A Review of Aerosol Optical Depth Using Various Data Over Jaipur Region

Aman Yadav[1*] (0009-0007-4752-0328), Ajay Singh Jethoo[1] (0000-0002-4610-4177), Sheikh Abbas Muhammad[1] (0000-0002-7401-9914), Kaushlandra Bairwa[1] (0009-0003-6966-8869) and Shivam Chauhan[2] (0000-0003-3047-3522)

[1]Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur, Rajasthan, India, 302017

[2]Department of Civil Engineering, University of Engineering and Management, Jaipur, Rajasthan, India, 303807

Abstract: This study offers an in-depth evaluation of methods used to retrieve aerosol optical depth (AOD) through visibility data, with a dedicated lens on Jaipur, India. AOD is a vital measure in understanding how aerosols are distributed in the atmosphere, influencing not only the regional climate but also the quality of the air and public health outcomes. Conventional tools for measuring AOD such as satellite instruments, radiative transfer techniques, and ground-based sun photometers though reliable, often come with high costs and practical limitations in terms of coverage and frequency. In contrast, visibility data, routinely recorded at weather stations, emerges as a promising and economical alternative for estimating AOD. This review delves into various methodologies that draw AOD values from visibility records, with a focus on statistical calibrations validated against direct AOD observations from sun photometers. The work is grounded in the atmospheric conditions of Jaipur, a city marked by high aerosol concentrations stemming from both natural occurrences like dust storms and human-driven sources such as crop residue burning. The study observes notable seasonal shifts, with higher AOD values typically seen during the pre-monsoon and winter months. It also critically discusses the limitations of relying solely on visibility data in complex urban environments, where pollution levels, humidity, and fog can distort visibility measurements. To improve the accuracy of AOD retrievals, the review suggests integrating visibility data with other meteorological indicators and applying advanced machine learning models for better precision. In conclusion, the findings reinforce the potential of visibility-based methods as practical substitutes for traditional AOD monitoring, especially in areas where modern equipment is unavailable. The study offers practical guidance on how to refine these methods, aiming to strengthen future assessments of air quality and climatic behaviour in regions like Jaipur and beyond.

Keywords: Aerosol Regime, Climate Change, Health, AOD Data.

1. Introduction

Aerosols are key atmospheric constituents that influence climate systems, weather patterns, and air quality. Aerosol Optical Depth (AOD) quantifies the total aerosol load within a vertical atmospheric column and is essential for assessing aerosol-induced radiative forcing and their role in climate change.(Guinot et al., 2006; Isaza et al., 2021)

Conventionally, AOD is measured using ground-based sun photometers, such as those in the AERONET network, and satellite remote sensing platforms(Holben et al., 1998). While sun photometers offer high-accuracy observations, their spatial coverage is limited and operationally demanding. Satellites, though more extensive in coverage, often suffer from retrieval uncertainties due to cloud interference, coarse resolution, and surface reflectance.

In recent years, visibility data has gained attention as a cost-effective alternative for estimating AOD. Visibility, regularly recorded at meteorological stations and airports, correlates inversely with aerosol concentrations(Hao et al., 2024). By establishing empirical relationships between reduced visibility and elevated aerosol levels, it becomes feasible to derive AOD estimates from this widely available dataset. This approach is particularly advantageous in regions lacking dense monitoring infrastructure(Guo et al., 2010).

Jaipur, India, offers a representative case for evaluating visibility-based AOD estimation due to its complex aerosol regime, influenced by rapid urbanization, frequent dust intrusions, vehicular emissions, and seasonal biomass burning(Mahesh Kumar Paliwal, 2023). These diverse sources result in pronounced spatiotemporal aerosol variability affecting both visibility and air quality.

This review synthesizes methodologies for retrieving AOD from visibility observations, emphasizing their applicability in Jaipur's atmospheric context. It assesses model performance, limitations, and prospects for integration with supplementary meteorological parameters and machine learning techniques(Ding et al., 2024; Gupta et al., 2016). The study highlights visibility data as a practical proxy for aerosol monitoring and supports its broader application in urban air quality assessment and climate studies, especially in data-limited regions(Dutta et al., 2021).

1.1 Research Gap and Novelty

While numerous studies have investigated the estimation of aerosol optical depth (AOD) using visibility data, the majority have concentrated on large-scale assessments or rural environments. Urban regions like Jaipur, however, remain underrepresented in this context, despite their complex atmospheric composition. In such settings, visibility readings are often distorted by a blend of natural and anthropogenic aerosols, compounded by variable climatic conditions such as high humidity, fog, and pollution, which challenge the accuracy of AOD retrieval.

