



Long-term AERONET observations reveal recurring aerosol regimes and contrasting radiative effects in the central Himalayan foothills

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Abstract. We analyzed AERONET Version 3 Level 2.0 observations over Pokhara, Nepal, from 2010 to 2024 to assess aerosol trends, regimes, and radiative effects. Theil–Sen and Mann–Kendall analyses showed no significant trend in AOD₄₄₀ annual medians (slope = -0.0024 yr^{-1} ; $\tau = -0.08$, $p = 0.747$) or deseasonalized monthly anomalies. AOD₄₄₀ was highest during pre-monsoon and lowest during monsoon. Gaussian mixture modeling identified four recurring, partially overlapping aerosol regimes with pronounced seasonal differences in occurrence. The mixed-size regime produced the strongest median surface dimming, while strongly absorbing regimes enhanced atmospheric forcing. Surface forcing was closely related to AOD₄₄₀ ($R^2 = 0.817$), whereas atmospheric forcing was most strongly related to absorption AOD ($R^2 = 0.892$). Almucantar and Hybrid retrievals agreed on 89.0% of regime assignments ($\kappa = 0.836$). Aerosol variability over Pokhara was therefore governed mainly by seasonal changes and recurring aerosol mixtures rather than by a persistent change in column loading. More broadly, the results show that a stable long-term AOD record does not necessarily imply stable aerosol radiative effects, because changes in particle size and absorption can substantially alter the radiative influence of the aerosol column.

1 Introduction

Atmospheric aerosols affect the Earth’s radiation budget by scattering and absorbing sunlight and by modifying clouds. Their radiative effects depend on aerosol loading, particle size, composition, mixing state, vertical distribution, and surface reflectance. These factors make aerosols an important source of uncertainty in climate assessments (Bellouin et al., 2020). Absorbing aerosols are particularly important in the Himalayan region. They heat the atmosphere and, after deposition on snow and ice, can contribute to cryospheric change (Bond et al., 2013; Ramachandran et al., 2023).

The southern Himalayan foothills lie downwind of the Indo-Gangetic Plain (IGP), a major source region for anthropogenic pollution, biomass burning emissions, and mineral dust. Seasonal circulation, monsoon rainfall, mountain–valley winds, and boundary-layer development regulate aerosol accumulation and transport. Observations across Nepal have identified contributions from combustion, biomass burning, dust, and regional transport (Gautam et al., 2011; Dhungel et al., 2018; Cho et al.,



2017; Rupakheti et al., 2019). Airborne measurements near Pokhara have also revealed strong vertical gradients and elevated layers containing mixed aerosol (Singh et al., 2019).

Previous studies showed that aerosol loading over Pokhara is generally highest during pre-monsoon and lowest during monsoon. They also reported bimodal particle-size distributions, enhanced dry-season absorption, and substantial radiative effects (Regmi et al., 2020; Ramachandran and Rupakheti, 2020, 2021). However, these studies used shorter observational records and largely examined aerosol properties separately. It remains unclear whether the extended record indicates a persistent change in aerosol loading, whether recurring aerosol states can be identified from several retrieved properties, and whether these states differ in radiative importance. These questions cannot be addressed using AOD or a single absorption indicator alone. Absorption indices are not chemically unique (Russell et al., 2010; Giles et al., 2012), and mixed aerosol populations do not fit neatly into fixed source categories.

This study uses AERONET Version 3 Level 2.0 direct-sun, Almucantar, and Hybrid observations collected over Pokhara from 2010 to 2024 to address three related questions. First, does the extended observational record provide evidence of a persistent change in aerosol loading once the pronounced seasonal cycle and uneven sampling are considered? Second, can recurring aerosol states identified jointly from particle-size, absorption, and microphysical properties explain differences in radiative behavior that are not captured by AOD alone? Third, are these multivariate aerosol-state interpretations robust to differences between AERONET Almucantar and Hybrid retrieval geometries? We address these questions using robust trend statistics, probabilistic Gaussian mixture modeling, regime-dependent radiative forcing, and temporally matched Almucantar–Hybrid retrievals. The aim is therefore not to repeat the established seasonal aerosol climatology of Pokhara, but to determine how recurring combinations of aerosol size and absorption properties influence radiative behavior at a Himalayan foothill receptor affected by seasonally varying aerosol mixtures.

2 Materials and methods

2.1 Site and AERONET observations

Pokhara (28.1866°N, 83.9752°E; 800 m a.s.l.) lies in a valley in the central Himalayan foothills of Nepal. Its aerosol column can include locally accumulated emissions and material transported from the IGP and other upwind regions. The South Asian monsoon produces a strong seasonal contrast between dry pre-monsoon conditions and cloudy, rainy monsoon months.

We used AERONET Version 3 Level 2.0 direct-sun, Almucantar, and Hybrid products for 2010–2024 (Holben et al., 1998; Giles et al., 2019; Sinyuk et al., 2020). Direct-sun measurements provided spectral AOD and the 440–870 nm extinction Ångström exponent (AE). Almucantar inversion products provided total, fine-mode, and coarse-mode extinction AOD, the extinction Ångström exponent, and fine-mode fraction (FMF). FMF_{440} was calculated as the ratio of fine-mode to total extinction AOD at 440 nm. Sky-radiance inversions supplied single-scattering albedo (SSA), absorption AOD (AAOD), absorption Ångström exponent (AAE), complex refractive index, fine- and coarse-mode effective radii and volumes, and shortwave aerosol radiative forcing (Dubovik and King, 2000; Sinyuk et al., 2020).



Table 1. AERONET datasets and products used in the analysis.

Dataset	Period	Products used
Direct sun	2010–2024	Spectral AOD and precipitable water. AOD ₄₄₀ was used for the long-term analysis.
Almucantar	2010–2024	Total, fine- and coarse-mode AOD; AE; FMF; SSA; AAOD; AAE; complex refractive index; particle volume-size distribution; mode volumes and effective radii; BOA and TOA radiative forcing.
Hybrid	2016–2024	The same main inversion products. Hybrid retrievals were used to test scan-to-scan consistency.

The cleaned direct-sun record contained 162,446 observations on 3,466 days. Almucantar data comprised 7,463 inversions on 1,922 days. The Hybrid record contained 3,784 inversions on 969 days and began in 2016. Table 1 lists the variables used from each product. AOD₄₄₀ was chosen as the main loading measure because 440 nm is common to the direct-sun and inversion datasets. It represents total extinction and should not be read as a measure of absorption.

Level 2.0 quality screening was retained. AERONET fill values and non-finite entries were treated as missing. Total and fine-mode AOD had to be positive and no greater than 5. Coarse-mode AOD was restricted to 0–2. AE was restricted to 0–3, while FMF and SSA were restricted to 0–1. AAOD, the imaginary refractive index, mode volumes, and volume-size distributions had to be non-negative. Missing values were not interpolated.

Measurements were summarized as daily medians to prevent days with many scans from dominating the analysis. A direct-sun day required at least three valid AOD₄₄₀ observations. Monthly values required at least three valid days. A centered 12-month rolling median required at least six available monthly values. Seasons were defined as winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). The number of valid days was retained for every temporal summary because cloud screening strongly reduces monsoon coverage. Inversion-based findings therefore describe the subset of days for which quality-assured sky-radiance retrievals were available.

