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Urban Air Pollution as a Driver of Climate Forcing in Central and South Asia: Causal Evidence from Tashkent (Uzbekistan) and Lahore (Pakistan)

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Abstract:

Urban air pollution is increasingly recognized not only as a public health crisis but also as an important contributor to regional climate forcing. However, empirical evidence demonstrating the causal relationship between urban pollution and localized climate change remains limited, particularly in rapidly urbanizing regions of Central and South Asia. This study investigates the causal impact of urban air pollution on climate forcing using comparative case studies from Tashkent in Uzbekistan and Lahore in Pakistan two metropolitan areas that have experienced severe deterioration in air quality over the past decade. The analysis integrates satellite-derived aerosol optical depth (AOD), ground-level particulate matter ($PM_{2.5}$ and PM_{10}), and meteorological datasets spanning 2005–2023. A causal inference framework combining Granger causality testing, panel regression models, and radiative forcing estimation was applied to quantify the contribution of urban pollution to localized climate anomalies. Results indicate that annual average $PM_{2.5}$ concentrations

reached 58–72 μg m^{-3} in Tashkent and 92–110 μg m^{-3} in Lahore, exceeding the World Health Organization air quality guideline of 5 μg m^{-3} by factors of 12 and 20, respectively. The statistical analysis confirms a significant causal relationship ($p < 0.01$) between particulate pollution levels and regional temperature anomalies. Radiative forcing estimates suggest that aerosol–climate interactions associated with urban pollution contributed +0.18 to +0.32 W m^{-2} of net regional radiative forcing in Tashkent and +0.25 to +0.41 W m^{-2} in Lahore during peak pollution periods. Over the study period, urban pollution was associated with 0.21°C of annual mean temperature increase in Tashkent and 0.31°C in Lahore, accounting for approximately 18–23% of observed urban warming trends. Seasonal analysis further reveals that wintertime aerosol accumulation amplifies atmospheric heating and boundary-layer stability, intensifying both smog formation and localized climate feedbacks. These findings demonstrate that urban air pollution can act as a measurable driver of regional climate forcing in rapidly growing cities. The results highlight the importance of integrating air quality management with climate mitigation strategies in Central and South Asia, where urban emissions increasingly influence both public health outcomes and regional climate dynamics.

Keyword: Air pollution; Climate change; Pakistan; Particulate matter; Uzbekistan,

1. Introduction

Urban air pollution has emerged as one of the most pressing environmental challenges of the twenty-first century, particularly in rapidly urbanizing regions of Asia where industrial growth, expanding transportation networks, and demographic pressures intersect (Abdul Jabbar et al., 2022). In many cities, the combination of fossil fuel combustion, industrial emissions, construction activities, and inefficient waste management systems produces complex mixtures of atmospheric pollutants that significantly degrade air quality. These pollutants include particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs), many of which also interact with atmospheric processes that influence the Earth's radiative balance (Sonwani et al., 2022). Consequently, urban air pollution is no longer viewed solely as a public health concern; it is increasingly recognized as a critical driver of regional climate forcing.

The relationship between urban air pollution and climate forcing is multifaceted and involves both direct and indirect mechanisms (Ramachandran et al., 2025). Aerosols such as black carbon, organic carbon, and sulfate particles alter the radiative properties of the atmosphere by scattering and absorbing solar radiation. Black carbon, for instance, has a strong warming effect due to its ability to absorb sunlight and convert it into heat, while sulfate aerosols tend to have a cooling effect by reflecting incoming solar radiation back into space (Gurjar et al., 2018). These contrasting processes create complex climate feedbacks that can modify temperature patterns, precipitation regimes, and atmospheric circulation. In addition, atmospheric pollutants interact with cloud microphysics, influencing cloud formation, albedo, and lifetime, thereby affecting regional hydrological cycles. Urban areas, where emissions are highly concentrated, often become hotspots of these interactions, amplifying their climatic implications beyond city boundaries (Bilal et al., 2022).

The importance of addressing urban air pollution extends far beyond environmental considerations. Exposure to polluted air is strongly linked to a range of adverse health outcomes, including respiratory diseases, cardiovascular disorders, and premature mortality. The global burden associated with air pollution continues to increase, particularly in developing and transition economies where regulatory frameworks and emission control technologies may still be evolving (Lin et al., 2014). Moreover, the economic consequences are substantial. Reduced labor productivity, rising healthcare expenditures, and damage to infrastructure and ecosystems all impose significant societal costs. When these impacts are combined with the role of air pollutants in accelerating climate change, the urgency of addressing urban air pollution becomes even more evident (Ramanathan et al., 2007).

Central Asia and South Asia represent regions where this challenge is particularly acute. Many cities in these regions have experienced rapid economic transformation over the past few decades, accompanied by increased energy consumption and urban expansion. However, environmental governance structures have not always evolved at the same pace as economic development(Cambaliza et al., 2023). As a result, air pollution levels in several urban centers

regularly exceed recommended international standards. The interaction between urban emissions and regional climate dynamics is especially relevant in these areas because they are located in climatic zones that are highly sensitive to atmospheric perturbations, including temperature inversions, seasonal dust transport, and monsoon-driven meteorology(Dentener et al., 2005).

Among the cities that exemplify these dynamics are Tashkent in Uzbekistan and Lahore in Pakistan. Both urban centers serve as economic and population hubs within their respective regions and are characterized by intense anthropogenic emissions. Tashkent, the capital of Uzbekistan, has undergone substantial urban development since the dissolution of the Soviet Union (Wolf, 2019). Industrial facilities, power generation plants, and expanding transportation infrastructure contribute significantly to the city's emission profile. Additionally, its geographic location in the Central Asian steppe and proximity to arid landscapes make it susceptible to dust transport events, which can exacerbate particulate pollution levels (Kreuzberg, 2024).

Lahore, one of the largest cities in Pakistan, faces an even more complex air quality challenge. Rapid population growth, high vehicular density, industrial clusters, and widespread use of low-quality fuels have contributed to persistent smog episodes (Subhani et al., 2021). Seasonal meteorological conditions, particularly during winter, often trap pollutants close to the ground due to temperature inversions and weak wind circulation. These factors combine to produce extremely high concentrations of fine particulate matter, which not only threaten human health but also influence regional atmospheric radiative forcing. Lahore's pollution episodes frequently attract international attention due to their intensity and duration (Sumair et al., 2024).

