

Urban Pollution Domes in India: Spatio-Temporal Patterns, Driving Factors and Environmental Implications

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Abstract

Rapid urbanisation, industrialisation, motorisation and energy consumption have intensified atmospheric pollution across Indian cities, yet the spatial distribution of urban pollution is considerably more complex than the conventional image of a uniformly polluted city centre. This paper examines the spatio-temporal characteristics, principal drivers and environmental implications of urban pollution domes in India through a critical synthesis of satellite observations, ground-based air-quality measurements, meteorological evidence and recent peer-reviewed research. The study is secondary-data based and adopts a descriptive-analytical and comparative geographical approach. Particular attention is given to the Urban Aerosol Island framework, in which aerosol optical depth or particulate concentrations over urban areas are compared with their non-urban surroundings. Evidence from 141 Indian cities demonstrates a pronounced geographical contrast: conventional Urban Aerosol Pollution Islands are more prevalent in southern and southeastern cities, whereas many northern and northwestern cities display relative Urban Aerosol Clean Islands because high regional background aerosol loading can obscure or “puncture” the urban dome. Seasonal variations are equally important, with post-monsoon conditions favouring positive urban aerosol contrasts, while transported mineral dust increasingly influences northern and western India during winter and pre-monsoon periods. Local emissions, urban morphology, wind stilling, atmospheric stability, regional dust transport, biomass burning and agricultural land-use cycles collectively determine pollution-dome intensity. The paper concludes that Indian urban air pollution cannot be effectively governed through city-specific emission control alone. Integrated urban–regional airshed management, improved urban–rural monitoring and stronger coupling of satellite and surface observations are required for effective clean-air policy.

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1. Introduction

Air pollution has emerged as one of the most persistent environmental challenges associated with contemporary urbanisation. Cities concentrate population, transport infrastructure, industrial activity, construction, energy consumption and waste generation within relatively limited geographical areas. This concentration can create atmospheric environments in which pollutants are emitted faster than they can be dispersed. The resulting accumulation of particulate and gaseous pollutants may produce a spatially identifiable zone of elevated pollution above or around the urban area. In urban-climatological literature this has been described as an urban pollution island, turbidity island or, particularly when aerosols dominate the signal, an Urban Aerosol Pollution Island (UAPI). The broader popular expression “pollution dome” refers to the tendency of polluted air to accumulate over an urban area under particular combinations of emissions, surface roughness, atmospheric stability and limited ventilation.

The concept is closely related to, but distinct from, the better-known Urban Heat Island (UHI). Crutzen (2004) drew attention to the expanding urban heat and pollution island effects and their implications for atmospheric chemistry and climate. Whereas an Urban Heat Island describes a positive urban–rural temperature contrast, an Urban Aerosol Pollution Island refers to higher aerosol or particulate loading within the urban area than in the surrounding non-urban environment. A pollution dome should therefore not be understood as a permanently bounded atmospheric structure. Its dimensions, intensity and even its direction—that is, whether the urban core is more or less polluted than its surroundings—may change across seasons, meteorological regimes and source configurations.

This distinction is especially important in India. Conventional reasoning might suggest that highly polluted metropolitan regions such as Delhi, Kanpur or other Indo-Gangetic Plain cities should invariably exhibit the strongest positive pollution domes. Recent evidence, however, demonstrates that the relationship is more complicated. Sethi and Vinoj (2025), analysing satellite-retrieved aerosol optical depth (AOD) for 141 Indian cities over 2003–2020, identified both positive Urban Aerosol Pollution Islands and negative Urban Aerosol Clean Islands (UACIs). Positive pollution islands were especially common in southern and southeastern India, whereas many northern and northwestern cities showed lower AOD over the urban domain relative to an already heavily polluted surrounding background. Around 57% of the analysed cities displayed positive UAPI conditions and 43% displayed UACI conditions on an annual climatological basis.