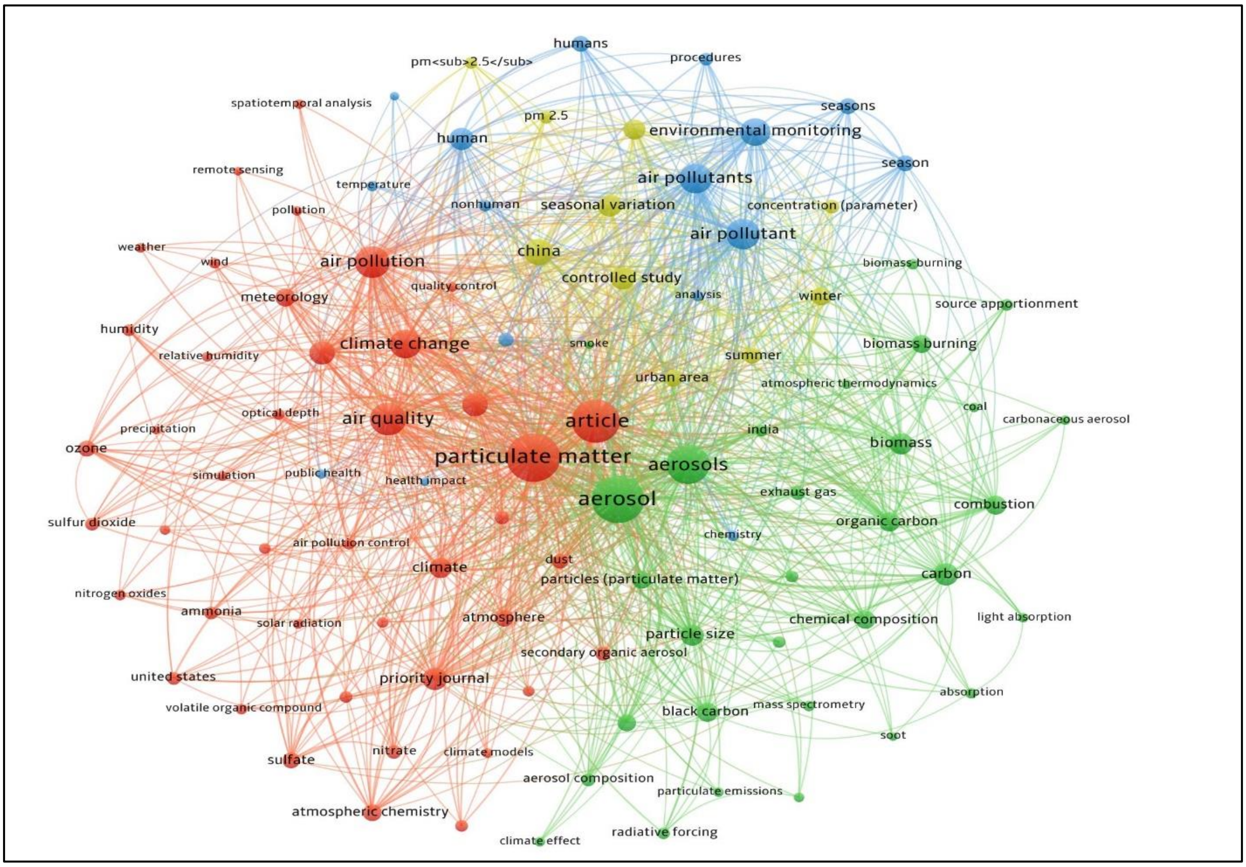
This study stands out in several key aspects:

- It presents a focused and critical review of visibility-based AOD retrieval approaches tailored specifically to the atmospheric conditions of Jaipur—an urban center marked by rapid development and diverse aerosol sources.
- It captures the pronounced seasonal variability in AOD across the region, shaped by events such as dust storms during pre-monsoon periods and biomass burning in winter.

- It identifies the major limitations of visibility-AOD correlations in urban settings, particularly the interfering effects of moisture and low-visibility events, and suggests targeted methodological refinements.
- It explores the potential of integrating machine learning models with visibility datasets to improve AOD estimation accuracy, offering a forward-looking and economically viable strategy for aerosol monitoring in cities of the Global South.

1.2 Literature Review

Aerosol Optical Depth (AOD) serves as a fundamental metric for quantifying aerosol concentrations in the atmosphere, directly influencing radiative balance, air quality, and human health. Over the years, several techniques have been developed to estimate AOD, each with its own strengths and operational constraints(Xu et al., 2015). This section provides an overview of established and emerging approaches used for AOD retrieval.



Thematic Structure of AOD and Particulate Matter Research

1.2.1 Ground-Based Sun Photometry

Ground-based sun photometers, notably those deployed through the AERONET (Aerosol Robotic Network)(Holben et al., n.d.-a, n.d.-b) program, are among the most precise tools available for measuring AOD. (Dey et al., 2004) demonstrated the capability of AERONET to deliver consistent, high-quality spectral data across a global array of sites(Kaskaoutis et al., 2012). These instruments allow for detailed aerosol characterization across multiple wavelengths(Arora et al., 2022; Varpe et al., n.d.). However, their widespread deployment is hindered by high setup and maintenance costs, limiting their presence in resource-constrained or developing regions.

1.2.2 Satellite Remote Sensing

Satellite platforms such as MODIS, MISR, and Himawari-8 have significantly expanded our ability to monitor AOD over large spatial domains(Jiang et al., 2007; Kumar et al., 2015; Mehta, 2015). Studies by (Dubovik et al., 2000; Kaufman et al., 1997) emphasized the potential of these sensors in generating global aerosol datasets. Nevertheless, satellite-derived AOD estimates often suffer from limitations related to cloud cover interference, low spatial resolution, and reduced accuracy over highly reflective surfaces, including urban landscapes and desert regions(Bilal et al., 2014; Dubovik et al., 2000).