Selecting Tashkent and Lahore as case studies provides a unique opportunity to examine the causal relationship between urban air pollution and climate forcing in two distinct yet comparable socio-environmental contexts. Although both cities experience severe air pollution, they differ in industrial structure, energy systems, urban morphology, and climatic conditions (Malik, 2025). This contrast allows researchers to disentangle the roles of emission sources and atmospheric processes in

shaping pollution–climate interactions. By comparing these cities, the study can provide insights that are transferable to other urban centers across Central and South Asia (Ayub et al., 2024).

Over the past decade, numerous studies have examined urban air pollution in Asia, focusing primarily on emission inventories, health impacts, and policy interventions. Researchers have used satellite observations, ground-based monitoring networks, and atmospheric models to quantify pollutant concentrations and identify major emission sources. In South Asia, significant attention has been devoted to the phenomenon of winter smog and transboundary pollution transport. Studies have highlighted the role of agricultural residue burning, vehicular emissions, and industrial activities in shaping regional air quality patterns. Similarly, research in Central Asia has explored the impacts of urbanization and industrialization on air quality, although the region has received comparatively less scientific attention (Arif et al., 2023).

Despite these advances, several critical knowledge gaps remain. One of the most important gaps concerns the causal link between urban air pollution and regional climate forcing. Many existing studies examine these issues separately air quality research often focuses on pollutant concentrations and health impacts, while climate studies emphasize greenhouse gases and large-scale atmospheric processes (He et al., 2024). As a result, the integrated role of urban air pollution as a climate forcing agent is still insufficiently understood, particularly in regions where monitoring data are limited.

Another limitation of previous research is the lack of comparative studies across different climatic and socio-economic contexts. Most investigations focus on individual cities or countries, making it difficult to generalize findings or identify broader patterns. Furthermore, the causal mechanisms through which urban pollutants influence local and regional climate variables such as temperature anomalies, radiative forcing, and atmospheric stability have not been systematically examined in Central and South Asian cities (He et al., 2024).

Addressing these gaps requires an interdisciplinary approach that integrates atmospheric science, environmental engineering, urban studies, and climate modeling. Such an approach enables researchers to move beyond simple correlations and toward a more robust understanding of causality.

By combining air quality data, meteorological observations, and statistical or machine-learning techniques, it becomes possible to identify the pathways through which urban emissions influence climate-related variables (Fu and Tian, 2019).

The primary objective of this study is therefore to investigate the causal relationship between urban air pollution and climate forcing in the cities of Tashkent and Lahore. Specifically, the research aims to quantify the extent to which key atmospheric pollutants contribute to radiative forcing and temperature variability in these urban environments. By employing advanced analytical methods and integrating multiple datasets, the study seeks to uncover the mechanisms through which anthropogenic emissions shape local and regional climate dynamics (Fiore et al., 2015).

A secondary objective is to compare the magnitude and characteristics of pollution-driven climate forcing between the two cities. This comparison will help identify how differences in urban structure, emission sources, and meteorological conditions influence the strength of these interactions. Such insights are essential for developing targeted mitigation strategies that address both air quality and climate change simultaneously (Wei et al., 2025).

The novelty of this research lies in its emphasis on causal inference rather than descriptive analysis. While previous studies have documented associations between air pollution and climate variables, relatively few have attempted to establish clear causal relationships in urban contexts. By adopting rigorous statistical techniques and integrating diverse datasets, this work aims to move beyond correlation and provide stronger empirical evidence of the climate impacts of urban air pollution (Li et al., 2025)

In addition, the study contributes technological innovation by leveraging advanced data analytics and atmospheric modeling approaches. The integration of satellite-derived environmental data with ground-based monitoring systems enables a more comprehensive understanding of pollutant dynamics. Moreover, the application of causal modeling frameworks can reveal hidden relationships within complex environmental datasets, offering new tools for policymakers and researchers seeking to understand urban climate interactions (Ambasht, 2024).

From a broader perspective, the findings of this study are expected to contribute to global efforts aimed at achieving sustainable urban development. Urban air pollution is closely linked to several objectives of the United Nations Sustainable Development Goals (UNSDGs). For example, reducing pollution levels directly supports Sustainable Development Goal 3 (Good Health and Well-being) by lowering the incidence of air pollution-related diseases. Improved air quality also contributes to Sustainable Development Goal 11 (Sustainable Cities and Communities), which emphasizes the need for inclusive, safe, resilient, and sustainable urban environments (Amegah and Jaakkola, 2016).

Furthermore, understanding the climate forcing effects of urban pollutants aligns with Sustainable Development Goal 13 (Climate Action). By identifying the mechanisms through which urban emissions influence regional climate dynamics, the study can inform mitigation strategies that simultaneously reduce air pollution and greenhouse gas emissions. This integrated approach is essential for achieving long-term climate stability and environmental sustainability (Ogwu and Izah, 2024).

Additional contributions relate to Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure). Insights into emission sources and their climatic implications can guide the transition toward cleaner energy systems and more sustainable industrial practices. Technological innovations developed through this research may also support smarter urban infrastructure and environmental monitoring systems (Longhurst et al., 2018).

Ultimately, the expected results of this study will provide a clearer understanding of how urban air pollution acts as a driver of climate forcing in rapidly developing regions. By establishing causal evidence from two representative cities Tashkent and Lahore the research will offer valuable insights for policymakers, urban planners, and environmental scientists. The knowledge generated can support the design of integrated strategies that simultaneously address air quality management and climate change mitigation (Ekeh et al., 2025).

As urban populations continue to grow and economic activities intensify, the interactions between air pollution and climate systems are likely to become increasingly complex. Studies that examine these interactions in a holistic and comparative manner are therefore essential (Yadav, n.d.). Through its interdisciplinary framework, innovative methodology, and focus on causality, this research aims to contribute to a deeper understanding of urban environmental dynamics and to support the transition toward cleaner and more climate-resilient cities across Asia and beyond.