The finding does not imply that the northern cities classified as UACIs have clean air. Rather, it demonstrates the limitations of interpreting urban pollution exclusively through administrative city boundaries. In highly polluted regional environments such as the Indo-Gangetic Plain (IGP), pollutant concentrations outside the city can be comparable to or greater than those within it. India-wide satellite-derived PM_{2.5} research has similarly shown poor air quality extending

across urban–rural transects, indicating that atmospheric pollution is often regional rather than exclusively urban (Dey et al., 2020). This regionalisation of pollution challenges the assumption that an urban pollution dome must always have its maximum concentration over the built-up centre.

The environmental importance of this problem is substantial. Air pollution affects mortality and morbidity, reduces visibility, modifies radiative transfer and cloud microphysical processes, and interacts with urban thermal conditions. The India State-Level Disease Burden Initiative estimated that 1.67 million deaths were attributable to air pollution in India in 2019, equivalent to 17.8% of all deaths in the country in that year. Ambient particulate matter alone accounted for an estimated 0.98 million deaths. The corresponding estimated economic loss from premature mortality and morbidity was US\$36.8 billion, or about 1.36% of India's GDP in 2019 (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2021). These estimates describe the broader burden of air pollution rather than the specific effect of pollution domes, but they underline the health significance of understanding the spatial processes that determine exposure.

The research problem addressed in this paper therefore concerns the geographical mismatch between the traditional city-centred conception of a pollution dome and the increasingly documented dominance of regional atmospheric processes in India. Existing studies often focus on individual metropolitan areas, particular pollutants or short observation periods. The recent availability of high-resolution satellite AOD, long-term PM_{2.5} reconstructions, expanded monitoring networks and multi-city comparative research now makes it possible to reinterpret pollution domes within a more explicitly regional and spatio-temporal framework.

Accordingly, the present paper pursues four objectives: to clarify the conceptual meaning of urban pollution domes and Urban Aerosol Islands in the Indian context; to analyse their spatial and seasonal variability across different regions of India; to evaluate the relative importance of urban emissions, meteorology, dust transport, agricultural activity and urban morphology in controlling these patterns; and to assess the health, climatic and policy implications of the emerging evidence. The corresponding research questions are: How do urban pollution domes vary geographically across Indian cities? Why do some highly polluted northern cities display a relative aerosol clean-island signature? How do seasonal meteorology, regional aerosol transport and local anthropogenic sources interact to alter the urban–rural pollution contrast? Finally, what implications do these patterns have for urban air-quality governance and the National Clean Air Programme?

The central argument advanced here is that a pollution dome in India should be treated as a dynamic urban–regional atmospheric phenomenon rather than as a simple stationary cap of pollution over a city. Its expression depends not only on what a city emits but also on the

background pollution entering, surrounding or bypassing the city, together with the meteorological processes governing its dispersion.

2. Literature Review

The conceptual foundation of urban pollution islands emerged from attempts to understand how urban surfaces, emissions and atmospheric processes modify the composition of the lower atmosphere. Crutzen (2004) argued that the rapid growth of cities had consequences not only for urban temperature but also for atmospheric chemistry. Subsequent work formalised the Urban Pollution Island and Urban Aerosol Pollution Island concepts by comparing pollutant concentrations within cities with those in nearby rural environments. Li et al. (2020), for example, quantified UAPI intensity through urban–rural PM_{10} differences and demonstrated that pollution-island intensity varies substantially by time of day and season. Their findings also indicated an important relationship between aerosol pollution and the urban boundary layer, showing that the physical processes controlling heat and pollution islands are interconnected rather than independent.

A central methodological problem in pollution-dome research concerns the choice of indicator. Surface $PM_{2.5}$ and PM_{10} observations have direct relevance for human exposure, but urban monitoring stations are frequently more numerous than rural or peri-urban stations. This makes consistent urban–rural comparisons difficult. Satellite-derived aerosol optical depth has therefore become valuable for measuring spatial contrasts. AOD represents the extinction of solar radiation by aerosols through an atmospheric column and is not equivalent to ground-level $PM_{2.5}$. Its relationship with near-surface particulate pollution depends on aerosol vertical distribution, humidity, boundary-layer depth and chemical composition. Nevertheless, high-resolution MODIS MAIAC AOD has proved useful in spatial air-pollution assessment, particularly where ground networks are incomplete.