1.2.3 Visibility-Based Methods

Visibility records, routinely collected at weather stations and airports, offer a practical and affordable avenue for estimating AOD. Empirical relationships between reduced visibility and higher aerosol concentrations have been effectively established in various studies, including those by (Hao et al., 2024; Li et al., 2010; H. Wang et al., 2021) These methods are particularly useful in regions with sparse instrumental coverage and provide an opportunity for long-term aerosol analysis using historical datasets.

1.2.4 Constraints of Visibility-Based Approaches

Despite their operational simplicity, visibility-based AOD retrievals are sensitive to atmospheric conditions. Research by (Bäumer et al., 2008) has shown that elevated humidity can induce aerosol hygroscopic growth, leading to a significant drop in visibility that may not correspond to a proportional increase in aerosol load. Additionally, fog, pollution, and varying meteorological parameters can introduce distortions, necessitating robust correction mechanisms and model calibration for reliable outputs.

1.2.5 Machine Learning Applications in AOD Estimation

Recent advancements have introduced machine learning (ML) frameworks as complementary tools in AOD retrieval. (Gupta & Christopher, 2009) applied neural network algorithms to integrate visibility and meteorological data, demonstrating marked improvement in estimating particulate concentrations. ML approaches offer considerable promise in enhancing the accuracy of visibility-based AOD estimates, particularly in urban settings where aerosol behaviour is influenced by a multitude of dynamic sources and environmental variables.

2. Aerosol Optical Depth

Aerosol Optical Depth (AOD) represents the total extinction of solar radiation by aerosols across a vertical column of the atmosphere. It is derived by integrating the aerosol extinction coefficient from the surface to the top of the atmosphere and serves as a vital parameter for assessing aerosol concentration and distribution(R. Wang et al., 2017). Aerosols, which interact with solar radiation through scattering and absorption, play a significant role in altering the Earth's energy balance and thereby influence both climate systems and weather dynamics(Bright & Gueymard, 2019; Onyeuwaoma et al., 2015). Elevated AOD values often correspond to hazy conditions, poor air quality, and diminished visibility, while lower AOD levels typically indicate cleaner, more transparent atmospheric states. The accurate quantification of AOD is essential for a wide range of applications ranging from global climate modeling and satellite radiative transfer studies to Earth's energy monitoring and public health assessments. Particularly in urban and industrial regions, reliable AOD measurements support forecasting efforts and epidemiological research linking aerosol exposure to respiratory and cardiovascular illnesses(Dockery & Pope, 1994; Eberhart & Shi, 2001).

2.1 Aerosol Optical Depth (AOD) Analysis

Aerosol Optical Depth (AOD) quantifies the degree to which aerosols attenuate incoming solar radiation along a vertical atmospheric column(Campbell & Shepard, 2003; Dong et al., 2023). It is mathematically expressed as the integral of the aerosol extinction coefficient with respect to height, encompassing both scattering and absorption effects throughout the depth of the atmosphere:

$$AOD(\lambda) = \int_0^{\infty} \sigma_a(z,\lambda)dz$$

where:

1. AOD(λ) is the aerosol optical depth at wavelength λ.
2. $\sigma_a(z,\lambda)$ is the aerosol extinction coefficient at height z and wavelength λ.
3. dz represents an infinitesimal vertical distance through the atmosphere (Mohammadi-Zadeh et al., 2017; Sun et al., 2015)).

In practical applications, AOD can also be estimated using empirical relationships that relate observed radiative measurements such as surface-based or satellite-measured radiance to aerosol extinction. One common formulation is based on the Beer–Lambert–Bouguer law, which describes the attenuation of direct solar irradiance as it passes through the atmosphere:

$$AOD(\lambda) = \frac{In(\frac{I_0(\lambda)}{I_\lambda})}{k(\lambda)}$$

where:

- $I_0(\lambda)$ is the measured radiance of the direct solar beam without aerosols (or at a reference condition).
- I(λ) is the measured radiance of the direct solar beam with aerosols.
- k(λ) is a factor that accounts for atmospheric conditions and the specific wavelength λ (Qiu, 2003)

This equation assumes that the primary influence on radiance is due to aerosols, with other atmospheric conditions such as water vapor or gases either being accounted for or considered negligible. In practice, retrieval algorithms and models may include additional terms to account for various atmospheric components and conditions.

3. Study Area

Jaipur, the capital city of Rajasthan, India, is situated at 26.9124° N latitude and 75.7873° E longitude, at an elevation of approximately 431 meters above sea level(Bairwa et al., 2024). The city experiences a semi-arid climate, characterized by distinct seasonal patterns hot summers, a monsoon period, and relatively mild winters each exerting varying influences on aerosol concentrations and atmospheric conditions.

During the summer months (March to June), ambient temperatures frequently exceed 45°C. The city's proximity to the Thar Desert results in frequent dust storms, significantly elevating aerosol optical depth (AOD) due to coarse mineral dust loading. In contrast, the monsoon season (July to September) generally lowers AOD values through wet deposition and atmospheric cleansing. However, elevated humidity during this period can enhance the formation of fine aerosols via secondary aerosol processes(Huang et al., 2007; Roesch et al., 2025; Sarangi et al., 2018).