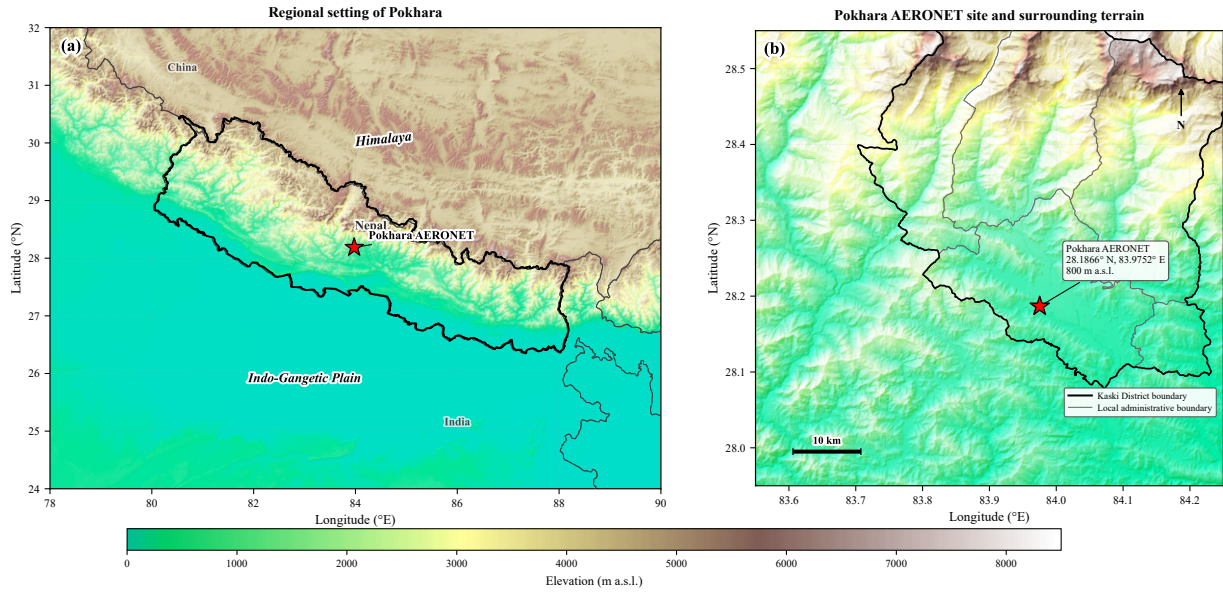


Figure 1. Location and topographic setting of the Pokhara AERONET station in the central Himalayan foothills of Nepal.

2.2 Trend and seasonal analyses

Annual median AOD₄₄₀ was calculated from the accepted daily medians. Only years with at least 90 valid days were included in the long-term analysis. The trend magnitude was estimated using the Theil–Sen estimator (Sen, 1968):

$$\hat{\beta}_{TS} = \text{median}_{j>i} \left(\frac{y_j - y_i}{t_j - t_i} \right), \quad (1)$$

where y_i and y_j are the annual median AOD₄₄₀ values at times t_i and t_j , respectively. The Mann–Kendall test was used to assess the statistical significance of monotonic change (Mann, 1945; Kendall, 1975). All tests were two-sided, with $p < 0.05$ considered statistically significant.

Because observational coverage varied among months and years, the analysis was repeated using deseasonalized monthly anomalies. For each calendar month, the corresponding 2010–2024 climatological median was subtracted from the observed monthly median:

$$A'_{y,m} = A_{y,m} - \tilde{A}_m, \quad (2)$$

where $A_{y,m}$ is the monthly median for year y and calendar month m , and $\tilde{A}_m$ is the 2010–2024 median for that calendar month. The resulting series contained 151 monthly anomalies. Decimal year was used as the time coordinate, so the reported slope has units of yr^{-1} . Theil–Sen slopes and Mann–Kendall statistics were calculated from the anomaly series. The 95% confidence interval for the slope was obtained from the distribution-free interval associated with the Theil–Sen estimator. This analysis tested whether uneven seasonal sampling affected the annual trend result.



Monthly and seasonal distributions of AOD₄₄₀, fine- and coarse-mode AOD, AE, FMF, SSA, AAOD, AAE, complex re-
fractive index, and particle volume-size distributions were used to interpret the multivariate regimes. Medians and interquartile
ranges were emphasized because several variables had skewed distributions.

2.3 Probabilistic aerosol regimes

Daily Almuqantar inversions containing all eight classification variables were retained, yielding a complete-case dataset of
1,233 days. The variables were AE_{440–870}, FMF₄₄₀, SSA₄₄₀, AAE_{440–870}, the imaginary refractive index at 440 nm (k_{440}),
 $\log_{10}(V_f/V_c)$, and the fine- and coarse-mode effective radii. Total AOD, AAOD, and radiative forcing were excluded from
model fitting and examined afterward as regime outcomes. Each variable was robust-scaled as

$$z_{ij} = \frac{x_{ij} - \tilde{x}_j}{Q_{0.75,j} - Q_{0.25,j}}, \quad (3)$$

where $\tilde{x}_j$ and $Q_{0.75,j} - Q_{0.25,j}$ denote the median and interquartile range of variable j . Gaussian mixture models (GMMs)
with two to six components and full, diagonal, or tied covariance matrices were fitted using expectation maximization (Demp-
ster et al., 1977; McLachlan and Peel, 2000). Each candidate was fitted with five initializations. A model was retained for
comparison only if it converged and every component contained at least 30 days and 5% of the training data.

Valid models were compared using the Bayesian Information Criterion (BIC) (Schwarz, 1978). The number of components
was selected using a prespecified BIC elbow criterion. Beginning with the three-component model, an additional component
was retained only when its reduction in BIC was at least 20% of the reduction obtained when moving from two to three com-
ponents. This criterion supported a four-component model with full covariance. The selected four-component full-covariance
GMM was then refitted from 20 different initializations, and the solution with the highest final log-likelihood was retained to
reduce sensitivity to local optima.

Each observation was assigned to the component with the highest posterior probability. Assignments with a maximum poste-
rior probability below 0.60 were marked as uncertain but retained in the primary analysis. The maximum posterior probability
measured assignment confidence, while the silhouette coefficient described component separation (Rousseeuw, 1987).

Model stability was evaluated through 100 repeated subsampling experiments. In each experiment, 80% of the complete days
were selected without replacement. The scaler was recalculated, and a four-component full-covariance GMM was refitted using
five initializations. The refitted model was then applied to the complete dataset. Agreement with the full-data classification was
measured using the adjusted Rand index (Hubert and Arabie, 1985). Principal-component analysis was used only to visualize
the regimes and did not contribute to model fitting (Jolliffe and Cadima, 2016). Regime names summarize retrieved aerosol
properties and should not be interpreted as unique chemical sources.

2.4 Radiative effects and scan robustness

AERONET shortwave forcing was defined as the difference between net flux with aerosol and the corresponding aerosol-free
calculation at the bottom (BOA) and top (TOA) of the atmosphere (García et al., 2012). Atmospheric forcing was calculated
as $\Delta F_{\text{ATM}} = \Delta F_{\text{TOA}} - \Delta F_{\text{BOA}}$. Negative BOA forcing denotes surface dimming, whereas positive atmospheric forcing de-



notes solar energy retained within the atmospheric column. Ordinary least-squares regression was used to describe the mean relationships and calculate R^2 . Spearman correlation was also calculated because the distributions were skewed and included high-aerosol events. These relationships are internal to the AERONET retrieval and radiative-transfer framework because the forcing products are calculated from retrieved aerosol properties.

120 Almucantar and Hybrid observations were paired when they came from the same instrument and UTC date and occurred within 30 minutes. One-to-one matching prevented reuse of either retrieval. Agreement in continuous variables was summarized using correlation, Hybrid-minus-Almucantar bias, RMSE, and Deming regression (Linnet, 1993). This comparison contained 1,927 pairs, including 1,026 with valid SSA and AAOD. The scaler and GMM trained on Almucantar retrievals were then applied unchanged to a separate complete-case match based on the eight regime variables. That procedure pro-
 125 duced 1,047 pairs. Regime agreement was quantified by percent agreement and Cohen's κ (Cohen, 1960). The calculation was repeated for pairs with posterior probabilities ≥ 0.60 in both scans.