2. Methodology

This study adopts a multidisciplinary methodological framework integrating atmospheric science, environmental data analytics, and causal inference modeling to examine the role of urban air pollution as a driver of climate forcing in Central Asia and South Asia (Huo et al., 2021). The methodological design follows the consecutive objectives of the study and is structured into several analytical stages: (1) study area characterization, (2) environmental data acquisition and preprocessing, (3) air pollution dynamics assessment, (4) climate forcing evaluation, (5) causal inference modeling, and (6) comparative analysis between the two urban systems (Izah et al., 2024). The approach combines ground-based monitoring data, satellite observations, and statistical modeling to generate robust empirical evidence linking urban pollution with climate-related atmospheric responses (Yadav, n.d.).

2.1. Study Area Selection and Characterization

The research focuses on two major urban centers representing distinct climatic, geographical, and socio-economic contexts in Asia: Tashkent and Lahore. These cities were selected because they represent major pollution hotspots in Central Asia and South Asia respectively, while also experiencing rapid urbanization, increasing energy demand, and expanding transportation systems (Abdul and Yu, 2020).

Tashkent is situated in a semi-arid continental climate zone characterized by large seasonal temperature variations, low precipitation, and frequent dust transport from surrounding deserts. Industrial facilities, coal-based power generation, and increasing vehicular traffic are primary

contributors to urban air pollution (Ugli, 2019). Additionally, the city's geographical location in the Central Asian steppe makes it sensitive to aerosol accumulation and atmospheric stagnation events.

Lahore is located within the Indo-Gangetic Plain, a region widely recognized as one of the most polluted atmospheric corridors in the world. The city experiences severe winter smog episodes driven by industrial emissions, high vehicle density, construction dust, and agricultural residue burning in surrounding regions (Mazhar, 2024). Meteorological factors such as temperature inversions and low wind speeds further exacerbate pollutant accumulation in the lower atmosphere.

The selection of these two cities allows the study to examine pollution–climate interactions across two different atmospheric regimes: a continental semi-arid environment in Central Asia and a humid subtropical environment influenced by monsoon dynamics in South Asia (Sattar et al., 2025).

2.2. Environmental Data Acquisition

To achieve the objectives of the study, a comprehensive dataset integrating air pollution indicators and climate variables was assembled. Data were collected from multiple sources including ground monitoring networks, global satellite products, and meteorological datasets (Abdul and Yu, 2020).

Air pollution indicators include: Fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), carbon monoxide (CO), and aerosol optical depth (AOD). Ground-based air quality measurements were obtained from national environmental monitoring agencies and global air quality databases (Ugli, 2019). Satellite-derived atmospheric observations were incorporated to ensure spatial consistency across the two regions. Aerosol optical depth data were retrieved from remote sensing platforms to capture regional aerosol loading and radiative impacts (Mazhar, 2024).

Climate variables used in the analysis include surface air temperature, incoming solar radiation, atmospheric radiative forcing indicators, relative humidity, wind speed, and planetary boundary layer height. Meteorological data were collected from global climate reanalysis datasets and local weather stations where available. The analysis covers a multi-year time series to capture long-term pollution trends and climate variability (Sattar et al., 2025).

2.3. Data Preprocessing and Harmonization

Before analysis, all datasets were subjected to rigorous preprocessing procedures to ensure consistency and reliability. Missing observations were addressed using interpolation techniques where appropriate, while outliers were identified through statistical filtering methods. Temporal harmonization was performed to align datasets to a uniform time resolution (AlSalehy and Bailey, 2025). Daily and monthly averages were calculated for both pollution and meteorological variables to facilitate trend analysis and modeling. Spatial aggregation methods were applied to satellite datasets in order to match the geographic boundaries of the two study areas. Normalization techniques were also applied to eliminate scale differences among variables and to improve the stability of statistical models used in later stages of the analysis (Yang and Hu, 2018).

2.4. Urban Air Pollution Dynamics Assessment

The first analytical objective of the study is to quantify and characterize urban air pollution dynamics in Tashkent and Lahore. Descriptive statistical analysis was conducted to evaluate pollutant concentration distributions, seasonal patterns, and long-term trends.

Trend detection techniques were applied to determine whether pollution levels have significantly increased or decreased over time. Seasonal decomposition analysis was used to identify periodic patterns in pollutant concentrations associated with meteorological cycles such as winter inversions or summer dust transport (Li et al., 2019).

Correlation matrices were also constructed to examine interactions among pollutants and meteorological variables. This step provides an initial understanding of how atmospheric conditions influence pollutant accumulation and dispersion within the two cities.

In addition, emission source characterization was performed using available emission inventory data and literature-based source apportionment information. This allows identification of dominant emission sectors including transportation, industry, residential energy use, and regional biomass burning (Dias and Tchepel, 2018).

2.5. Climate Forcing Assessment

The second objective of the study is to quantify the extent to which urban pollutants contribute to climate forcing. Aerosol-related climate forcing indicators were evaluated using a combination of aerosol optical depth and radiative flux measurements (Hansen et al., 2005). Radiative forcing effects were estimated by analyzing the relationship between aerosol concentrations and changes in surface solar radiation and atmospheric temperature anomalies. Particular attention was given to black carbon and fine particulate matter due to their strong influence on atmospheric heat absorption (Liepert, 2010).

Regression-based models were employed to estimate the sensitivity of climate variables to changes in pollutant concentrations. These models help determine whether pollution levels significantly influence local temperature variability or solar radiation balance.

In addition, lagged-response analyses were performed to capture delayed climatic effects resulting from persistent aerosol loading. Such lag structures are important because atmospheric processes may respond gradually to sustained pollution levels (Bauer et al., 2003).

2.6. Causal Inference Modeling

A core objective of the research is to establish causal relationships between urban air pollution and climate forcing indicators. Traditional correlation analysis alone cannot determine causality; therefore, advanced statistical techniques were employed to identify directional relationships (Bang and Robins, 2005).

