistical Analysis Methods to Identify Potential Sources from Long–Term Air Pollution Measurement Data. *Environ. Model. Softw.* **2009**, *24*, 938–939. [\[CrossRef\]](#)
93. Dimitriou, K.; Grivas, G.; Liakakou, E.; Gerasopoulos, E.; Mihalopoulos, N. Assessing the Contribution of Regional Sources to Urban Air Pollution by Applying 3D–PSCF Modeling. *Atmos. Res.* **2021**, *248*, 105187. [\[CrossRef\]](#)
94. Dumka, U.C.; Saheb, S.D.; Kaskaoutis, D.G.; Kant, Y.; Mitra, D. Columnar Aerosol Characteristics and Radiative Forcing over the Doon Valley in the Shivalik Range of Northwestern Himalayas. *Environ. Sci. Pollut. Res.* **2016**, *23*, 25467–25484. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Hess, M.; Koepke, P.; Schult, I. Optical Properties of Aerosols and Clouds: The Software Package OPAC. *Bull. Am. Meteorol. Soc.* **1998**, *79*, 831–844. [\[CrossRef\]](#)
96. Ricchiazzi, P.; Yang, S.; Gautier, C.; Sowle, D. SBDART: A Research and Teaching Software Tool for Plane–Parallel Radiative Transfer in the Earth’s Atmosphere. *Bull. Am. Meteorol. Soc.* **1998**, *79*, 2101–2114. [\[CrossRef\]](#)
97. Sinha, P.; Dumka, U.; Manchanda, R.; Kaskaoutis, D.; Sreenivasan, S.; Krishna Moorthy, K.; Suresh Babu, S. Contrasting Aerosol Characteristics and Radiative Forcing over Hyderabad, India Due to Seasonal Mesoscale and Synoptic–scale Processes. *Q. J. R. Meteorol. Soc.* **2013**, *139*, 434–450. [\[CrossRef\]](#)
98. Pandithurai, G.; Dipu, S.; Dani, K.; Tiwari, S.; Bisht, D.; Devara, P.; Pinker, R. Aerosol Radiative Forcing during Dust Events over New Delhi, India. *J. Geophys. Res. Atmos.* **2008**, *113*, D13209. [\[CrossRef\]](#)
99. Moorthy, K.K.; Nair, V.S.; Babu, S.S.; Satheesh, S.K. Spatial and Vertical Heterogeneities in Aerosol Properties over Oceanic Regions around India: Implications for Radiative Forcing. *Q. J. R. Meteorol. Soc.* **2009**, *135*, 2131–2145. [\[CrossRef\]](#)
100. Myhre, G.; Samset, B.H.; Schulz, M.; Balkanski, Y.; Bauer, S.; Bernsten, T.K.; Bian, H.; Bellouin, N.; Chin, M.; Diehl, T.; et al. Radiative Forcing of the Direct Aerosol Effect from AeroCom Phase II Simulations. *Atmos. Chem. Phys.* **2013**, *13*, 1853–1877. [\[CrossRef\]](#)
101. Tiwari, S.; Hopke, P.K.; Pipal, A.S.; Srivastava, A.K.; Bisht, D.S.; Tiwari, S.; Singh, A.K.; Soni, V.K.; Attri, S.D. Intra–Urban Variability of Particulate Matter (PM_{2.5} and PM₁₀) and Its Relationship with Optical Properties of Aerosols over Delhi, India. *Atmos. Res.* **2015**, *166*, 223–232. [\[CrossRef\]](#)
102. Levy, R.; Remer, L.; Kleidman, R.; Mattoo, S.; Ichoku, C.; Kahn, R.; Eck, T. Global Evaluation of the Collection 5 MODIS Dark–Target Aerosol Products over Land. *Atmos. Chem. Phys.* **2010**, *10*, 10399–10420. [\[CrossRef\]](#)

103. Holben, B.N.; Tanré, D.; Smirnov, A.; Eck, T.F.; Slutsker, I.; Abuhassan, N.; Newcomb, W.W.; Schafer, J.S.; Chatenet, B.; Lavenu, F.; et al. An Emerging Ground-Based Aerosol Climatology: Aerosol Optical Depth from AERONET. *J. Geophys. Res. Atmos.* **2001**, *106*, 12067–12097. [[CrossRef](#)]
104. Kaufman, Y.J.; Tanré, D.; Boucher, O. A Satellite View of Aerosols in the Climate System. *Nature* **2002**, *419*, 215–223. [[CrossRef](#)] [[PubMed](#)]