3 Results and discussion

3.1 Long-term behavior and seasonal context

AOD₄₄₀ varied strongly from day to day and among years (Fig. 2a). Large enhancements occurred in 2016 and 2024. Even so,
 130 annual medians showed no monotonic trend. The Theil–Sen slope was -0.0024 yr^{-1} , with Kendall's $\tau = -0.08$ ($p = 0.747$; Fig. 2b). The monthly anomaly analysis gave a slope of 0.0029 yr^{-1} (95% confidence interval: -0.0028 to 0.0088 yr^{-1} ; $p = 0.344$). The two slopes had opposite signs, but neither differed significantly from zero. Thus, seasonal variation and short-lived high-aerosol periods were more prominent than any persistent increase or decrease. Long AERONET records elsewhere also show that aerosol trends vary across sites and within the IGP (Zhang et al., 2025; Kumar et al., 2018).

135 The monthly distributions retained the established seasonal cycle (Fig. 3). Aerosol loading rose from winter to pre-monsoon and declined during monsoon. Fine-mode aerosol dominated most months, while the coarse-mode contribution increased during pre-monsoon. Dry surfaces, fires, combustion emissions, and regional transport can all contribute during this period. Monsoon rainfall favors wet removal, although persistent cloud cover also reduces the number of valid observations. These patterns agree with earlier work at Pokhara (Regmi et al., 2020; Ramachandran and Rupakheti, 2021) and provide context for the regime
 140 analysis below.

Absorption also varied with season (Fig. 4). Pre-monsoon retrievals had lower SSA and higher AAOD than the other seasons, indicating enhanced aerosol absorption. The imaginary refractive index was elevated during both winter and pre-monsoon, with the highest median at 440 nm occurring during pre-monsoon. AAE distributions overlapped considerably, however, so AAE alone could not separate black carbon, brown carbon, and mineral dust (Russell et al., 2010; Giles et al., 2012).

145 The particle volume distributions were bimodal in every season (Fig. 5). Fine-mode maxima occurred near $0.15\text{--}0.20 \mu\text{m}$, while coarse-mode maxima occurred near $3\text{--}5 \mu\text{m}$. Both mode volumes increased during pre-monsoon. The simultaneous increase supports the interpretation of a mixed aerosol column rather than a single dominant particle type. Similar bimodal distributions have been reported over Pokhara and the IGP (Eck et al., 2010; Ramachandran and Rupakheti, 2021).

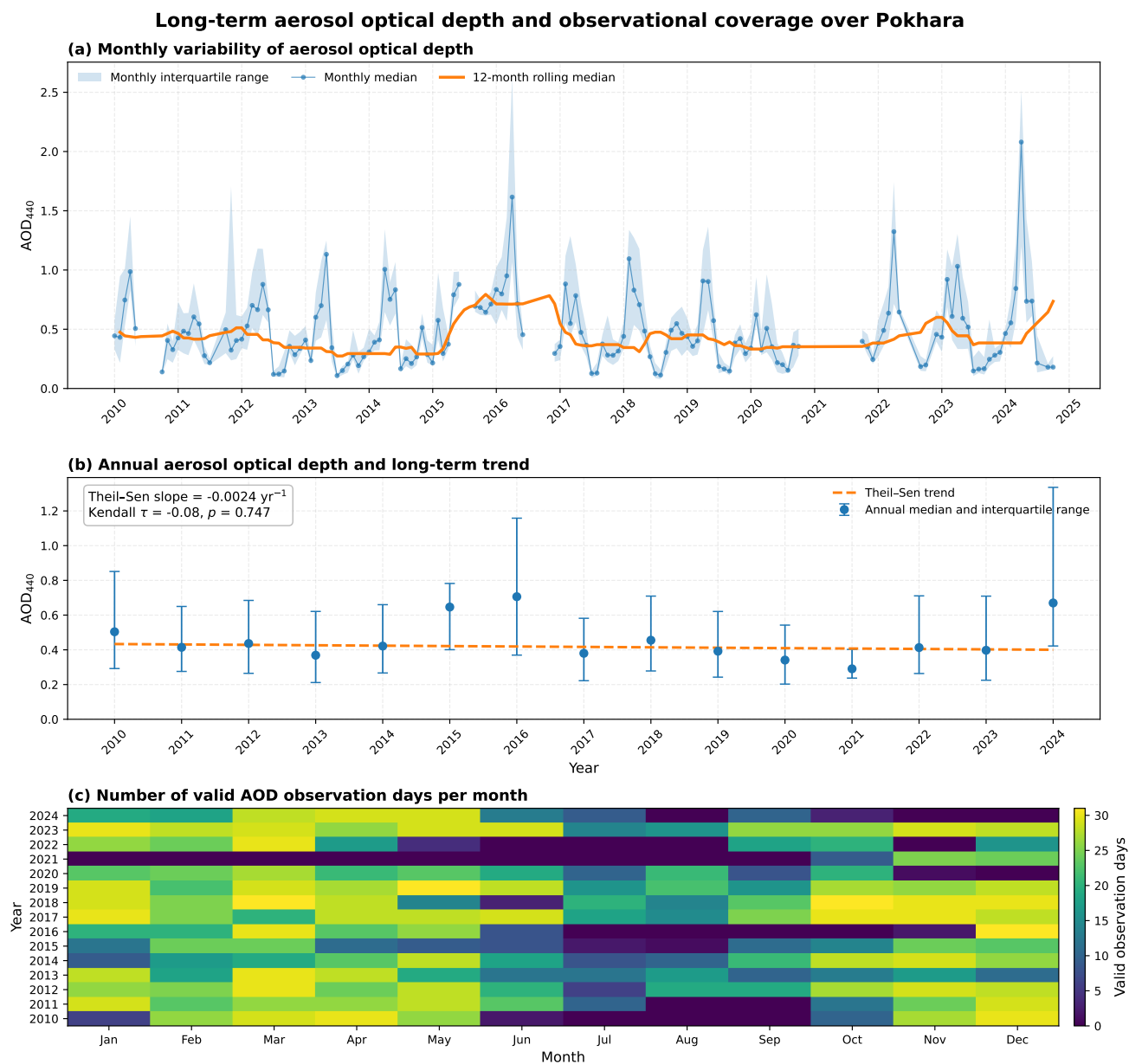


Figure 2. Daily and annual AOD₄₄₀ variability and observational coverage over Pokhara during 2010–2024. The annual Theil–Sen trend was not statistically significant.