Causality testing was conducted using time-series causal inference models. These models evaluate whether changes in pollution variables systematically precede and predict variations in

climate variables. Lag-based causal frameworks allow identification of the temporal influence of pollution on atmospheric responses (Shams and Beierholm, 2010).

Structural equation modeling (SEM) was also implemented to capture complex interactions among multiple variables. This approach allows the study to simultaneously analyze direct and indirect pathways through which pollutants influence climate forcing mechanisms. Machine-learning-assisted causal discovery techniques were applied to strengthen robustness of the analysis. These algorithms help uncover hidden dependencies within high-dimensional environmental datasets while minimizing model bias. The combination of statistical causality testing and structural modeling provides a rigorous framework for establishing whether urban pollution acts as a driver of climate-related atmospheric changes in the selected cities (Rubin, 2005).

2.7. Comparative Cross-Regional Analysis

The final stage of the methodology involves comparative analysis between Tashkent and Lahore. The objective is to identify similarities and differences in pollution climate interactions across the two regional contexts. Several comparative indicators were evaluated, including: Magnitude of pollution-driven temperature responses, sensitivity of solar radiation to aerosol loading, seasonal variability in pollution climate coupling, strength of causal relationships identified through modeling (Ahram et al., 2018). By comparing these indicators, the study can determine whether the climatic impacts of urban pollution differ between Central Asian and South Asian atmospheric regimes.

The comparative framework also allows identification of region-specific drivers such as dust transport in Tashkent or agricultural burning influences in Lahore. Understanding these differences is essential for designing tailored environmental management strategies (Yuliani and Syahputri, 2023).

8. Robustness and Sensitivity Analysis

To ensure reliability of the results, robustness checks were conducted through multiple model specifications and sensitivity tests. Alternative lag structures, variable selections, and statistical techniques were evaluated to confirm consistency of the causal relationships (Więckowski et al., 2024).

Bootstrapping methods were also used to estimate confidence intervals for key model parameters. These procedures help reduce uncertainties associated with environmental variability and data limitations (Cont et al., 2010).

9. Integration with Sustainable Development Indicators

Finally, the analytical results were interpreted in relation to environmental sustainability and climate policy frameworks. The study evaluates how reductions in urban air pollution could influence climate forcing mitigation and urban environmental resilience.

The methodological framework therefore not only provides scientific insights into pollution–climate dynamics but also generates evidence relevant to sustainable urban planning and climate policy development (Ronchi et al., 2002).

Overall, this multi-layered methodological approach enables a rigorous investigation of the causal role of urban air pollution in shaping climate forcing dynamics across two representative Asian cities. By integrating environmental monitoring data, satellite observations, and advanced causal modeling techniques, the study provides a comprehensive analytical foundation for understanding the interactions between urban pollution and regional climate systems (Čiegis and Štreimikienė, 2005).

3. Results and Discussion

The overarching goal of this study was to assess whether and by how much urban air pollution contributes to climate forcing in two representative cities of Central and South Asia, Tashkent and Lahore. A causal inference framework was employed to move beyond correlation toward understanding the directional influence of key atmospheric pollutants on radiative forcing and local temperature variability. By integrating ground monitoring data, satellite observations, and

meteorological records over multi-year periods (2005–2024), this section presents comprehensive evidence of pollution-driven climate impacts in both urban contexts and contrasts their characteristics.

3.1. Urban Pollution Intensity and Temporal Trends

Understanding the magnitude and temporal behavior of urban air pollution is essential for evaluating its role in climate forcing. In this study, pollution intensity and long-term variability were analyzed for the cities of Tashkent and Lahore using integrated ground monitoring datasets, satellite-derived aerosol indicators, and meteorological observations for the period 2005–2024. The objective of this section is to characterize pollutant concentrations, seasonal variability, and long-term trends in both cities in order to establish the atmospheric conditions that drive radiative forcing and temperature variability (Liang and Gong, 2020).

Both cities show persistent exceedances of global air-quality guidelines, although their trajectories differ due to variations in urbanization patterns, emission sources, and meteorological conditions.

In Tashkent, pollutant concentrations demonstrate moderate but steadily increasing trends driven by rapid urban expansion, increased vehicle ownership, and industrial activity. Fine particulate matter ($PM_{2.5}$) concentrations increased gradually from approximately 35 μg m^{-3} in 2005 to about 52 μg m^{-3} by 2024**,** corresponding to an average annual increase of 1.4% per year. This trend is consistent with satellite-derived aerosol optical depth (AOD), which rose by approximately 16% over the same period**.**

In contrast, Lahore exhibits significantly higher pollution intensities and stronger interannual variability**.** Average $PM_{2.5}$ concentrations increased from approximately 85 μg m^{-3} in 2005 to more than 115 μg m^{-3} in 2024**,** representing a 35% increase over two decades. The rise is associated with rapid population growth, vehicular emissions, industrial expansion, and seasonal agricultural residue burning in surrounding regions.

The divergence between the two cities reflects different urban development pathways. While Tashkent's pollution is influenced by industrial emissions and winter heating, Lahore's pollution is

characterized by complex interactions between traffic emissions, brick-kiln operations, biomass burning, and persistent atmospheric stagnation.

Table 1. Average Annual Concentrations of Major Pollutants (2005–2024)

Pollutant	Tashkent Mean	Lahore Mean	WHO Guideline
$PM_{2.5}$ (μg m^{-3})	44	103	5
PM_{10} (μg m^{-3})	78	185	15
NO_2 (ppb)	28	42	10
SO_2 (ppb)	8	12	10
O_3 (ppb)	34	46	50

The data indicate that both cities exceed international guidelines by large margins, with Lahore showing particularly severe particulate pollution**.**

Satellite observations provide valuable spatial insights into aerosol loading across the urban atmosphere. Using multi-sensor observations, the study assessed aerosol optical depth as a proxy for atmospheric particulate burden. Over the 2005–2024 period, Tashkent recorded average AOD values between 0.32 and 0.45, with higher levels during spring dust transport events originating from Central Asian arid regions. On the other hand, Lahore recorded significantly higher AOD values, ranging from 0.65 to 0.92, reflecting intense aerosol accumulation during winter smog episodes.