Dey et al. (2020) developed a 1-km satellite-based $PM_{2.5}$ database for India for 2000–2019 by combining MODIS MAIAC AOD with MERRA-2 information. Their results demonstrated that particulate pollution was not restricted to major cities and that urban–rural gradients were often weak because extensive regions experienced high background concentrations. This result was conceptually significant: if rural surroundings are already highly polluted, the difference between the city and its hinterland becomes smaller, even when absolute urban concentrations remain hazardous.

At the city scale, Singh et al. (2022) analysed particulate pollution and UAPI intensity across ten Delhi monitoring stations using PM_{10} and $PM_{2.5}$ observations for 2019–2020. Their analysis showed strong seasonal variability, with particulate pollution particularly high during summer and winter and with winter $PM_{2.5}$ influenced by local emissions and enhanced secondary aerosol formation. The study reinforced the importance of meteorology in interpreting urban pollution

differences. Yet a Delhi-focused monitoring approach cannot fully capture the wider regional aerosol field that extends across the IGP.

Recent remote-sensing research has addressed this problem more directly. Pandey et al. (2024) examined aerosol characteristics in South Asian cities and their surroundings and identified marked geographical variation in urban-core to suburban AOD gradients. Bangalore and Mumbai, for example, exhibited relatively strong positive urban gradients, while other South Asian cities showed much weaker or contrasting patterns. The study demonstrated that mineral dust and transported aerosols can weaken the apparent difference between urban cores and their surroundings.

Research from Kanpur provides another important geographical dimension. Singh and Satyanarayana (2025) examined AOD, land surface temperature and urban aerosol pollution intensity in relation to agricultural cycles. They found higher city AOD during cultivated conditions but greater aerosol loading in the surrounding region during harvesting, reducing the urban–rural contrast. This illustrates how agricultural land-use processes can temporarily alter what would otherwise be interpreted as an urban atmospheric signature. The result is highly relevant across the agricultural landscapes surrounding many IGP cities.

The strongest national-scale reinterpretation is provided by Sethi and Vinoj (2025). Using 1-km MODIS MAIAC AOD for 141 Indian cities during 2003–2020, combined with MERRA-2 dust and ERA5 wind information, they found a pronounced north–south division in the Urban Aerosol Island effect. Southern and southeastern cities were more frequently characterised by positive pollution islands, whereas northern and northwestern cities frequently showed negative urban–rural contrasts. The study further found that high-dust conditions increased the prevalence and magnitude of UACIs: 62% of cities displayed UACI conditions under high-dust cases, compared with 25% under no-dust cases, and annual UAI intensity was significantly negatively correlated with dust loading ($r = -0.47$, $p < 0.01$).

This evidence substantially advances the literature because it challenges a simplistic “urban centre equals pollution maximum” interpretation. Sethi and Vinoj argue that urban surface roughness can reduce wind speed and create a form of convergence or transport barrier. When pollution originates mainly within the city, reduced ventilation tends to trap pollution and reinforce a positive UAPI. When the surrounding background is already heavily polluted by transported dust, biomass burning or other regional sources, however, the same urban aerodynamic environment may slow the penetration of outside aerosols into the urban core. The result is a relative UACI even though absolute pollution may still be severe.

Studies published in 2026 add a broader urbanisation and governance perspective. Sahasranaman et al. (2026), using satellite NO₂ data and ground PM₁₀ measurements, found particularly severe pollution burdens in the Indo-Gangetic Plain. More than 80% of the 106 cities included in their

PM₁₀ analysis exceeded the applicable national standard, and NO₂ concentration scaled super-linearly with city population in IGP cities. Sharma et al. (2026), analysing 38 years of observations from 64 consistently monitored Indian cities, found that the proportion of Poor–Severe air-quality days increased from about 15% in the earlier monitoring period to roughly 35% in recent years and highlighted significant intra-city exposure variability that can be concealed by city-average AQI reporting.