The winter season (October to February) is characterized by lower temperatures, frequent temperature inversions, and calm atmospheric conditions. These factors, coupled with biomass burning and increased residential fuel use, contribute to the accumulation of fine particulate matter, leading to heightened AOD levels(Silva et al., 2007).

In addition to seasonal variability, Jaipur’s accelerating urban growth and industrial expansion have markedly increased anthropogenic aerosol emissions. Major contributors include vehicular exhaust, industrial discharge, construction dust, and open biomass burning. Natural sources, particularly desert dust intrusions, further compound the aerosol burden(Saxena et al., 2010).

Given this complex interplay of natural and human-induced sources, accurate retrieval and monitoring of AOD over Jaipur are essential for assessing air quality, evaluating climate forcing, and understanding the implications for public health in this rapidly developing urban environment(Kanakidou et al., 2005; Qin et al., 2016).

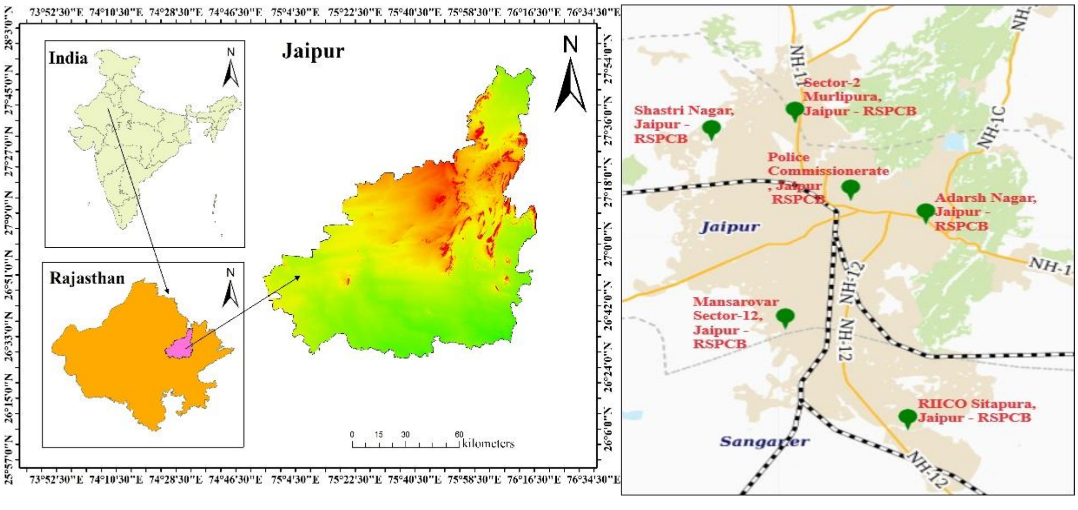


Figure 1. Jaipur City map with location of RSPCB data collection instrument sites

4. Methods of AOD Retrieval

4.1 Ground-Based Sun Photometry Ground-based sun photometers measure direct solar radiation at various wavelengths to estimate AOD. Instruments from networks such as AERONET provide highly accurate and spectrally rich data. However, their limited geographic distribution and operational requirements restrict widespread deployment(Dubovik et al., 2000).

4.2 Satellite Remote Sensing Satellite sensors including MODIS, MISR, and VIIRS determine AOD by analyzing reflected radiance from Earth's surface and atmosphere. These systems offer continuous and large-scale monitoring capabilities but face challenges in resolution and performance over bright or cloudy regions.

4.3 Visibility-Based Methods Visibility records, commonly collected at weather stations, offer a cost-effective option for estimating AOD using statistical correlations between visibility and aerosol concentration. This method is particularly useful in areas where advanced observational systems are lacking.

4.4 Lidar Remote Sensing Lidar instruments emit laser pulses and detect backscattered light to map vertical profiles of aerosols. These systems provide insight into the distribution and layering of aerosols, aiding in comprehensive atmospheric assessments.

4.5 Radiative Transfer Models Radiative transfer simulations replicate solar radiation interactions with atmospheric particles to estimate AOD. Comparing observed and modeled radiance values allows for more refined AOD retrieval and better understanding of aerosol effects on radiative balance(Gupta & Christopher, 2009).

4.6 Ground-Based Radiometers These devices measure incoming radiance from multiple directions and wavelengths, contributing to detailed assessments of aerosol characteristics and supporting AOD estimation alongside other ground-based tools.

5. Aerosol Regime Over Jaipur, India

Jaipur, situated in northwestern India, experiences significant aerosol loading influenced by natural and human-induced sources(Liu et al., 2018). Dust from the Thar Desert, emissions from transport and industry, and seasonal biomass burning all contribute to atmospheric aerosol concentrations.

5.1 Seasonal Variation in AOD

- **Pre-Monsoon (Mar–May):** High AOD levels prevail due to desert dust transported by strong winds.
- **Monsoon (Jun–Sep):** AOD decreases because of rain-driven aerosol removal, though localized emissions persist.
- **Post-Monsoon (Oct–Nov):** AOD rises again, influenced by agricultural residue burning and urban emissions.
- **Winter (Dec–Feb):** Stable atmospheric conditions and low boundary layer heights lead to aerosol accumulation, particularly from biomass use(Kant et al., 2021).