Monthly and seasonal aerosol optical climatology over Pokhara

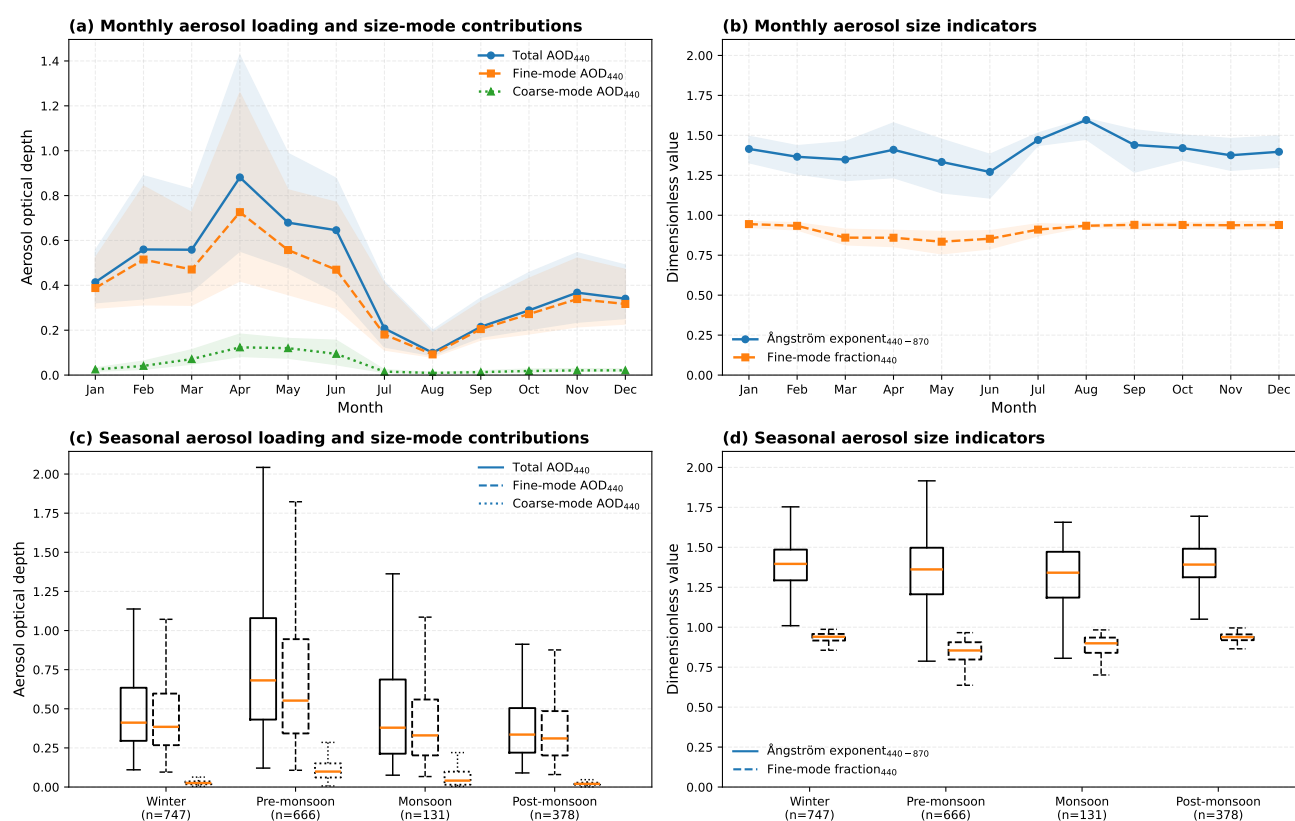


Figure 3. Monthly and seasonal aerosol optical characteristics derived from daily median Almucantar retrievals over Pokhara. Panels show total, fine-mode, and coarse-mode extinction AOD at 440 nm, the extinction Ångström exponent ($AE_{440-870}$), and FMF₄₄₀. Lines and boxes indicate medians and interquartile ranges. Seasonal sample sizes give the number of valid daily retrievals and should be considered when interpreting monsoon conditions.



Seasonal aerosol absorption and scattering characteristics over Pokhara

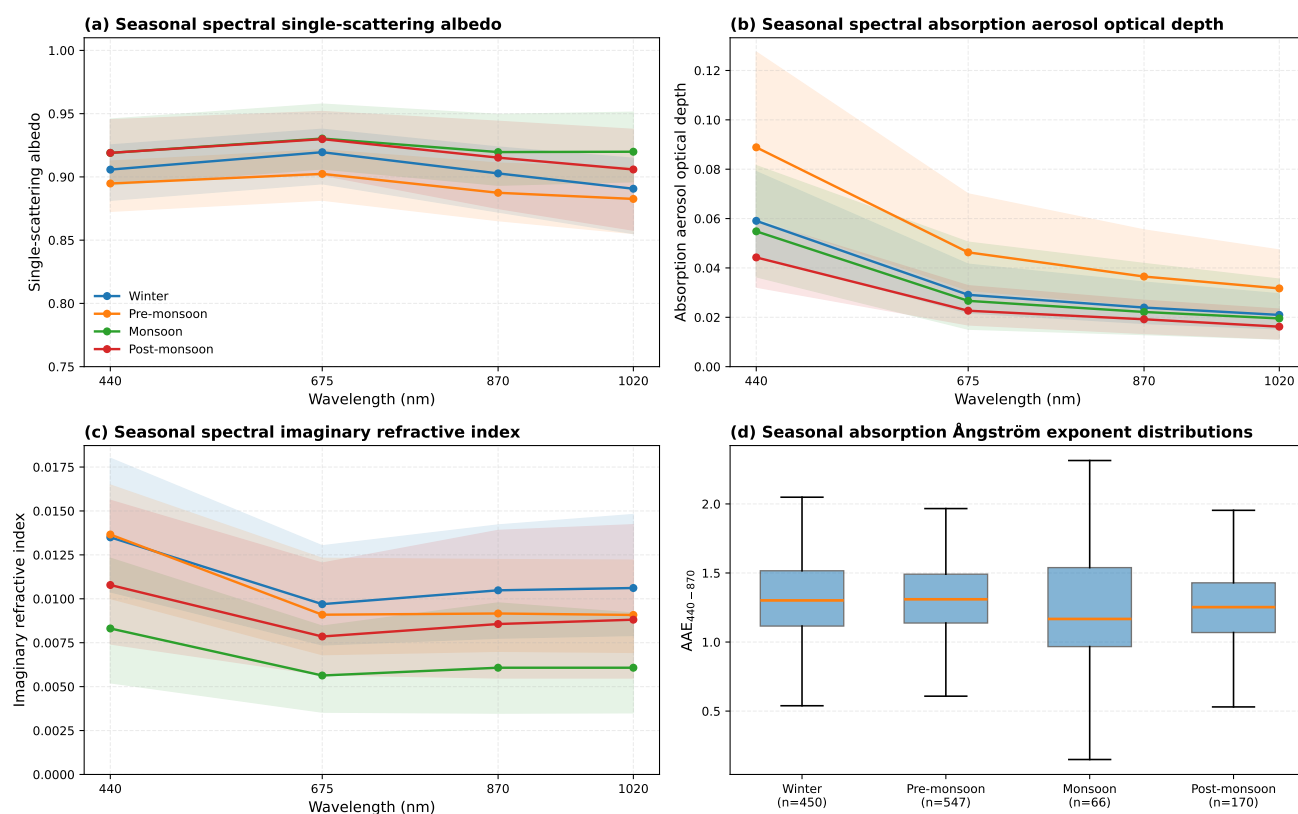


Figure 4. Seasonal aerosol absorption and scattering properties from daily median Almucantar retrievals. Panels show spectral SSA, AAOD, the imaginary refractive index, and AAE_{440–870}. Boxes indicate medians and interquartile ranges.