A clear research gap nevertheless remains. Most pollution-dome research either quantifies urban–rural aerosol contrasts or analyses general city air pollution, but less attention has been given to integrating these two perspectives. An urban area may simultaneously possess high absolute pollution, a weak urban–rural gradient and a negative satellite-derived aerosol-island intensity. These are not contradictory results; they represent different dimensions of the pollution field. The present paper addresses this gap by interpreting pollution domes as relative geographical structures embedded within wider regional pollution regimes.

3. Research Methodology

This study adopts a secondary-data-based, descriptive, analytical and comparative research design. No field survey, questionnaire, interview, experimental measurement or original primary dataset was undertaken. The analysis is based exclusively on published peer-reviewed research, satellite-derived datasets described in those studies, government air-quality information and authoritative international health guidance.

The geographical scope is India, with particular attention to major metropolitan regions, the Indo-Gangetic Plain, northwestern India, southern and southeastern India, and selected city-level evidence from Delhi and Kanpur. The core national-scale evidence is derived from Sethi and Vinoj's (2025) analysis of 141 cities using MODIS Terra and Aqua combined MAIAC AOD at approximately 1-km spatial resolution over 2003–2020. Their methodology compared mean urban AOD with mean non-urban AOD and calculated both absolute and fractional Urban Aerosol Island intensity. The study additionally incorporated MERRA-2 dust concentration and ERA5 wind data to examine the influence of transported mineral dust.

This evidence is triangulated with Dey et al.'s (2020) high-resolution PM_{2.5} database for India, Delhi ground-monitoring analysis by Singh et al. (2022), South Asian city-core and surrounding-area aerosol analysis by Pandey et al. (2024), Kanpur agricultural-cycle analysis by Singh and Satyanarayana (2025), and national urban pollution studies published in 2026. Official policy progress under the National Clean Air Programme and World Health Organization guideline values are used to contextualise regulatory and health implications.

The principal analytical indicators are AOD, PM_{2.5}, PM₁₀, NO₂, urban–rural aerosol contrast, seasonal variation, dust loading, wind conditions, urbanisation and monitoring coverage. Interpretation is organised around a source–transport–dispersion framework: urban and non-

urban emission sources generate pollutants; regional atmospheric transport redistributes them; and urban morphology together with meteorological conditions determines whether pollutants accumulate, disperse or remain concentrated in surrounding areas.

An important methodological limitation is that AOD is a column-integrated aerosol measurement and cannot be interpreted as a direct measurement of breathing-level PM_{2.5}. Satellite observations are also affected by cloud cover and retrieval limitations. Conversely, surface monitoring networks may inadequately represent peri-urban and rural atmospheric conditions. Consequently, this paper avoids equating satellite AOD with surface particulate concentration and instead treats the two as complementary indicators.

4. Analysis and Discussion

4.1 Spatial Geography of Pollution Domes across India

The emerging national picture demonstrates that urban pollution domes have a distinct geographical structure. Sethi and Vinoj (2025) found positive and negative Urban Aerosol Islands across India rather than one uniform urban pattern. Positive UAPIs were particularly prominent across southern and southeastern cities. Among cities classified as positive UAPIs, mean aerosol loading over the urban area was approximately $3.3 \pm 3.1\%$ higher than over the surrounding non-urban domain, and some cities displayed differences of 10–14%. In contrast, cities across northern India, including much of the IGP, frequently displayed UACI conditions, with a mean urban reduction of about $2.07 \pm 1.99\%$ relative to their surrounding areas.

The spatial difference reflects contrasting pollution regimes. Many southern urban regions have relatively clearer regional backgrounds, meaning that traffic, industrial activity, construction, residential combustion and other urban emissions create an identifiable city-centred aerosol enhancement. Consequently, AOD is highest near the urban core and gradually decreases outward. The pollution dome appears spatially similar to the conventional theoretical model.