5.2 Source Attribution

- **Dust Aerosols:** Transport from the Thar Desert is a major contributor during the pre-monsoon season.
- **Anthropogenic Sources:** Urban emissions from vehicles, industry, and domestic burning contribute year-round, with peaks during cooler months(Soni et al., 2018).

5.3 Impact on Climate and Health

- **Climate:** Aerosols affect solar radiation and surface temperature, influencing local weather and agriculture.
- **Health:** Elevated particulate matter levels are linked to respiratory and cardiovascular issues, particularly during winter.

5.4 Challenges with Visibility-Based AOD Retrieval Visibility data are affected by environmental factors such as humidity and fog. These conditions can lead to visibility reductions not directly proportional to aerosol concentration, requiring adjustment mechanisms for accurate AOD estimation.

6. Comparative Analysis of Visibility-Based AOD Retrieval

6.1 Methodology

- Visibility-based AOD estimates were developed using region-specific models.
- MODIS satellite data served as the comparative benchmark.
- AERONET measurements were used for validation where available.

6.2 Performance Metrics

Season	**R^2**	**RMSE**	**MBE**
Pre-Monsoon	0.78	0.09	-0.03
Monsoon	0.81	0.07	+0.02
Post-Monsoon	0.75	0.10	-0.04
Winter	0.72	0.12	-0.05

6.3 Interpretation Visibility-derived AOD shows strongest agreement with satellite data during the monsoon. Seasonal discrepancies are observed in pre-monsoon and winter, influenced by dust, fog, and hygroscopic effects.

6.4 Discussion Visibility methods offer practical value but are susceptible to atmospheric variability. Improved accuracy can be achieved by applying correction factors and incorporating additional data sources such as meteorological inputs and machine learning techniques.

7. Recommendations for Enhancing AOD Retrieval

7.1 Integrate Multiple Data Sources

- Combine visibility with satellite AOD data.
- Validate models using ground observations.

7.2 Improve Empirical Models

- Tailor models to regional climate and aerosol conditions.
- Include dynamic meteorological variables.

7.3 Apply Machine Learning Techniques

- Use advanced algorithms to model non-linear patterns.
- Integrate multi-variable inputs for better accuracy.

7.4 Enhance Data Resolution and Quality

- Utilize finer-resolution and real-time datasets.
- Increase the density of observational stations.

7.5 Account for Seasonal and Diurnal Effects

- Develop models specific to seasonal aerosol behaviour.
- Incorporate daily variations in boundary layer and sunlight.

7.6 Strengthen Atmospheric Corrections

- Adjust for relative humidity and temperature effects.
- Differentiate between aerosol types using optical or chemical indicators.

7.7 Conduct Sensitivity and Uncertainty Analyses

- Analyse model error sources.
- Provide uncertainty bounds for AOD estimates.

7.8 Foster Interdisciplinary Collaboration

- Engage with atmospheric scientists and health professionals for integrated assessments.

7.9 Embrace Technological Advances

- Use emerging satellite sensors and processing tools.
- Apply big data analytics for pattern recognition and trend detection.

7.10 Promote Long-Term Monitoring

- Establish sustained observation programs.
- Analyse long-term trends to enhance model development.

8. Conclusions

This report has reviewed various techniques for estimating aerosol optical depth, with particular emphasis on visibility-based methods in the context of Jaipur. While visibility data offer an accessible solution for aerosol monitoring, they require refinement through localized calibration and integration with satellite and ground observations. With continued methodological improvements, visibility-based AOD retrieval can contribute significantly to air quality assessment, climate studies, and health risk analysis in regions with limited monitoring infrastructure.

Acknowledgements Authors sincerely thanks to all the anonymous reviewers and responsible editor for their insightful comments and suggestions, which have greatly improved the quality of this paper. Authors also sincerely acknowledge the articles which have been used in this review paper.

Author Contributions

The study was conceived and designed by Aman Yadav, Shivam Chauhan, Ajay Singh Jethoo and Kaushlandra Bairwa, while Sheikh Abbas Muhammad, Shivam Chauhan and Kaushlandra Bairwa were responsible for the acquisition of data. The analysis and interpretation of the data was conducted by Aman Yadav, Shivam Chauhan and Ajay Singh Jethoo. The manuscript was drafted by Aman Yadav, Shivam Chauhan, Kaushlandra Bairwa, and Ajay Singh Jethoo, while Ajay Singh Jethoo and Sheikh Abbas Muhammad revised it critically for important intellectual content. Finally, the version of the manuscript to be published was approved by Aman Yadav, Sheikh Abbas Muhammad, Shivam Chauhan, Ajay Singh Jethoo, and Kaushlandra Bairwa.

Funding

No funding was received for conducting this study. Availability of data and materials the data that support the findings of this study are available from the corresponding and the first author upon reasonable request.

Code availability

The codes that support the findings of this study are available from the corresponding and the first author upon reasonable request.

Declarations

Conflict of interest

The authors have no relevant financial or nonfinancial interests to disclose.