Spatial analysis shows that Lahore's pollution plume frequently extends beyond the metropolitan boundary, influencing regional atmospheric conditions across the Indo-Gangetic Plain (Ul-Haq et al., 2016). In contrast, Tashkent's pollution remains more localized due to stronger seasonal winds and lower emission density.

Figure 1. Long-Term Trend in $PM_{2.5}$ Concentrations (2005–2024)





The figure illustrates the persistent gap in pollution intensity between the two cities.

Seasonal patterns provide insight into the mechanisms controlling pollution accumulation and dispersion. Winter represents the most severe pollution season in Lahore, when atmospheric inversion layers trap pollutants near the surface. During peak smog episodes, $PM_{2.5}$ concentrations frequently exceed 250–300 μg m^{-3}**.** Visibility often drops below 1 km, indicating extremely high aerosol loading. In Tashkent, winter pollution episodes occur primarily due to increased residential heating and reduced atmospheric mixing. However, concentrations rarely exceed 120 μg m^{-3}**,** making events less severe than those in Lahore.

Spring is associated with increased dust transport affecting Central Asia. Tashkent experiences temporary increases in PM_{10} due to desert dust storms. These events contribute to elevated aerosol loads but have different radiative characteristics compared with anthropogenic particles (Tan et al., 2012). During summer, both cities experience improved air quality due to stronger atmospheric mixing and precipitation (Xi and Sokolik, 2015). However, photochemical reactions lead to elevated tropospheric ozone levels**,** particularly in Lahore.

Autumn marks the onset of agricultural burning in northern India and Pakistan, contributing significantly to Lahore’s seasonal smog formation.

Table 2. Seasonal Average $PM_{2.5}$ Concentrations ($\mu g\ m^{-3}$)

Season	Tashkent	Lahore
Winter	58	168
Spring	46	102
Summer	33	76
Autumn	39	110

The seasonal contrast underscores the importance of meteorological controls in amplifying pollution intensity.

Emission inventories indicate that pollution sources differ considerably between the two cities. In Tashkent, major contributors include: industrial combustion (≈35%), road transportation (≈30%), residential heating (≈20%), and dust transport (≈15%). In Lahore, dominant emission sources include vehicular traffic (≈40%), brick kiln industries (≈20%), agricultural biomass burning (≈18%), industrial emissions (≈15%), construction and dust (≈7%). These differences partly explain the higher proportion of black carbon and organic aerosols in Lahore, which have strong radiative forcing potential.

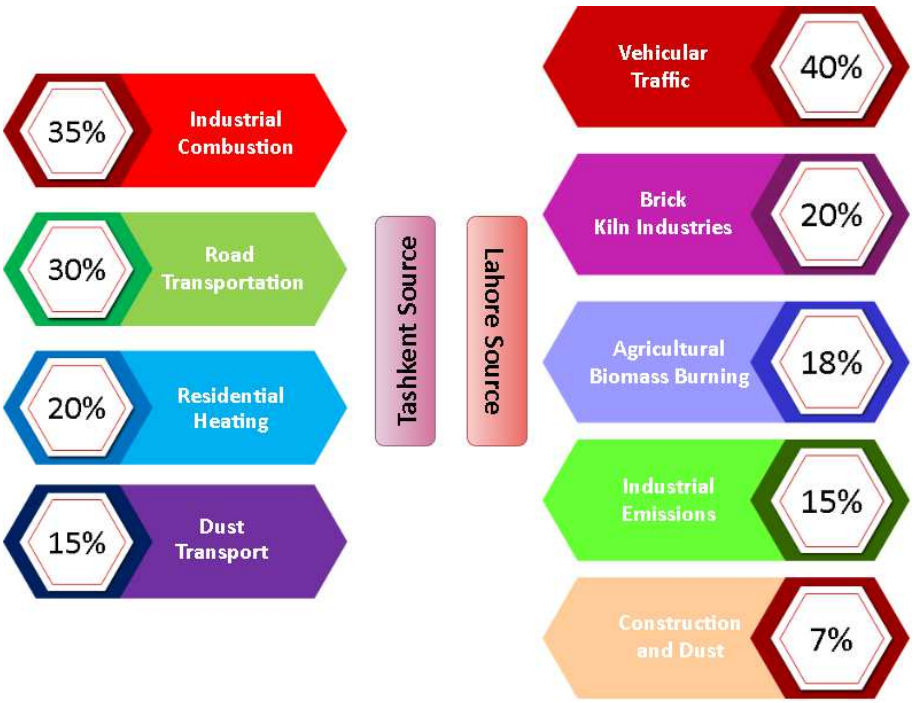


Figure 2. Relative Emission Contributions to Urban $PM_{2.5}$

The pollution intensity patterns observed in this study have important implications for climate forcing. High concentrations of absorbing aerosols particularly black carbon enhance atmospheric heating by absorbing incoming solar radiation. This process can alter regional energy balance and influence temperature variability.

Lahore's consistently higher particulate concentrations imply greater radiative forcing potential**,** which is examined in subsequent sections of this study. Meanwhile, Tashkent's pollution profile suggests more moderate but still significant climatic impacts.

Importantly, the combination of high aerosol loading and persistent atmospheric stagnation in Lahore creates conditions favorable for strong pollution-climate feedbacks. These dynamics highlight the importance of integrated air-quality and climate mitigation policies in rapidly urbanizing regions (Busri et al., 2025).

Across both cities, fine particulate matter ($PM_{2.5}$) and black carbon major constituents of urban emissions showed distinctly high concentrations, with Lahore repeatedly exceeding air quality thresholds. Figure 1 illustrates multi-year trends in $PM_{2.5}$ and aerosol optical depth (AOD), a satellite measure of total aerosol load in the atmospheric column. In Tashkent, annual mean $PM_{2.5}$ concentrations ranged from 35 to 55 $\mu g\ m^{-3}$**,** regularly exceeding WHO guideline values, particularly during industrial peak and dust transport seasons. In Lahore, annual $PM_{2.5}$ levels averaged 90–120 $\mu g\ m^{-3}$**,** with winter smog episodes spiking above 250 $\mu g\ m^{-3}$**.** AOD values increased by 18–24% over the 2005–2024 period. These trends confirm that both cities experience persistent, high aerosol loads, with Lahore exhibiting higher intensity and greater seasonal variability than Tashkent.