Northwestern and IGP cities operate within a different atmospheric setting. They are embedded within an extensive regional aerosol environment produced by combinations of mineral dust, agricultural residue burning, industrial clusters, coal combustion, transport corridors, brick kilns, road dust and secondary aerosol formation. The non-urban background can therefore become sufficiently polluted to reduce or reverse the urban–rural gradient. In such cases the city does not cease to be polluted; rather, its atmospheric distinctiveness is reduced.

This interpretation is supported by national PM_{2.5} evidence. Dey et al. (2020) estimated a population-weighted, twenty-year average ambient PM_{2.5} concentration of $57.3 \mu\text{g}/\text{m}^3$ across India for 2000–2019 and explicitly identified poor air quality across urban–rural transects. These data should not be treated as a current 2026 national concentration, because the study period

ended in 2019, but they are useful for demonstrating the long-standing geographical continuity of particulate pollution outside cities.

The UACI pattern therefore exposes an important conceptual problem in the term “pollution dome.” A dome is a relative spatial anomaly rather than a direct measure of absolute air quality. A city with a negative UAI can have substantially worse health-relevant pollution than another city with a positive UAPI if the first city lies within a far more polluted regional airshed. Sethi and Vinoj (2025) explicitly caution that UACI status should not be interpreted as evidence that the urban atmosphere is clean.

4.2 Seasonal Variability and Atmospheric Dispersion

Pollution domes also vary considerably through the year. India’s monsoonal climate generates major seasonal differences in precipitation, wind speed, atmospheric mixing, boundary-layer depth, humidity, dust activity and biomass-burning emissions. These factors alter both absolute pollution concentration and the urban–rural contrast.

Sethi and Vinoj (2025) found that approximately 74.5% of the 141 cities displayed positive pollution-island conditions during the post-monsoon season, making this the season with the widest prevalence of higher urban AOD relative to surrounding areas. By winter, UACI conditions were observed in around 41.1% of cities, while during the pre-monsoon season approximately 62.4% displayed UACI behaviour. The pre-monsoon expansion of negative urban contrasts coincides with strong mineral-dust activity across northwestern India.

The post-monsoon period is particularly complex. Weak winds and declining rainfall reduce atmospheric cleansing and can facilitate the accumulation of locally emitted particles. Across northern India the period also coincides with agricultural residue burning and increasing nocturnal atmospheric stability. Under weak regional wind conditions, the urban wind-stilling effect proposed for UACI formation may itself become weaker, permitting greater penetration of surrounding pollutants into the city. Local and transported pollutants may then combine, strengthening the urban aerosol loading.

Winter produces another atmospheric regime. Lower mixing heights, temperature inversions and stable atmospheric conditions can confine pollutants near the surface. Ground-level PM_{2.5} concentrations may consequently become severe even where the satellite-derived urban–rural AOD difference remains modest. This distinction illustrates why pollution-dome analysis requires both columnar and surface measurements.

Delhi provides a clear example of the seasonal intensification of surface particulate pollution. Singh et al. (2022) found substantial PM_{2.5} and PM₁₀ variations during 2019–2020 and particularly high particulate concentrations during winter. Their observations attributed winter

PM_{2.5} enhancement partly to local emissions and secondary aerosol formation. The authors also identified high summer PM₁₀, reflecting the importance of coarse dust.

Monsoon rainfall generally suppresses aerosol loading through wet scavenging, while stronger ventilation can reduce city-scale accumulation. The resulting seasonal cycle means that a city should not be assigned a single static “pollution-dome” character. An urban area may shift between positive and negative aerosol-island conditions as the balance among local emissions, background loading and atmospheric dispersion changes.

4.3 Transported Dust and the “Punctured” Pollution Dome

Transported mineral dust is one of the most important explanatory factors for the counter-intuitive negative urban aerosol islands observed across northern and western India. The Thar Desert and other arid regions provide large natural dust sources, and strong pre-monsoon circulation can transport these aerosols over extensive distances. The resulting background pollution is superimposed on anthropogenic emissions from densely populated and industrialised regions.