Ethical Responsibilities of Authors

All authors have read, understood, and have compiled as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Consent to participate

Not Applicable

Consent for publication

Not Applicable

10. References

Arora, S., Nag, A., Kalra, A., Sinha, V., Meena, E., Saxena, S., Sutaria, D., Kaur, M., Pamnani, T., Sharma, K., Saxena, S., Shrivastava, S. K., Gupta, A. B., Li, X., & Jiang, G. (2022). Successful application of wastewater-based epidemiology in prediction and monitoring of the second wave of COVID-19 with fragmented sewerage systems–a case study of Jaipur (India). *Environmental Monitoring and Assessment*, *194*(5). https://doi.org/10.1007/s10661-022-09942-5

Bairwa, K., Jethoo, A. S., Yadav, A., Muhammad, S. A., & Chauhan, S. (2024). Longitudinal Assessment of Urban Land Transformations with Multi-Sensory Remote Sensing in a Semi-Arid Metropolitan City. *IEMECON 2024 - 12th International Conference on Internet of Everything, Microwave, Embedded, Communication and Networks*. https://doi.org/10.1109/IEMECON62401.2024.10846040

Bäumer, D., Vogel, B., Versick, S., Rinke, R., Möhler, O., & Schnaiter, M. (2008). Relationship of visibility, aerosol optical thickness and aerosol size distribution in an ageing air mass over South-West Germany. *Atmospheric Environment*, *42*(5), 989–998. https://doi.org/10.1016/j.atmosenv.2007.10.017

Bilal, M., Nichol, J. E., & Chan, P. W. (2014). Validation and accuracy assessment of a Simplified Aerosol Retrieval Algorithm (SARA) over Beijing under low and high aerosol loadings and dust storms. *Remote Sensing of Environment*, *153*, 50–60. https://doi.org/10.1016/j.rse.2014.07.015

Bright, J. M., & Gueymard, C. A. (2019). Climate-specific and global validation of MODIS Aqua and Terra aerosol optical depth at 452 AERONET stations. *Solar Energy*, *183*, 594–605. https://doi.org/10.1016/j.solener.2019.03.043

Campbell, B. A., & Shepard, M. K. (2003). Coherent and incoherent components in near-nadir radar scattering: Applications to radar sounding of Mars. *Journal of Geophysical Research: Planets*, *108*(12). https://doi.org/10.1029/2003JE002164

Dey, S., Tripathi, S. N., Singh, R. P., & Holben, B. N. (2004). Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. *Journal of Geophysical Research D: Atmospheres*, *109*(20). https://doi.org/10.1029/2004JD004924

Ding, Y., Li, S., Xing, J., Li, X., Ma, X., Song, G., Teng, M., Yang, J., Dong, J., & Meng, S. (2024). Retrieving hourly seamless PM2.5 concentration across China with physically informed spatiotemporal connection. *Remote Sensing of Environment*, *301*. https://doi.org/10.1016/j.rse.2023.113901

Dockery, D. W., & Pope, C. A. (1994). Acute respiratory effects of particulate air pollution. *Annual Review of Public Health*, *15*, 107–132. https://doi.org/10.1146/ANNUREV.PU.15.050194.000543

Dong, Y., Li, J., Yan, X., Li, C., Jiang, Z., Xiong, C., Chang, L., Zhang, L., Ying, T., & Zhang, Z. (2023). Retrieval of aerosol single scattering albedo using joint satellite and surface visibility measurements. *Remote Sensing of Environment*, *294*. https://doi.org/10.1016/j.rse.2023.113654

Dubovik, O., Smirnov, A., Holben, B. N., King, M. D., Kaufman, Y. J., Eck, T. F., & Slutsker, I. (2000). Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) Sun and sky radiance measurements. *Journal of Geophysical Research Atmospheres*, *105*(D8), 9791–9806. https://doi.org/10.1029/2000JD900040

Dutta, S., Ghosh, S., & Dinda, S. (2021). Urban Air-Quality Assessment and Inferring the Association Between Different Factors: A Comparative Study Among Delhi, Kolkata and Chennai Megacity of India. *Aerosol Science and Engineering*, *5*(1), 93–111. https://doi.org/10.1007/s41810-020-00087-x

Eberhart, R. C., & Shi, Y. (2001). Particle swarm optimization: Developments, applications and resources. *Proceedings of the IEEE Conference on Evolutionary Computation, ICEC*, *1*, 81–86. https://doi.org/10.1109/CEC.2001.934374

Guinot, B., Roger, J. C., Cachier, H., Pucai, W., Jianhui, B., & Tong, Y. (2006). Impact of vertical atmospheric structure on Beijing aerosol distribution. *Atmospheric Environment*, *40*(27), 5167–5180. https://doi.org/10.1016/J.ATMOSENV.2006.03.051

Guo, J., Zhang, X., Cao, C., Che, H., Liu, H., Gupta, P., Zhang, H., Xu, M., & Li, X. (2010). Monitoring haze episodes over the yellow sea by combining multisensor measurements. *International Journal of Remote Sensing*, *31*(17), 4743–4755. https://doi.org/10.1080/01431161.2010.485213

Gupta, P., & Christopher, S. A. (2009). Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: 2. A neural network approach. *Journal of Geophysical Research Atmospheres*, *114*(20). https://doi.org/10.1029/2008JD011497