Seasonal aerosol particle volume-size distributions over Pokhara

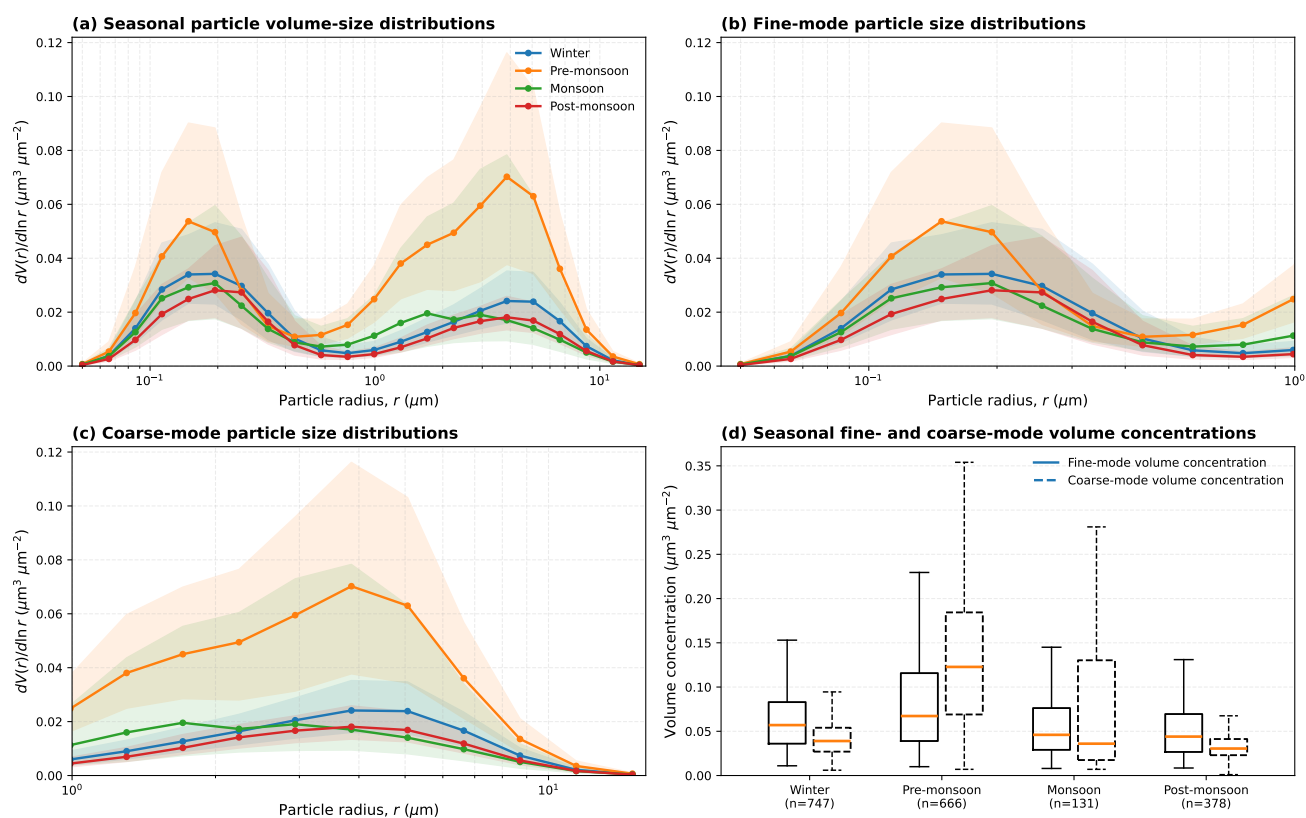


Figure 5. Seasonal particle volume-size distributions over Pokhara. Curves show seasonal medians and interquartile envelopes for the full, fine-mode, and coarse-mode radius ranges. The final panel compares daily fine- and coarse-mode volume concentrations.

3.2 Recurring aerosol regimes

150 BIC improvement and the minimum-size criterion supported a four-component full-covariance GMM. The silhouette coefficient was 0.140, indicating considerable overlap among neighboring components. The median adjusted Rand index from repeated subsampling was 0.855. The classification was therefore reproducible even though its boundaries were not sharp. We interpret the components as recurring regions within a continuous aerosol-property space rather than as discrete chemical types.

Probabilistic aerosol regimes, seasonal occurrence, radiative effects, and scan consistency over Pokhara

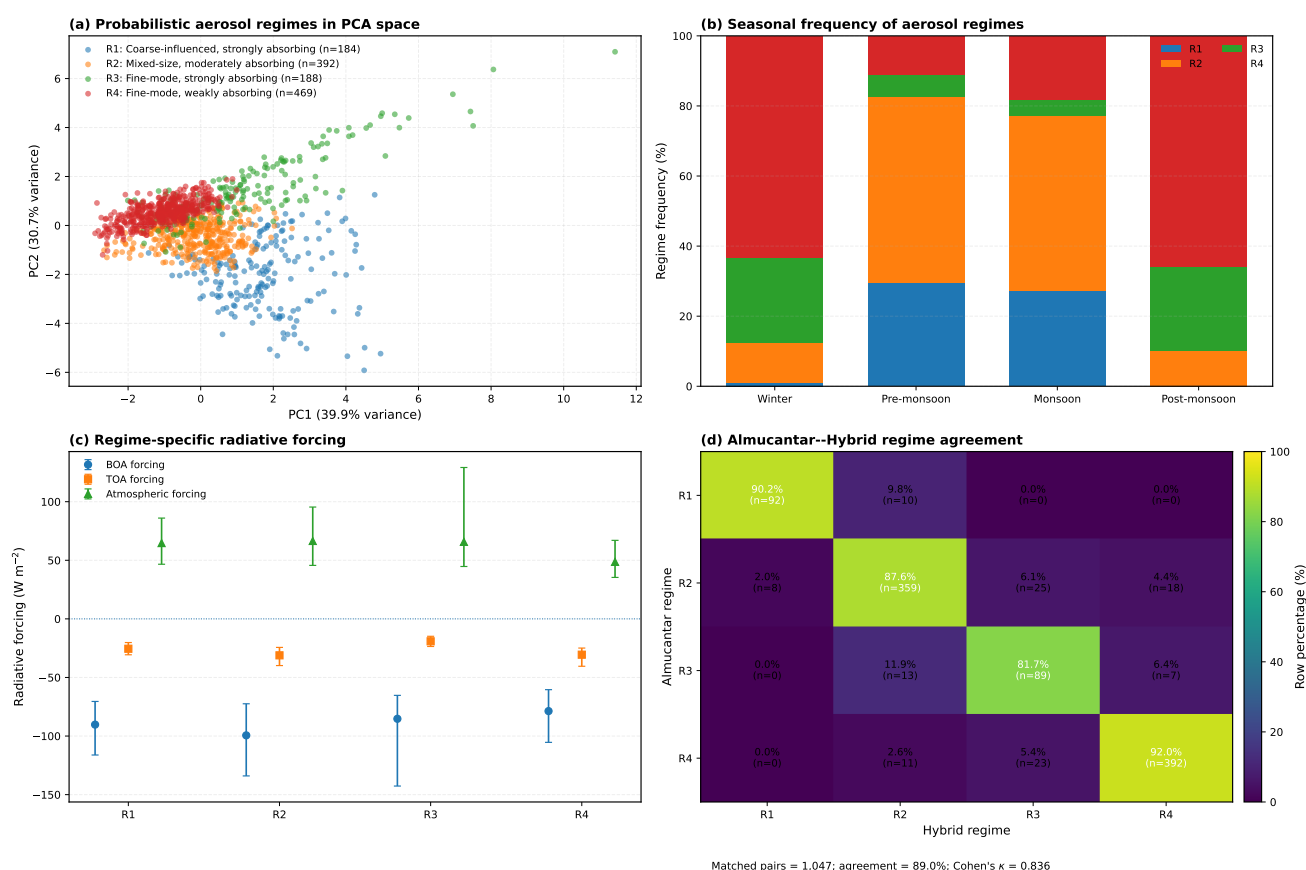


Figure 6. Probabilistic aerosol regimes over Pokhara: (a) principal-component visualization; (b) seasonal regime occurrence; (c) median BOA, TOA, and atmospheric forcing with interquartile ranges; and (d) row-normalized Almucantar-Hybrid regime agreement. R1 is coarse-influenced strongly absorbing, R2 mixed-size moderately absorbing, R3 fine-mode strongly absorbing, and R4 fine-mode weakly absorbing.

155 R1 ($n = 184$) had the lowest median $AE_{440-870}$ (1.093) and FMF_{440} (0.739), together with a median SSA_{440} of 0.870. It was identified as coarse-influenced, strongly absorbing aerosol. R2 ($n = 392$) had intermediate size and absorption properties.



Its median FMF_{440} and SSA_{440} were 0.885 and 0.901, respectively. R3 ($n = 188$) was fine-mode dominated and showed the strongest absorption, with median $SSA_{440} = 0.863$ and $k_{440} = 0.0230$. R4 ($n = 469$) had the highest FMF_{440} (0.952) and SSA_{440} (0.922) and was classified as fine-mode, weakly absorbing aerosol. Combining eight properties gives a more complete description than classifications based on one or two thresholds (Shin et al., 2019; Wei et al., 2024).