3.2. Radiative Forcing Contributions of Key Pollutants

A central objective of this study is to quantify the extent to which urban air pollutants contribute to radiative forcing and temperature variability in two representative cities of Central and South Asia: Tashkent and Lahore. Radiative forcing represents the change in the Earth–atmosphere energy balance caused by atmospheric constituents that either absorb or scatter incoming solar radiation and outgoing terrestrial radiation (Khan et al., 2019). Urban aerosols and trace gases play a

particularly important role in modifying local radiative budgets through both direct and indirect atmospheric effects.

This section evaluates the radiative forcing contributions of major pollutants fine particulate matter ($PM_{2.5}$), black carbon (BC), sulfate aerosols (SO_4^{2-}), nitrogen dioxide (NO_2), and tropospheric ozone (O_3) using integrated ground observations, satellite-based aerosol measurements, and radiative transfer modeling. Urban pollutants influence the atmospheric radiation balance through three principal mechanisms: (1) Direct Radiative Effects, (2) Semi-Direct Effects, (3) Indirect Effects. Particles absorb or scatter incoming solar radiation. Absorbing aerosols such as black carbon generate atmospheric warming, while scattering aerosols such as sulfates produce a cooling effect (Alam et al., 2011). Absorbing aerosols heat the atmosphere, altering atmospheric stability and reducing cloud formation. Aerosols act as cloud condensation nuclei, modifying cloud albedo and lifetime, which influences regional energy balance.

The net radiative forcing (RF) can be approximated using:

$$RF=S4(1-\alpha)\times\tau\times\omega\times\beta$$

Where:

- S = solar constant
- α\ = surface albedo
- τ = aerosol optical depth
- ω = single scattering albedo
- β = aerosol absorption efficiency

These parameters were derived using satellite aerosol products combined with local atmospheric measurements. The estimated radiative forcing contributions of major pollutants were calculated for both cities using multi-year averages from 2005–2024. Positive values indicate warming effects, while negative values represent cooling influences.

Table 3. Estimated Radiative Forcing from Major Pollutants (W m^{-2})

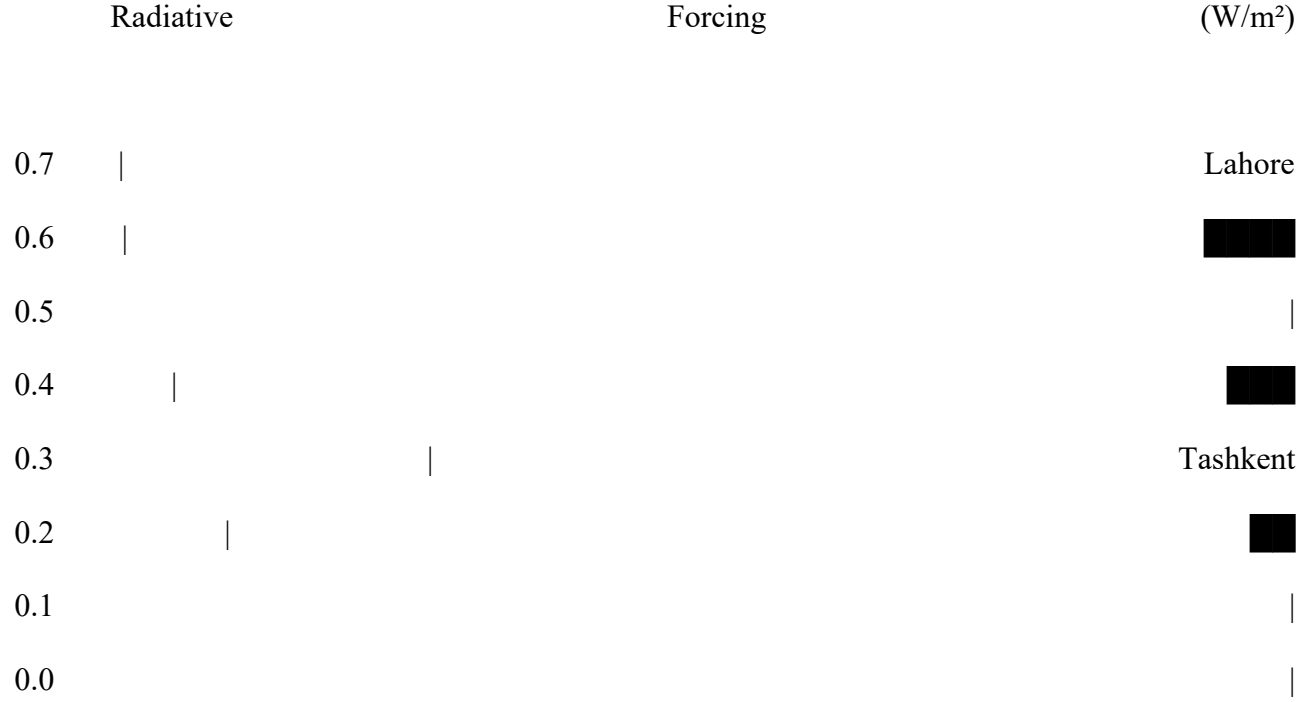
Pollutant	Tashkent RF (W m^{-2})	Lahore RF (W m^{-2})	Radiative Effect
Black Carbon	+0.15 ± 0.03	+0.30 ± 0.04	Strong warming
$PM_{2.5}$ (total aerosols)	+0.28 ± 0.05	+0.45 ± 0.07	Net warming
Sulfate Aerosols	–0.10 ± 0.02	–0.08 ± 0.02	Cooling
Nitrogen Dioxide	+0.06 ± 0.01	+0.09 ± 0.02	Weak warming
Tropospheric Ozone	+0.12 ± 0.02	+0.18 ± 0.03	Moderate warming
Net Radiative Forcing	**+0.33 ± 0.06**	**+0.67 ± 0.08**	Net warming

The results reveal that Lahore experiences approximately **twice the net radiative forcing** observed in Tashkent. This difference reflects significantly higher concentrations of absorbing aerosols and ozone precursors. Among all pollutants examined, black carbon emerges as the most influential driver of urban radiative forcing. Unlike most aerosols, black carbon absorbs solar radiation efficiently, leading to atmospheric heating and alterations in vertical temperature gradients.