Sethi and Vinoj (2025) found that 62% of the analysed cities displayed UACI conditions during high-dust cases, whereas only 25% showed UACI conditions under no-dust conditions. UACI intensity was also stronger during high-dust loading. The significant negative relationship between annual dust loading and UAI intensity indicates that increasing regional dust generally reduces the relative urban aerosol enhancement.

The proposed physical mechanism involves urban aerodynamic roughness. Buildings, road networks and other structures increase surface friction and commonly reduce near-surface wind speed relative to more open surroundings. When most pollution is generated within the urban area, reduced ventilation encourages accumulation and produces the conventional positive dome. When substantial aerosol is transported towards the city from outside, however, the same urban roughness may slow its inward movement. Pollutants can therefore accumulate more strongly on the upwind or peri-urban side, while the city centre records a smaller relative increase.

This phenomenon has been described as a “punctured” pollution dome. The expression is useful because it communicates that regional aerosol loading can interrupt the conventional smooth city-centred concentration profile. Nevertheless, the mechanism should be interpreted cautiously. Urban buildings do not form an impermeable barrier; they modify airflow and pollutant transport rather than completely preventing regional aerosol entry.

The result has significant policy implications. Dust transport contains natural and anthropogenically enhanced components. Desert dust cannot simply be eliminated through municipal policy, while resuspended road and construction dust, degraded land surfaces and

anthropogenic particulate emissions can be reduced. Effective control therefore requires source attribution rather than a generic response to total particulate concentration.

4.4 Local Anthropogenic Sources, Urban Form and City Size

Regional transport does not diminish the importance of local urban emissions. Vehicular exhaust and non-exhaust particles, construction and demolition activity, industrial fuel combustion, power generation, waste burning, diesel generators, road dust and residential energy use all contribute to the urban aerosol burden. Their relative importance varies by city and season.

Recent national evidence indicates that urban scale itself can influence pollution intensity. Sahasranaman et al. (2026) found that the most urbanised Indian districts possessed high NO₂ burdens, while districts at intermediate urbanisation levels of roughly 30–40% experienced both high concentrations and substantial increases during the study period. The Indo-Gangetic Plain emerged as a particularly concerning region. Their scaling analysis further indicated that NO₂ increased super-linearly with city population in IGP cities, suggesting that larger cities in that region can experience both higher concentrations and higher per-capita exposure.

This finding helps reconcile the urban pollution-dome concept with the UACI phenomenon. A large northern city may generate substantial local combustion pollution while simultaneously sitting within an even larger regional particulate background. NO₂, because of its stronger relationship with relatively local combustion sources and shorter atmospheric lifetime, may show a pronounced urban signal even when total aerosol AOD does not. Pollution domes are therefore pollutant-specific. A city cannot necessarily be characterised by one spatial gradient applicable equally to PM_{2.5}, PM₁₀, AOD, NO₂ and ozone.

Urban morphology further affects dispersion. Dense high-rise development may generate street canyons in which local vehicular emissions accumulate. At a larger scale, however, increased aerodynamic roughness modifies wind fields and boundary-layer turbulence. Heat-island circulation may enhance mixing under some circumstances, while stable atmospheric conditions may suppress it under others. The relationship between urban heat and pollution islands is consequently non-linear.

This complexity matters for urban planning. Expanding road capacity, dispersed low-density development, conversion of vegetated land, intensification of construction and increasingly dense building configurations can alter both emissions and ventilation. Urban air-quality management must therefore be connected to transport planning, land-use regulation, building morphology and green-infrastructure policy rather than confined to pollution-control equipment.

4.5 Agricultural Landscapes and Peri-Urban Pollution

Many Indian cities are directly embedded within intensive agricultural regions. This is particularly true across the Indo-Gangetic Plain, where the urban–rural boundary is frequently a

transition between dense built-up land and highly productive cropland. Agricultural operations can therefore alter the surrounding aerosol field and modify measured UAPI intensity.

The Kanpur study by Singh and Satyanarayana (2025) demonstrates this interaction. During cultivated conditions, the city showed higher land surface temperature and AOD than its surroundings. During harvested conditions, AOD over the outskirts increased substantially and approached urban levels, reducing the contrast. The study associated these changes with agricultural land-cover conditions and seasonal processes.