Seasonal occurrence differed markedly (Fig. 6). Winter and post-monsoon were dominated by R4, with a secondary contribution from R3. Pre-monsoon contained larger contributions from mixed-size R2 and coarse-influenced R1. R1 and R2 also represented most classified monsoon retrievals, although the relatively small inversion sample limits inference for that season. The seasonal transition was therefore not merely a change in total AOD: it involved coordinated shifts in size distribution and absorption.

The shift toward R1 and R2 during pre-monsoon agrees with the known coexistence of dust and combustion aerosol along the southern Himalayan foothills (Gautam et al., 2011; Eck et al., 2010). Dry surfaces favor dust entrainment, while fires and regional emissions add absorbing fine particles. R3 represents periods when absorbing fine aerosol was prominent without a comparable coarse contribution. R4 was common in winter and post-monsoon and showed weaker absorption. These descriptions refer to column aerosol mixtures and do not establish specific sources.

3.3 Radiative significance of the regimes

BOA forcing became more negative as aerosol loading increased ($R^2 = 0.817$), showing stronger surface dimming at higher AOD_{440} (Fig. 7a). TOA forcing also became more negative with aerosol loading, although the relationship was weaker ($R^2 = 0.616$; Fig. 7b). Among the examined predictors, $AAOD_{440}$ showed the strongest relationship with atmospheric forcing ($R^2 = 0.892$; Fig. 7c). This result reflects the role of absorption in retaining solar energy within the atmospheric column.

R2 produced the most negative median BOA forcing, approximately -100 W m^{-2} , and one of the largest positive atmospheric forcing values. R1 and R3 produced median atmospheric forcing of approximately $60\text{--}70 \text{ W m}^{-2}$, whereas the frequent weakly absorbing R4 regime produced the least negative BOA forcing and atmospheric forcing near 50 W m^{-2} . Thus, frequency and radiative importance were not equivalent. The radiative influence of a regime depended jointly on aerosol amount, particle-size distribution, and absorption. This distinction is important because the absence of a significant long-term AOD trend does not preclude substantial forcing during particular aerosol states or high-loading episodes.

The strong surface dimming in R2 does not conflict with the lower SSA of R1 and R3. BOA forcing responds to both extinction and absorption. A mixed-size state can therefore produce greater surface attenuation when its aerosol loading is high, even if another state absorbs a larger fraction of the intercepted radiation. Atmospheric forcing is more sensitive to absorption and was correspondingly larger in the more absorbing regimes. Similar dry-season surface cooling and atmospheric heating have been reported at Pokhara and Lumbini (Ramachandran and Rupakheti, 2020; Rupakheti et al., 2020).

AERONET forcing products are derived from the same retrieved aerosol quantities used as predictors. The regressions are therefore not comparisons between independent measurements. They describe internally consistent radiative relationships within the AERONET retrieval framework. Comparisons with ground-based broadband radiation observations nevertheless support the general reliability of AERONET flux and forcing estimates (García et al., 2008).



Aerosol radiative forcing and associated aerosol properties over Pokhara

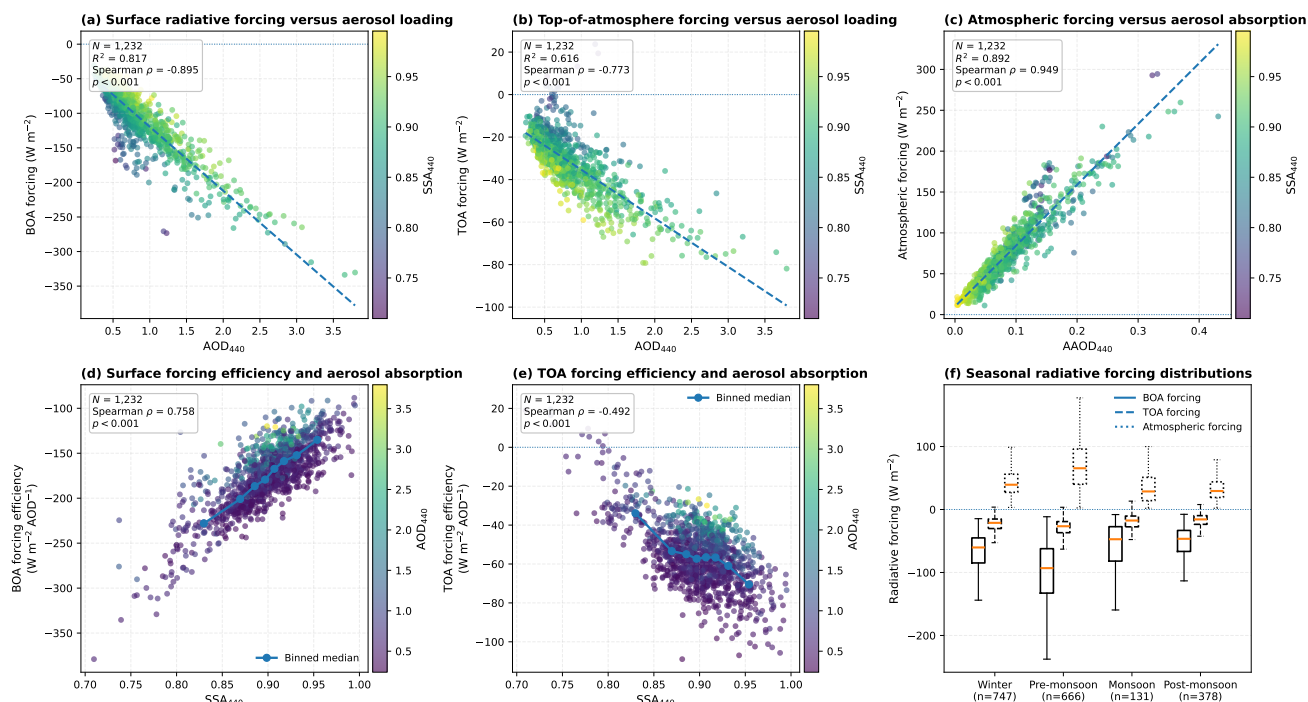


Figure 7. Associations of AERONET shortwave BOA, TOA, and atmospheric aerosol radiative forcing and forcing efficiency with aerosol loading and absorption properties. Panels (a)–(e) use complete variable pairs ($N = 1,232$). Panel (f) uses all days with valid forcing and therefore has larger seasonal samples. Reported relationships are internal to the AERONET retrieval and radiative-transfer framework.

3.4 Robustness and limitations

Matched Almuqantar and Hybrid retrievals showed nearly identical AOD_{440} values ($r = 0.999$, $RMSE = 0.021$; Table 2). Agreement was also high for AE and radiative forcing, consistent with the Version 3 evaluation of Sinyuk et al. (2020). The continuous-variable comparison contained 1,927 pairs, of which 1,026 had valid SSA and AAOD. Small biases remained in the two absorption-sensitive quantities. Hybrid SSA was lower by 0.0078 on average, while Hybrid AAOD was higher by 0.0057.

The separate eight-variable complete-case match produced 1,047 pairs for the regime comparison (Fig. 6d). Of these, 89.0% received the same assignment in both scan geometries ($\kappa = 0.836$). Agreement increased to 92.4% ($\kappa = 0.886$) for the 961 high-confidence pairs. Most disagreements occurred between neighboring regimes. Scan geometry therefore affected observations near regime boundaries more than the broader classification.

Four limitations shape the interpretation. First, cloud screening and inversion requirements reduce monsoon coverage, so seasonal samples are not uniform. Second, AERONET optical retrievals cannot assign the regimes to specific sources. Third, GMM components approximate a continuous distribution. Their names summarize retrieved properties rather than pure aerosol



Table 2. Agreement between temporally matched Almucantar and Hybrid retrievals. Bias is Hybrid minus Almucantar.