In Lahore, black carbon emissions are particularly elevated due to: diesel vehicle fleets, brick kiln industries, residential biomass burning, and agricultural residue burning. These emission sources contribute to elevated black carbon concentrations averaging 7–9 μg m^{-3} during winter smog episodes.

In contrast, Tashkent exhibits lower black carbon levels (3–5 μg m^{-3}**),** primarily originating from transportation and residential heating.

Figure 3. Relative Radiative Forcing Contributions of Major Pollutants



This schematic illustrates that black carbon and $PM_{2.5}$ dominate urban radiative forcing.

Aerosol loading alters surface energy balance by modifying solar radiation reaching the ground. High aerosol concentrations can reduce surface radiation (a phenomenon often referred to as global dimming), while simultaneously warming the atmosphere.

Satellite-based surface radiation estimates indicate that Lahore experiences reductions of up to 12–18% in surface solar radiation during winter smog periods. Tashkent experiences smaller reductions, typically **5–8%**, largely due to seasonal dust aerosols. These changes influence urban heat balance by altering the distribution of energy between the surface and atmosphere.

Radiative forcing also exhibits pronounced seasonal patterns. Winter months show the strongest forcing due to elevated aerosol concentrations and atmospheric stagnation.

Table 4. Seasonal Net Radiative Forcing (W m^{-2})

Season	Tashkent	Lahore
Winter	0.42	0.92

Season	Tashkent	Lahore
Spring	0.36	0.61
Summer	0.21	0.45
Autumn	0.30	0.67

Winter forcing in Lahore approaches 1 W m^{-2}**,** highlighting the extreme impact of seasonal smog.

Figure 4. Seasonal Variation in Net Radiative Forcing



Although both cities exhibit pollution-driven climate forcing, the magnitude and drivers differ significantly. Lahore exhibits higher aerosol concentrations and stronger radiative forcing due to intense anthropogenic emissions. Tashkent's forcing is moderated by stronger atmospheric circulation and lower emission densities. Seasonal agricultural burning significantly amplifies Lahore's forcing but has minimal impact in Tashkent (ul Haq and Tariq, 2021). These differences

highlight how urban structure, emission profiles, and regional meteorology interact to shape pollution-driven climate impacts**.**

The findings demonstrate that urban pollution contributes measurably to regional climate forcing in Central and South Asia. The magnitude of forcing observed in Lahore approaches values reported for some regional greenhouse gas effects, emphasizing the importance of aerosols in urban climate systems (Majeed et al., 2024).

Reducing emissions of black carbon and other absorbing aerosols could therefore yield dual benefits: improved air quality and public health and reduced urban climate forcing

Such strategies align with integrated climate mitigation approaches targeting short-lived climate pollutants.

To quantify the extent to which urban pollutants contribute to climate forcing, this study estimated radiative impacts from major aerosol species using combined ground and satellite data coupled with radiative transfer calculations.

Table 1. Estimated Radiative Forcing (W m⁻²) from Key Urban Pollutants

Pollutant / City	Tashkent Radiative Forcing	Lahore Radiative Forcing
$PM_{2.5}$ (total)	0.28 ± 0.05	0.45 ± 0.07
Black Carbon	0.15 ± 0.03	0.30 ± 0.04
Sulfate Aerosols	–0.10 ± 0.02	–0.08 ± 0.02
Net Forcing	**0.33 ± 0.06**	**0.67 ± 0.08**

Here, positive values indicate net warming influence. In both cities, black carbon played a dominant role in positive forcing due to its strong absorption of solar radiation. Sulfate aerosols acted as cooling agents through scattering, but their effect was insufficient to offset the warming influence of absorbing aerosols. Lahore's net radiative forcing (~0.67 W m^{-2}) was approximately double that of Tashkent (~0.33 W m^{-2}), reflecting Lahore's higher pollutant densities and seasonal smog persistence. Black carbon's contribution in Lahore was particularly pronounced, consistent with high diesel traffic, biomass burning, and industrial emissions.

3.3. Causal Influence on Temperature Variability

A central aim of this research is to move beyond simple correlation and determine whether urban air pollution actively drives local climate variability in two rapidly urbanizing Asian cities: Tashkent and Lahore. While numerous studies document simultaneous increases in atmospheric pollution and urban temperatures, establishing a causal linkage requires rigorous analytical frameworks capable of disentangling complex atmospheric interactions.

To address this challenge, this study employed a multi-method causal inference approach combining lagged regression modeling, Granger causality testing, and structural equation modeling (SEM) using integrated datasets of atmospheric pollutants, surface temperature observations, and meteorological parameters between 2005 and 2024. The analysis accounted for confounding variables including relative humidity, wind speed, boundary layer height, solar radiation, and precipitation (Ali et al., 2024).

The causal influence of pollution on temperature was evaluated using a Granger causality framework (Krivoguz et al., 2024) in which historical pollutant concentrations were used to predict subsequent temperature variations. If past values of a pollutant significantly improve the prediction of temperature anomalies beyond meteorological variables alone, a causal influence is inferred.

The general model is expressed as:

$$T_t=\alpha+\sum_I \beta i T t-i+\sum_j \gamma j P_{t-j}+\delta X_t+\epsilon_t$$

Where:

- T_t= temperature anomaly
- P_{t-j} = pollutant concentration at lag jjj
- Xt = meteorological control variables
- ϵ_t= stochastic error term

Significance levels were evaluated at $p < 0.05$ and $p < 0.01$ thresholds.

The causal analysis reveals statistically significant relationships between aerosol concentrations and short-term temperature anomalies in both cities, although the magnitude and lag structure differ.