Gupta, P., Levy, R. C., Mattoo, S., Remer, L. A., & Munchak, L. A. (2016). A surface reflectance scheme for retrieving aerosol optical depth over urban surfaces in MODIS Dark Target retrieval algorithm. *Atmospheric Measurement Techniques*, *9*(7), 3293–3308. https://doi.org/10.5194/amt-9-3293-2016

Hao, H., Wang, K., Zhao, C., Wu, G., & Li, J. (2024). Visibility-derived aerosol optical depth over global land from 1959 to 2021. *Earth System Science Data*, *16*(7), 3233–3260. https://doi.org/10.5194/essd-16-3233-2024

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., Jankowiak, I., & Smirnov, A. (1998). AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. *Remote Sensing of Environment*, *66*(1), 1–16. https://doi.org/https://doi.org/10.1016/S0034-4257(98)00031-5

Holben, B. N., Tanré, D., Smirnov, A., Eck, T. F., Slutsker, I., Abuhassan, N., Newcomb, W. W., Schafer, J. S., Chatenet, B., Lavenu, F., Kaufman, Y. J., Castle, J. Vande, Setzer, A., Markham, B., Clark, D., Frouin, R., Halthore, R., Karneli, A., O'neill, N. T., … Zibordi, G. (n.d.-a). *An emerging ground-based aerosol climatology: Aerosol Optical Depth from AERONET*.

Holben, B. N., Tanré, D., Smirnov, A., Eck, T. F., Slutsker, I., Abuhassan, N., Newcomb, W. W., Schafer, J. S., Chatenet, B., Lavenu, F., Kaufman, Y. J., Castle, J. Vande, Setzer, A., Markham, B., Clark, D., Frouin, R., Halthore, R., Karneli, A., O'neill, N. T., … Zibordi, G. (n.d.-b). *An emerging ground-based aerosol climatology: Aerosol Optical Depth from AERONET*.

Huang, J., Minnis, P., Yi, Y., Tang, Q., Wang, X., Hu, Y., Liu, Z., Ayers, K., Trepte, C., & Winker, D. (2007). Summer dust aerosols detected from CALIPSO over the Tibetan Plateau. *Geophysical Research Letters*, *34*(18). https://doi.org/10.1029/2007GL029938

Isaza, A., Kay, M., Evans, J. P., Bremner, S., & Prasad, A. (2021). Validation of Australian atmospheric aerosols from reanalysis data and CMIP6 simulations. *Atmospheric Research*, *264*. https://doi.org/10.1016/j.atmosres.2021.105856

Jiang, X., Liu, Y., Yu, B., & Jiang, M. (2007). Comparison of MISR aerosol optical thickness with AERONET measurements in Beijing metropolitan area. *Remote Sensing of Environment*, *107*(1–2), 45–53. https://doi.org/10.1016/j.rse.2006.06.022

Kanakidou, M., Seinfeld, J. H., Pandis, S. N., Barnes, I., Dentener, F. J., Facchini, M. C., Van Dingenen, R., Ervens, B., Nenes, A., Nielsen, C. J., Swietlicki, E., Putaud, J. P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, G. K., Winterhalter, R., Myhre, C. E. L., Tsigaridis, K., … Wilson, J. (2005). Organic aerosol and global climate modelling: a review. *Atmospheric Chemistry and Physics*, *5*(4), 1053–1123. https://doi.org/10.5194/acp-5-1053-2005

Kant, S., Panda, J., Rao, P., Sarangi, C., & Ghude, S. D. (2021). Study of aerosol-cloud-precipitation-meteorology interaction during a distinct weather event over the Indian region using WRF-Chem. *Atmospheric Research*, *247*. https://doi.org/10.1016/j.atmosres.2020.105144

Kaskaoutis, D. G., Singh, R. P., Gautam, R., Sharma, M., Kosmopoulos, P. G., & Tripathi, S. N. (2012). Variability and trends of aerosol properties over Kanpur, northern India using AERONET data (200110). *Environmental Research Letters*, *7*(2). https://doi.org/10.1088/1748-9326/7/2/024003

Kaufman, Y. J., Tanré, D., Remer, L. A., Vermote, E. F., Chu, A., & Holben, B. N. (1997). Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *Journal of Geophysical Research Atmospheres*, *102*(14), 17051–17067. https://doi.org/10.1029/96jd03988

Kumar, K. R., Yin, Y., Sivakumar, V., Kang, N., Yu, X., Diao, Y., Adesina, A. J., & Reddy, R. R. (2015). Aerosol climatology and discrimination of aerosol types retrieved from MODIS, MISR and OMI over Durban (29.88°S, 31.02°E), South Africa. *Atmospheric Environment*, *117*, 9–18. https://doi.org/10.1016/j.atmosenv.2015.06.058

Li, Z., Lee, K. H., Wang, Y., Xin, J., & Hao, W. M. (2010). First observation-based estimates of cloud-free aerosol radiative forcing across China. *Journal of Geophysical Research Atmospheres*, *115*(17). https://doi.org/10.1029/2009JD013306