105. Kumharn, W.; Rimmer, J.S.; Smedley, A.R.D.; Ying, T.Y.; Webb, A.R. Aerosol Optical Depth and the Global Brewer Network: A Study Using U.K.- and Malaysia-Based Brewer Spectrophotometers. *J. Atmos. Ocean. Technol.* **2012**, *29*, 857–866. [[CrossRef](#)]
106. Kang, N.; Kumar, K.R.; Hu, K.; Yu, X.; Yin, Y. Long-Term (2002–2014) Evolution and Trend in Collection 5.1 Level-2 Aerosol Products Derived from the MODIS and MISR Sensors over the Chinese Yangtze River Delta. *Atmos. Res.* **2016**, *181*, 29–43. [[CrossRef](#)]
107. Kumar, A.; Suresh, K.; Rahaman, W. Geochemical Characterization of Modern Aeolian Dust over the Northeastern Arabian Sea: Implication for Dust Transport in the Arabian Sea. *Sci. Total Environ.* **2020**, *729*, 138576. [[CrossRef](#)] [[PubMed](#)]
108. Kaskaoutis, D.G.; Gautam, R.; Singh, R.P.; Houssos, E.; Goto, D.; Singh, S.; Bartzokas, A.; Kosmopoulos, P.; Sharma, M.; Hsu, N. Influence of Anomalous Dry Conditions on Aerosols over India: Transport, Distribution and Properties. *J. Geophys. Res. Atmos.* **2012**, *117*, D09106. [[CrossRef](#)]
109. Mor, V.; Dhankhar, R. Atmospheric Aerosol Loading and Properties over India: A Review. *Pollution* **2022**, *8*, 211–224.
110. Dahal, S.; Rupakheti, D.; Sharma, R.K.; Bhattarai, B.K.; Adhikary, B. Aerosols over the Foothills of the Eastern Himalayan Region during Post-Monsoon and Winter Seasons. *Aerosol Air Qual. Res.* **2022**, *22*, 210152. [[CrossRef](#)]
111. Gogoi, M.M.; Babu, S.S.; Moorthy, K.K.; Bhuyan, P.K.; Pathak, B.; Subba, T.; Chutia, L.; Kundu, S.S.; Bharali, C.; Borgohain, A.; et al. Radiative Effects of Absorbing Aerosols over Northeastern India: Observations and Model Simulations. *J. Geophys. Res. Atmos.* **2017**, *122*, 1132–1157. [[CrossRef](#)]
112. Ramachandran, S.; Rupakheti, M. Trends in the Types and Absorption Characteristics of Ambient Aerosols over the Indo-Gangetic Plain and North China Plain in Last Two Decades. *Sci. Total Environ.* **2022**, *831*, 154867. [[CrossRef](#)] [[PubMed](#)]
113. Kumar, K.R.; Narasimhulu, K.; Reddy, R.R.; Gopal, K.R.; Reddy, L.S.S.; Balakrishnaiah, G.; Moorthy, K.K.; Babu, S.S. Temporal and Spectral Characteristics of Aerosol Optical Depths in a Semi-Arid Region of Southern India. *Sci. Total Environ.* **2009**, *407*, 2673–2688. [[CrossRef](#)] [[PubMed](#)]
114. Badarinath, K.V.S.; Kharol, S.K.; Sharma, A.R. Long-Range Transport of Aerosols from Agriculture Crop Residue Burning in Indo-Gangetic Plains—A Study Using LIDAR, Ground Measurements and Satellite Data. *J. Atmos. Sol.-Terr. Phys.* **2009**, *71*, 112–120. [[CrossRef](#)]
115. Kalluri, R.O.R.; Gugamsetty, B.; Kotalo, R.G.; Nagireddy, S.K.R.; Tandule, C.R.; Thotli, L.R.; Shaik, N.H.; Maraka, V.R.; Rajuru, R.R.; Nair, S.B.S. Seasonal Variation of near Surface Black Carbon and Satellite Derived Vertical Distribution of Aerosols over a Semi-Arid Station in India. *Atmos. Res.* **2017**, *184*, 77–87. [[CrossRef](#)]
116. Rana, A.; Jia, S.; Sarkar, S. Black Carbon Aerosol in India: A Comprehensive Review of Current Status and Future Prospects. *Atmos. Res.* **2019**, *218*, 207–230. [[CrossRef](#)]
117. Meena, G.S.; Mukherjee, S.; Buchunde, P.; Safai, P.D.; Singla, V.; Aslam, M.Y.; Sonbawne, S.M.; Made, R.; Anand, V.; Dani, K.K.; et al. Seasonal Variability and Source Apportionment of Black Carbon over a Rural High-Altitude and an Urban Site in Western India. *Atmos. Pollut. Res.* **2021**, *12*, 32–45. [[CrossRef](#)]