Variable	Matched pairs	r	Bias	RMSE
AOD ₄₄₀	1,927	0.999	0.001	0.021
AE _{440–870}	1,927	0.997	−0.001	0.014
SSA ₄₄₀	1,026	0.957	−0.0078	0.0111
AAOD ₄₄₀	1,026	0.992	0.0057	0.0084
BOA forcing (W m ^{−2})	1,927	0.994	−2.24	5.74
TOA forcing (W m ^{−2})	1,927	0.988	1.14	2.47

types. Fourth, AERONET radiative forcing is retrieval-derived and does not directly measure surface-temperature response. Chemical observations, vertical profiles, emission inventories, and systematic trajectory clustering would be needed for source attribution.

In addition, absorption and radiative-forcing products were available for fewer days than direct-sun AOD. Their seasonal distributions and regime associations therefore represent the quality-assured inversion subset rather than all aerosol conditions over Pokhara.

4 Conclusions

The 2010–2024 AERONET record showed strong seasonal and episodic aerosol variability over Pokhara but no statistically significant long-term trend in AOD₄₄₀. Annual and deseasonalized monthly analyses agreed on the absence of a robust monotonic change. Pre-monsoon enhancement involved not only greater aerosol loading but also stronger absorption and increased contributions from both fine- and coarse-mode particles.

Probabilistic classification identified four reproducible but partially overlapping aerosol regimes. Their seasonal occurrence demonstrated coordinated changes in particle size and absorption, while their radiative contrasts showed that the most common aerosol state was not necessarily the most influential. Mixed-size aerosol produced the strongest median surface dimming, and the more absorbing regimes retained more solar energy within the atmospheric column. Classification agreement between matched Almucantar and Hybrid retrievals further supported the robustness of the broad regime structure.

The central implication is that a stable long-term median does not imply stable aerosol effects. Over Pokhara, particular aerosol mixtures and episodic high-loading conditions produced substantial radiative effects despite the absence of a significant long-term trend in AOD₄₄₀. Continued AERONET observations, systematic trajectory clustering, and composition-resolving measurements would help identify the sources and vertical pathways associated with these radiatively important states.



Code and data availability. AERONET Version 3 Level 2.0 data are publicly available from the NASA AERONET portal. Processed data and analysis scripts are available from the corresponding author upon reasonable request.

225 *Author contributions.* GPA contributed to conceptualization, methodology, software, data curation, formal analysis, visualization, and writing of the original draft. SR contributed to investigation, validation, and review and editing of the manuscript. MNU contributed to validation and review and editing of the manuscript. BRT contributed to conceptualization, methodology, supervision, and review and editing of the manuscript. KNP contributed to supervision, validation, and review and editing of the manuscript. NPC contributed to supervision, validation, and review and editing of the manuscript. All authors reviewed and approved the final manuscript.

230 *Competing interests.* The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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235 References

- Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K. S., Christensen, M., Daniau, A.-L., Dufresne, J.-L., Feingold, G., Fiedler, S., Forster, P. M., Gettelman, A., Haywood, J. M., Lohmann, U., Malavelle, F., Mauritsen, T., McCoy, D. T., Myhre, G., Mülmenstädt, J., Neubauer, D., Possner, A., Rugenstein, M., Sato, Y., Schulz, M., Schwartz, S. E., Sourdeval, O., Storelvmo, T., Toll, V., Winker, D., and Stevens, B.: Bounding Global Aerosol Radiative Forcing of Climate Change, *Reviews of Geophysics*, 58, e2019RG000660, <https://doi.org/10.1029/2019RG000660>, 2020.
- 240 Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment, *Journal of Geophysical Research: Atmospheres*, 118, 5380–5552, <https://doi.org/10.1002/jgrd.50171>, 2013.
- 245 Cho, C., Kim, S.-W., Rupakheti, M., Park, J.-S., Panday, A., Yoon, S.-C., Kim, J.-H., Kim, H., Jeon, H., Sung, M., Kim, B. M., Hong, S. K., Park, R. J., Rupakheti, D., Mahata, K. S., Praveen, P. S., Lawrence, M. G., and Holben, B. N.: Wintertime Aerosol Optical and Radiative Properties in the Kathmandu Valley during the SusKat-ABC Field Campaign, *Atmospheric Chemistry and Physics*, 17, 12617–12632, <https://doi.org/10.5194/acp-17-12617-2017>, 2017.
- 250 Cohen, J.: A Coefficient of Agreement for Nominal Scales, *Educational and Psychological Measurement*, 20, 37–46, <https://doi.org/10.1177/001316446002000104>, 1960.
- Dempster, A. P., Laird, N. M., and Rubin, D. B.: Maximum Likelihood from Incomplete Data via the EM Algorithm, *Journal of the Royal Statistical Society: Series B (Methodological)*, 39, 1–22, <https://doi.org/10.1111/j.2517-6161.1977.tb01600.x>, 1977.
- Dhungel, S., Kathayat, B., Mahata, K., and Panday, A.: Transport of Regional Pollutants through a Remote Trans-Himalayan Valley in Nepal, *Atmospheric Chemistry and Physics*, 18, 1203–1216, <https://doi.org/10.5194/acp-18-1203-2018>, 2018.
- 255 Dubovik, O. and King, M. D.: A Flexible Inversion Algorithm for Retrieval of Aerosol Optical Properties from Sun and Sky Radiance Measurements, *Journal of Geophysical Research: Atmospheres*, 105, 20673–20696, <https://doi.org/10.1029/2000JD900282>, 2000.
- Eck, T. F., Holben, B. N., Sinyuk, A., Pinker, R. T., Goloub, P., Chen, H., Chatenet, B., Li, Z., Singh, R. P., Tripathi, S. N., Reid, J. S., Giles, D. M., Dubovik, O., O'Neill, N. T., Smirnov, A., Wang, P., and Xia, X.: Climatological aspects of the optical properties of fine/coarse mode aerosol mixtures, *Journal of Geophysical Research: Atmospheres*, 115, D19205, <https://doi.org/10.1029/2010JD014002>, 2010.
- 260 García, O. E., Díaz, A. M., Expósito, F. J., Díaz, J. P., Dubovik, O., Dubuisson, P., Roger, J.-C., Eck, T. F., Sinyuk, A., Derimian, Y., Dutton, E. G., Schafer, J. S., Holben, B. N., and García, C. A.: Validation of AERONET estimates of atmospheric solar fluxes and aerosol radiative forcing by ground-based broadband measurements, *Journal of Geophysical Research: Atmospheres*, 113, D21207, <https://doi.org/10.1029/2008JD010211>, 2008.
- 265 García, O. E., Díaz, J. P., Expósito, F. J., Díaz, A. M., Dubovik, O., Derimian, Y., Dubuisson, P., and Roger, J.-C.: Shortwave Radiative Forcing and Efficiency of Key Aerosol Types Using AERONET Data, *Atmospheric Chemistry and Physics*, 12, 5129–5145, <https://doi.org/10.5194/acp-12-5129-2012>, 2012.
- Gautam, R., Hsu, N. C., Tsay, S.-C., Lau, K.-M., Holben, B., Bell, S., Smirnov, A., Li, C., Hansell, R., Ji, Q., Payra, S., Aryal, D., Kayastha, R., and Kim, K. M.: Accumulation of Aerosols over the Indo-Gangetic Plains and Southern Slopes of the Himalayas: Distribution, Properties and Radiative Effects during the 2009 Pre-Monsoon Season, *Atmospheric Chemistry and Physics*, 11, 12841–12863, <https://doi.org/10.5194/acp-11-12841-2011>, 2011.
- 270