Liu, B., Ma, Y., Gong, W., Zhang, M., Wang, W., & Shi, Y. (2018). Comparison of AOD from CALIPSO, MODIS, and Sun Photometer under Different Conditions over Central China. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-28417-7

Mahesh Kumar Paliwal. (2023). Assessment of air quality index of Jaipur city (Rajasthan) India. *International Journal of Science and Research Archive*, *8*(1), 465–473. https://doi.org/10.30574/ijsra.2023.8.1.0069

Mehta, M. (2015). A study of aerosol optical depth variations over the Indian region using thirteen years (2001-2013) of MODIS and MISR Level 3 data. *Atmospheric Environment*, *109*, 161–170. https://doi.org/10.1016/j.atmosenv.2015.03.021

Mohammadi-Zadeh, M. J., Karbassi, A., Bidhendi, G. N., Abbaspour, M., & Padash, A. (2017). An Analysis of Air Pollutants' Emission Coefficient in the Transport Sector of Tehran. *Open Journal of Ecology*, *07*(05), 309–323. https://doi.org/10.4236/oje.2017.75022

Onyeuwaoma, N. D., Nwofor, O. K., Chineke, T. C., Eguaroje, E. O., & Dike, V. N. (2015). Implications of MODIS impression of aerosol loading over urban and rural settlements in Nigeria: Possible links to energy consumption patterns in the country. *Atmospheric Pollution Research*, *6*(3), 484–494. https://doi.org/10.5094/APR.2015.054

Qin, K., Wu, L., Wong, M. S., Letu, H., Hu, M., Lang, H., Sheng, S., Teng, J., Xiao, X., & Yuan, L. (2016). Trans-boundary aerosol transport during a winter haze episode in China revealed by ground-based Lidar and CALIPSO satellite. *Atmospheric Environment*, *141*, 20–29. https://doi.org/10.1016/j.atmosenv.2016.06.042

Qiu, J. (2003). *Broadband Extinction Method to Determine Aerosol Optical Depth from Accumulated Direct Solar Radiation*.

Roesch, C. M., Fons, E., Ballinger, A. P., Runge, J., & Hegerl, G. C. (2025). Decreasing aerosols increase the European summer diurnal temperature range. *Npj Climate and Atmospheric Science*, *8*(1). https://doi.org/10.1038/s41612-025-00922-3

Sarangi, C., Kanawade, V. P., Tripathi, S. N., Thomas, A., & Ganguly, D. (2018). Aerosol-induced intensification of cooling effect of clouds during Indian summer monsoon. *Nature Communications*, *9*(1), 3754. https://doi.org/10.1038/s41467-018-06015-5

Saxena, D., Yadav, R., Kumar, A., & Rai, J. (2010). Measurement of atmospheric aerosols during monsoon and winter seasons at Roorkee, India. In *Indian Journal of Radio & Space Physics* (Vol. 39).

Silva, P. J., Vawdrey, E. L., Corbett, M., & Erupe, M. (2007). Fine particle concentrations and composition during wintertime inversions in Logan, Utah, USA. *Atmospheric Environment*, *41*(26), 5410–5422. https://doi.org/10.1016/J.ATMOSENV.2007.02.016

Soni, M., Payra, S., & Verma, S. (2018). Particulate matter estimation over a semi arid region Jaipur, India using satellite AOD and meteorological parameters. *Atmospheric Pollution Research*, *9*(5), 949–958. https://doi.org/10.1016/j.apr.2018.03.001

Sun, Y., Du, W., Wang, Q., Zhang, Q., Chen, C., Chen, Y., Chen, Z., Fu, P., Wang, Z., Gao, Z., & Worsnop, D. R. (2015). Real-Time Characterization of Aerosol Particle Composition above the Urban Canopy in Beijing: Insights into the Interactions between the Atmospheric Boundary Layer and Aerosol Chemistry. *Environmental Science and Technology*, *49*(19), 11340–11347. https://doi.org/10.1021/ACS.EST.5B02373

Varpe, S., Mhamane, R., Kutal, G., Aher, G., Jain, S., Prasarak, V., & Keshri, M. S. (n.d.). *Evaluation of MODIS Retrieved AOD Products and MODIS AOD Climatology over the Pune*. www.linojournal.com

Wang, H., Liu, Z., Zhang, Y., Yu, Z., & Chen, C. (2021). Impact of different urban canopy models on air quality simulation in Chengdu, southwestern China. *Atmospheric Environment*, *267*. https://doi.org/10.1016/j.atmosenv.2021.118775

Wang, R., Xu, X., Jia, S., Ma, R., Ran, L., Deng, Z., Lin, W., Wang, Y., & Ma, Z. (2017). Lower tropospheric distributions of O3 and aerosol over Raoyang, a rural site in the North China Plain. *Atmospheric Chemistry and Physics*, *17*(6), 3891–3903. https://doi.org/10.5194/ACP-17-3891-2017

Xu, H., Guang, J., Xue, Y., de Leeuw, G., Che, Y. H., Guo, J., He, X. W., & Wang, T. K. (2015). A consistent aerosol optical depth (AOD) dataset over mainland China by integration of several AOD products. *Atmospheric Environment*, *114*, 48–56. https://doi.org/10.1016/j.atmosenv.2015.05.023