118. Kumar, R.; Barth, M.; Pfister, G.; Nair, V.; Ghude, S.D.; Ojha, N. What Controls the Seasonal Cycle of Black Carbon Aerosols in India? *J. Geophys. Res. Atmos.* **2015**, *120*, 7788–7812. [[CrossRef](#)]
119. Sinha, P.R.; Kaskaoutis, D.G.; Manchanda, R.K.; Sreenivasan, S. Characteristics of Aerosols over Hyderabad in Southern Peninsular India: Synergy in the Classification Techniques. *Ann. Geophys.* **2012**, *30*, 1393–1410. [[CrossRef](#)]
120. Boiyo, R.; Kumar, K.R.; Zhao, T. Spatial Variations and Trends in AOD Climatology over East Africa during 2002–2016: A Comparative Study Using Three Satellite Data Sets. *Int. J. Climatol.* **2018**, *38*, e1221–e1240. [[CrossRef](#)]
121. El-Metwally, M.; Alfaro, S.; Wahab, M.A.; Favez, O.; Mohamed, Z.; Chatenet, B. Aerosol Properties and Associated Radiative Effects over Cairo (Egypt). *Atmos. Res.* **2011**, *99*, 263–276. [[CrossRef](#)]
122. Gong, C.; Xin, J.; Wang, S.; Wang, Y.; Zhang, T. Anthropogenic Aerosol Optical and Radiative Properties in the Typical Urban/Suburban Regions in China. *Atmos. Res.* **2017**, *197*, 177–187. [[CrossRef](#)]
123. Patel, P.N.; Dumka, U.; Kaskaoutis, D.; Babu, K.; Mathur, A.K. Optical and Radiative Properties of Aerosols over Desalpar, a Remote Site in Western India: Source Identification, Modification Processes and Aerosol Type Discrimination. *Sci. Total Environ.* **2017**, *575*, 612–627. [[CrossRef](#)] [[PubMed](#)]
124. Kaskaoutis, D.; Kalapureddy, M.; Krishna Moorthy, K.; Devara, P.; Nastos, P.; Kosmopoulos, P.; Kambezidis, H. Heterogeneity in Pre-Monsoon Aerosol Types over the Arabian Sea Deduced from Ship-Borne Measurements of Spectral AODs. *Atmos. Chem. Phys.* **2010**, *10*, 4893–4908. [[CrossRef](#)]
125. Kumar, P.; Kapur, S.; Choudhary, A.; Singh, A.K. Spatiotemporal Variability of Optical Properties of Aerosols over the Indo-Gangetic Plain during 2011–2015. *Indian J. Phys.* **2022**, *96*, 329–341. [[CrossRef](#)]

126. Rajesh, T.A.; Ramachandran, S. Black Carbon Aerosols over Urban and High Altitude Remote Regions: Characteristics and Radiative Implications. *Atmos. Environ.* **2018**, *194*, 110–122. [[CrossRef](#)]
127. Tiwari, S.; Srivastava, A.K.; Singh, A.K.; Singh, S. Identification of Aerosol Types over Indo–Gangetic Basin: Implications to Optical Properties and Associated Radiative Forcing. *Environ. Sci. Pollut. Res.* **2015**, *22*, 12246–12260. [[CrossRef](#)] [[PubMed](#)]
128. Vaishya, A.; Raj, S.S.; Singh, A.; Sivakumar, S.; Ojha, N.; Sharma, S.K.; Ravikrishna, R.; Gunthe, S.S. Black Carbon over Tropical Indian Coast during the COVID–19 Lockdown: Inconspicuous Role of Coastal Meteorology. *Environ. Sci. Pollut. Res.* **2023**, *30*, 44773–44781. [[CrossRef](#)] [[PubMed](#)]
129. Arora, A.; Gadhavi, H.; Ramachandran, S.; Rajesh, T.A. Evaluation of Black Carbon Emission Inventories over Indian Subcontinent: Role of Open Biomass Burning and Its Representation in Emission Fluxes. *Atmos. Environ.* **2025**, *359*, 121367. [[CrossRef](#)]