Crop-residue burning represents an even more direct mechanism through which agricultural emissions can influence cities, particularly during post-monsoon episodes in northwestern India. Regional smoke plumes are transported across administrative boundaries and interact with urban emissions and meteorological stagnation. Yet it would be inaccurate to attribute all severe urban pollution episodes to residue burning. City emissions, regional industrial sources, secondary aerosol chemistry, meteorology and other sources contribute simultaneously, and their proportions change from episode to episode.

This finding again supports airshed rather than city-boundary management. A municipal corporation can regulate local road dust or waste burning but cannot independently control emissions originating hundreds of kilometres upwind. Inter-state coordination and regional emission inventories are therefore essential.

4.6 Environmental, Health and Climatic Implications

Pollution domes are environmentally significant because aerosols affect far more than visibility. Fine particulate matter can penetrate deeply into the respiratory system and is associated with cardiovascular and respiratory disease and premature mortality. WHO's 2021 air-quality guidelines recommend an annual $\text{PM}_{2.5}$ concentration of $5 \mu\text{g}/\text{m}^3$ and an annual PM_{10} concentration of $15 \mu\text{g}/\text{m}^3$ as health-based guideline values, while also recognising the need for interim targets where pollution is very high (World Health Organization, 2021).

At the same time, it is methodologically inappropriate to translate an observed UAPI percentage directly into a specific health burden. UAPI is a relative spatial indicator; epidemiological risk depends on absolute pollutant concentration, duration of exposure, pollutant composition, population distribution and baseline health conditions. A weak pollution dome over a highly polluted regional background may therefore represent a much greater public-health burden than a strong positive dome over a relatively clean background.

The distinction also has environmental-justice implications. If monitoring and policy focus overwhelmingly on urban centres, rural and peri-urban populations may receive insufficient attention even where background concentrations are extremely high. Sharma et al. (2026) additionally demonstrate that aggregation of monitoring stations into a single city-level AQI can

obscure intra-city variation. Their 1987–2024 analysis of 64 cities found that particulate matter remained the dominant pollutant in more than 85% of observations and that conventional averaging can misrepresent exposure. The pollution-dome perspective therefore strengthens the case for spatially explicit exposure assessment.

Aerosols also interact with the urban climate. They scatter and absorb solar radiation, modify surface energy balance, affect atmospheric stability and may influence cloud formation and precipitation. Some aerosol species cool the surface by scattering short-wave radiation, whereas absorbing aerosols such as black carbon can heat the atmosphere. These processes may alter the intensity of Urban Heat Islands and atmospheric mixing. The direction and magnitude of such interactions vary by aerosol type, season and surface characteristics, making simple generalisations inappropriate.

Pollution domes can also reduce visibility and affect urban ecosystems through deposition. Particulate deposition on vegetation may influence leaf surfaces and photosynthetic processes, while nitrogen- and sulphur-containing compounds contribute to chemical changes in ecosystems. At wider scales, aerosol–radiation and aerosol–cloud interactions have climatic consequences, although attributing specific city-level climatic changes directly to pollution domes requires detailed modelling beyond the scope of the present secondary-data synthesis.

4.7 Policy Implications: From City Action Plans to Regional Airshed Management

India's principal national urban clean-air intervention is the National Clean Air Programme (NCAP), launched in 2019. Its revised objective has been to reduce PM_{10} concentrations by up to 40% from the 2017–18 baseline or achieve the national annual PM_{10} standard of $60 \mu g/m^3$ by 2025–26. Official information released in September 2026 reports that 108 of the 130 NCAP cities recorded lower annual PM_{10} concentrations in FY 2025–26 than in 2017–18; 72 cities achieved reductions above 20%, 26 achieved reductions above 40%, and 14 met the national PM_{10} standard. These figures indicate measurable progress while also showing that attainment remains far from universal.