- Giles, D. M., Holben, B. N., Eck, T. F., Sinyuk, A., Smirnov, A., Slutsker, I., Dickerson, R. R., Thompson, A. M., and Schafer, J. S.: An analysis of AERONET aerosol absorption properties and classifications representative of aerosol source regions, *Journal of Geophysical Research: Atmospheres*, 117, D17 203, <https://doi.org/10.1029/2012JD018127>, 2012.
- 275 Giles, D. M., Sinyuk, A., Sorokin, M. G., Schafer, J. S., Smirnov, A., Slutsker, I., Eck, T. F., Holben, B. N., Lewis, J. R., Campbell, J. R., Welton, E. J., Korkin, S. V., and Lyapustin, A. I.: Advancements in the Aerosol Robotic Network (AERONET) Version 3 Database—Automated Near-Real-Time Quality Control Algorithm with Improved Cloud Screening for Sun Photometer Aerosol Optical Depth (AOD) Measurements, *Atmospheric Measurement Techniques*, 12, 169–209, <https://doi.org/10.5194/amt-12-169-2019>, 2019.
- Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F.,
280 Jankowiak, I., and Smirnov, A.: AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization, *Remote Sensing of Environment*, 66, 1–16, [https://doi.org/10.1016/S0034-4257\(98\)00031-5](https://doi.org/10.1016/S0034-4257(98)00031-5), 1998.
- Hubert, L. and Arabie, P.: Comparing Partitions, *Journal of Classification*, 2, 193–218, <https://doi.org/10.1007/BF01908075>, 1985.
- Jolliffe, I. T. and Cadima, J.: Principal Component Analysis: A Review and Recent Developments, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374, 20150 202, <https://doi.org/10.1098/rsta.2015.0202>, 2016.
- 285 Kendall, M. G.: *Rank Correlation Methods*, Charles Griffin, London, 4 edn., 1975.
- Kumar, M., Parmar, K. S., Kumar, D. B., Mhawish, A., Broday, D. M., Mall, R. K., and Banerjee, T.: Long-Term Aerosol Climatology over the Indo-Gangetic Plain: Trend, prediction and potential source fields, *Atmospheric Environment*, 180, 37–50, <https://doi.org/10.1016/j.atmosenv.2018.02.027>, 2018.
- Linnet, K.: Evaluation of Regression Procedures for Methods Comparison Studies, *Clinical Chemistry*, 39, 424–432,
290 <https://doi.org/10.1093/clinchem/39.3.424>, 1993.
- Mann, H. B.: Nonparametric Tests against Trend, *Econometrica*, 13, 245–259, <https://doi.org/10.2307/1907187>, 1945.
- McLachlan, G. J. and Peel, D.: *Finite Mixture Models*, Wiley Series in Probability and Statistics, John Wiley & Sons, New York, <https://doi.org/10.1002/0471721182>, 2000.
- Ramachandran, S. and Rupakheti, M.: Inter-annual and seasonal variations in columnar aerosol characteristics and radiative effects over
295 the Pokhara Valley in the Himalayan foothills—Composition, radiative forcing, and atmospheric heating, *Environmental Pollution*, 264, 114 799, <https://doi.org/10.1016/j.envpol.2020.114799>, 2020.
- Ramachandran, S. and Rupakheti, M.: Inter-annual and seasonal variations in optical and physical characteristics of columnar aerosols over the Pokhara Valley in the Himalayan foothills, *Atmospheric Research*, 248, 105 254, <https://doi.org/10.1016/j.atmosres.2020.105254>, 2021.
- 300 Ramachandran, S., Rupakheti, M., Cherian, R., and Lawrence, M. G.: Aerosols Heat Up the Himalayan Climate, *Science of the Total Environment*, 894, 164 733, <https://doi.org/10.1016/j.scitotenv.2023.164733>, 2023.
- Regmi, J., Poudyal, K. N., Pokhrel, A., Gyawali, M., Tripathi, L., Panday, A. K., Barinelli, A., and Aryal, R.: Investigation of Aerosol Climatology and Long-Range Transport of Aerosols over Pokhara, Nepal, *Atmosphere*, 11, 874, <https://doi.org/10.3390/atmos11080874>, 2020.
- 305 Rousseeuw, P. J.: Silhouettes: A Graphical Aid to the Interpretation and Validation of Cluster Analysis, *Journal of Computational and Applied Mathematics*, 20, 53–65, [https://doi.org/10.1016/0377-0427\(87\)90125-7](https://doi.org/10.1016/0377-0427(87)90125-7), 1987.
- Rupakheti, D., Kang, S., Rupakheti, M., Cong, Z., Panday, A. K., and Holben, B. N.: Identification of Absorbing Aerosol Types at a Site in the Northern Edge of the Indo-Gangetic Plain and a Polluted Valley in the Foothills of the Central Himalayas, *Atmospheric Research*, 223, 15–23, <https://doi.org/10.1016/j.atmosres.2019.03.003>, 2019.



- 310 Rupakheti, D., Kang, S., and Rupakheti, M.: Two Heavy Haze Events over Lumbini in Southern Nepal: Enhanced Aerosol Radiative Forcing and Heating Rates, *Atmospheric Environment*, 236, 117 658, <https://doi.org/10.1016/j.atmosenv.2020.117658>, 2020.
- Russell, P. B., Bergstrom, R. W., Shinozuka, Y., Clarke, A. D., DeCarlo, P. F., Jimenez, J. L., Livingston, J. M., Redemann, J., Dubovik, O., and Strawa, A.: Absorption Ångström Exponent in AERONET and Related Data as an Indicator of Aerosol Composition, *Atmospheric Chemistry and Physics*, 10, 1155–1169, <https://doi.org/10.5194/acp-10-1155-2010>, 2010.
- 315 Schwarz, G.: Estimating the Dimension of a Model, *The Annals of Statistics*, 6, 461–464, <https://doi.org/10.1214/aos/1176344136>, 1978.
- Sen, P. K.: Estimates of the Regression Coefficient Based on Kendall’s Tau, *Journal of the American Statistical Association*, 63, 1379–1389, <https://doi.org/10.1080/01621459.1968.10480934>, 1968.
- Shin, S.-K., Tesche, M., Noh, Y., and Müller, D.: Aerosol-type classification based on AERONET version 3 inversion products, *Atmospheric Measurement Techniques*, 12, 3789–3803, <https://doi.org/10.5194/amt-12-3789-2019>, 2019.
- 320 Singh, A., Mahata, K. S., Rupakheti, M., Junkermann, W., Panday, A. K., and Lawrence, M. G.: An Overview of Airborne Measurement in Nepal—Part 1: Vertical Profile of Aerosol Size, Number, Spectral Absorption, and Meteorology, *Atmospheric Chemistry and Physics*, 19, 245–258, <https://doi.org/10.5194/acp-19-245-2019>, 2019.
- Sinyuk, A., Holben, B. N., Eck, T. F., Giles, D. M., Slutsker, I., Korkin, S., Schafer, J. S., Smirnov, A., Sorokin, M., and Lyapustin, A.: The AERONET Version 3 aerosol retrieval algorithm, associated uncertainties and comparisons to Version 2, *Atmospheric Measurement Techniques*, 13, 3375–3411, <https://doi.org/10.5194/amt-13-3375-2020>, 2020.
- 325 Wei, X., Cui, Q., Ma, L., Zhang, F., Li, W., and Liu, P.: Global Aerosol-Type Classification Using a New Hybrid Algorithm and Aerosol Robotic Network Data, *Atmospheric Chemistry and Physics*, 24, 5025–5045, <https://doi.org/10.5194/acp-24-5025-2024>, 2024.
- Zhang, Z., Li, J., Che, H., Dong, Y., Dubovik, O., Eck, T. F., Gupta, P., Holben, B. N., Kim, J., Lind, E., Saud, T., Tripathi, S. N., and Ying, T.: Long-term trends in aerosol properties derived from AERONET measurements, *Atmospheric Chemistry and Physics*, 25, 4617–4637, <https://doi.org/10.5194/acp-25-4617-2025>, 2025.
- 330