130. Mhawish, A.; Sorek–Hamer, M.; Chatfield, R.; Banerjee, T.; Bilal, M.; Kumar, M.; Sarangi, C.; Franklin, M.; Chau, K.; Garay, M. Aerosol Characteristics from Earth Observation Systems: A Comprehensive Investigation over South Asia (2000–2019). *Remote Sens. Environ.* **2021**, *259*, 112410. [[CrossRef](#)]
131. Badarinath, K.; Kharol, S.K.; Kaskaoutis, D.; Kambezidis, H. Case Study of a Dust Storm over Hyderabad Area, India: Its Impact on Solar Radiation Using Satellite Data and Ground Measurements. *Sci. Total Environ.* **2007**, *384*, 316–332. [[CrossRef](#)] [[PubMed](#)]
132. Zeng, Y.; Hopke, P.K. A Study of the Sources of Acid Precipitation in Ontario, Canada. *Atmos. Environ.* **1989**, *23*, 1499–1509. [[CrossRef](#)]
133. Asutosh, A.; Vinoj, V. Role of Local Absorbing Aerosols in Modulating Indian Summer Monsoon Rainfall. *Sci. Total Environ.* **2024**, *910*, 168663. [[CrossRef](#)] [[PubMed](#)]
134. Kumar, S.; Singh, A.; Srivastava, A.K.; Sahu, S.K.; Hooda, R.K.; Dumka, U.C.; Pathak, V. Long–Term Change in Aerosol Characteristics over Indo–Gangetic Basin: How Significant Is the Impact of Emerging Anthropogenic Activities? *Urban Clim.* **2021**, *38*, 100880. [[CrossRef](#)]
135. Goyal, P.; Gulia, S.; Goyal, S. Critical Review of Air Pollution Contribution in Delhi Due to Paddy Stubble Burning in North Indian States. *Atmos. Environ.* **2025**, *346*, 121058. [[CrossRef](#)]
136. Giles, D.M.; Holben, B.N.; Eck, T.F.; Sinyuk, A.; Smirnov, A.; Slutsker, I.; Dickerson, R.R.; Thompson, A.M.; Schafer, J.S. An Analysis of AERONET Aerosol Absorption Properties and Classifications Representative of Aerosol Source Regions. *J. Geophys. Res. Atmos.* **2012**, *117*, D17203. [[CrossRef](#)]
137. Dey, S.; Ghosh, P.; Rawat, P.; Choudhary, N.; Rai, A.; Meena, R.; Mandal, T.K.; Mao, J.; Jia, S.; Rastogi, N.; et al. Optical Source Apportionment of Aqueous Brown Carbon (BrC) on a Daytime and Nighttime Basis in the Eastern Indo–Gangetic Plain (IGP) and Insights from ^{13}C and ^{15}N Isotopic Signatures. *Sci. Total Environ.* **2023**, *894*, 164872. [[CrossRef](#)] [[PubMed](#)]
138. Jethva, H.; Chand, D.; Torres, O.; Gupta, P.; Lyapustin, A.; Patadia, F. Agricultural Burning and Air Quality over Northern India: A Synergistic Analysis Using NASA’s A–Train Satellite Data and Ground Measurements. *Aerosol Air Qual. Res.* **2018**, *18*, 1756–1773. [[CrossRef](#)]
139. Kedia, S.; Ramachandran, S.; Holben, B.N.; Tripathi, S.N. Quantification of Aerosol Type, and Sources of Aerosols over the Indo–Gangetic Plain. *Atmos. Environ.* **2014**, *98*, 607–619. [[CrossRef](#)]
140. Soyam, P.S.; Safai, P.D.; Bankar, S.; Todekar, K.; Malap, N.; Kondle, S.; Zambare, P.; Mane, M.; Kale, S.S.; Prabhakaran, T. Absorbing and Scattering Aerosols over Semi–Arid Region in India: Temporal Variation and Possible Sources. *J. Atmos. Sol.–Terr. Phys.* **2025**, *275*, 106613. [[CrossRef](#)]
141. Srivastava, A.; Singh, S.; Pant, P.; Dumka, U. Characteristics of Black Carbon over Delhi and Manora Peak—A Comparative Study. *Atmos. Sci. Lett.* **2012**, *13*, 223–230. [[CrossRef](#)]
142. Ramachandran, S.; Rupakheti, M.; Lawrence, M.G. Black Carbon Dominates the Aerosol Absorption over the Indo–Gangetic Plain and the Himalayan Foothills. *Environ. Int.* **2020**, *142*, 105814. [[CrossRef](#)] [[PubMed](#)]

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