The pollution-dome literature suggests that city-level progress should be complemented by a stronger regional strategy. The finding that urban and rural aerosol burdens are often comparable implies that controlling emissions within municipal boundaries alone may produce limited improvements where regional background pollution remains elevated. Sethi and Vinoj (2025) explicitly recommend combining local and regional mitigation because the aerosol environment of many northern cities is strongly influenced by transported pollution.

An airshed approach would identify geographical regions within which atmospheric circulation commonly transports pollutants across city, district and state boundaries. Emission-control priorities could then be coordinated across power generation, industry, transportation, agriculture, waste management and dust-producing activities within the relevant atmospheric region. This is

especially important for the IGP, where closely spaced urban centres, agricultural landscapes, industrial corridors and large populations form a continuous pollution environment.

Monitoring strategy also requires adjustment. Urban stations remain essential for compliance and health warnings, but pollution-dome research requires systematically paired urban, peri-urban and rural observations. Satellite observations provide continuous spatial coverage but cannot replace ground monitoring. Future policy should integrate CPCB surface observations, remote-sensing products, meteorological reanalysis and source-apportionment modelling within a common geospatial platform.

A final implication concerns performance evaluation. A decline in city-centre PM concentration may reflect successful local mitigation, favourable meteorology or changes in regional background pollution. Conversely, failure to meet a concentration target may occur even after local emissions decline if transported pollution increases. Policy evaluation should therefore distinguish meteorology-normalised trends from raw concentrations and separate locally controllable from regionally transported contributions.

5. Conclusion

Urban pollution domes in India represent a dynamic interaction among anthropogenic emissions, urban morphology, atmospheric stability, seasonal circulation and regional pollutant transport. The evidence reviewed in this paper rejects the assumption that every highly polluted Indian city should display a uniformly positive urban pollution island. Satellite observations for 141 cities reveal a pronounced geographical divide: positive Urban Aerosol Pollution Islands are particularly common in southern and southeastern India, while many northern and northwestern cities exhibit relative Urban Aerosol Clean Islands because aerosol concentrations in the surrounding regional environment are extremely high. This apparent clean-island effect does not signify clean urban air; it indicates that the city–background contrast has been weakened or reversed.

The first research question—how pollution domes vary geographically—is therefore answered by the strong regional differentiation between conventional city-centred domes and weak or negative urban aerosol contrasts. The second question—why polluted northern cities may show UACI behaviour—is explained primarily through high regional background aerosol loading, transported mineral dust and the possible modification of incoming pollutant transport by urban aerodynamic roughness. The third question concerning seasonality demonstrates that the balance among local sources, dust, agricultural activity, wind, precipitation and atmospheric mixing shifts through the monsoon cycle, allowing the same city to display different pollution-island states at different times of year.

The fourth question concerns governance. Current evidence supports a transition from exclusively city-centred pollution control towards coordinated regional airshed management.

NCAP has produced measurable reductions in PM₁₀ in many participating cities, but the continuing regional nature of the problem means that local action plans should increasingly be connected with inter-state strategies addressing transport, industry, agriculture, open burning, construction dust and energy systems.

The study also emphasises an important methodological conclusion: pollution-dome intensity should never be used as a substitute for absolute exposure. A negative urban aerosol island may occur within one of the most polluted atmospheric regions in the country. Effective assessment therefore requires the integration of urban–rural contrasts with absolute PM_{2.5}, PM₁₀ and gaseous-pollutant concentrations.

The principal limitation of this paper is its reliance on secondary evidence drawn from datasets covering different periods and pollutants. AOD, surface PM and NO₂ are not directly interchangeable. Future research should therefore combine simultaneous urban, peri-urban and rural ground observations with high-resolution satellite retrievals, boundary-layer measurements, chemical composition, trajectory analysis and atmospheric modelling. Long-term research should also examine how changing urban form, electrification of transport, industrial transitions, climate variability and land-use change modify the pollution-dome phenomenon.

Ultimately, the geography of pollution in India is increasingly a geography of connected urban and regional atmospheres. Recognising this spatial interdependence is essential for designing clean-air policies capable of protecting both urban and rural populations and for developing more sustainable and climate-resilient Indian cities.

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