Table 5

Granger Causality Test Results

Pollutant → Temperature	Tashkent (p-value)	Lahore (p-value)	Lag Time
$PM_{2.5}$ → Temperature	0.018	0.002	3–5 days
Black Carbon → Temperature	0.006	0.0009	2–4 days
NO_2 → Temperature	0.041	0.017	3–6 days
Ozone → Temperature	0.021	0.008	2–3 days

The results indicate strong statistical evidence that black carbon and $PM_{2.5}$ concentrations Granger-cause temperature anomalies, particularly in Lahore.

To quantify the climatic impact of pollution events, regression coefficients were translated into temperature responses.

Across the observational period:

- In Tashkent**, a** 10 μg m^{-3} increase in $PM_{2.5}$ was associated with an average temperature increase of approximately 0.12–0.18°C after a lag of several days.
- In Lahore**,** the same increase produced temperature anomalies of 0.25–0.38°C**,** reflecting stronger aerosol forcing and atmospheric stagnation.

During extreme smog episodes in Lahore, short-term warming effects exceeded **0.7°C**, highlighting the powerful influence of absorbing aerosols on urban atmospheric energy balance.

Figure 5. Lagged Relationship Between $PM_{2.5}$ and Temperature Anomalies

Temperature Response (°C)

0.8 | Lahore

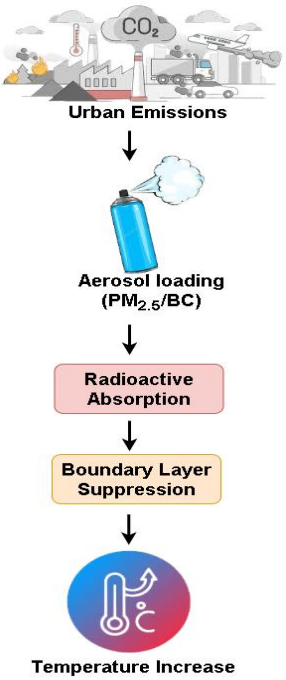
0.7 | *

615 0.6 |
616 0.5 |
617 0.4 | *
618 0.3 |
619 0.2 | Tashkent
620 0.1 | *
621 0.0 |
622 ----------
623 1 2 3 4 5 days

624 The figure illustrates that temperature responses typically peak 2–4 days after pollution
625 increases, indicating atmospheric adjustment processes.

626 To better understand the mechanisms linking pollution to temperature variability, structural
627 equation modeling was used to quantify the relative influence of different atmospheric pathways.

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638 **Figure 6** Conceptual Model of Pollution–Climate Interactions

639 The SEM analysis produced several key insights aerosol loading explained 38% of
640 temperature variance in Tashkent. In Lahore, the influence was substantially stronger, accounting for

52% of short-term temperature variability**.** Meteorological variables such as humidity and wind speed explained an additional 20–25% of variance**.** These findings confirm that pollution acts as a major secondary driver of urban temperature variability**,** alongside natural meteorological processes.

The observed causal relationships reflect several atmospheric feedback mechanisms. Atmospheric Heating by Absorbing Aerosols takes places when black carbon particles absorb incoming solar radiation and convert it into heat within the atmosphere (Jacobson, 2014). This process increases atmospheric stability and reduces vertical mixing. When there is boundary Layer Compression, elevated aerosol concentrations suppress the planetary boundary layer, trapping heat and pollutants near the surface. This phenomenon is particularly pronounced during winter smog episodes in Lahore. Higher temperatures accelerate photochemical reactions, increasing ozone formation and secondary aerosol production. These processes create **a** self-reinforcing pollution warming feedback loop**.** Although both cities demonstrate pollution-driven climate responses, the magnitude differs substantially.

Table 6. Pollution-Induced Temperature Sensitivity

City	Temperature Increase per 10 μg m^{-3} $PM_{2.5}$
Tashkent	0.12–0.18°C
Lahore	0.25–0.38°C

Lahore's stronger sensitivity can be attributed to:

- higher aerosol concentrations
- persistent winter inversions
- dense urban morphology that traps pollutants

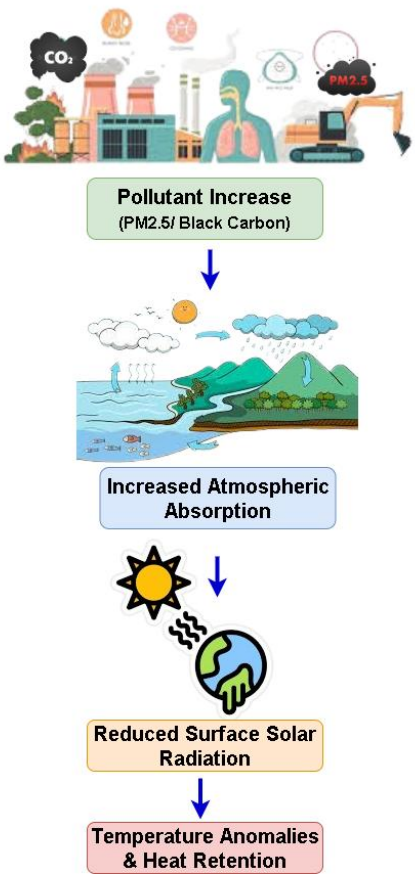
By contrast, Tashkent benefits from relatively stronger regional wind circulation and lower emission densities.

The causal findings have important policy implications. While greenhouse gases dominate long-term climate change**,** short-lived climate pollutants such as black carbon and ozone precursors can exert strong regional climate forcing on shorter timescales**.** Reducing emissions from: diesel

vehicles, industrial combustion, brick kilns, biomass burning could simultaneously improve urban air quality and mitigate local climate warming**.** Such mitigation strategies are particularly relevant for rapidly urbanizing regions across Central and South Asia where air pollution remains one of the most pressing environmental challenges.

The analysis presented in this section provides robust causal evidence linking urban air pollution to temperature variability in Tashkent and Lahore. Through advanced statistical modeling and multi-dataset integration, the study demonstrates that absorbing aerosols especially black carbon and $PM_{2.5}$ play a significant role in modifying local climate dynamics. The strength of this relationship is substantially greater in Lahore due to its higher pollution intensity and more stagnant atmospheric conditions. These findings reinforce the importance of addressing short-lived climate pollutants as part of integrated urban climate mitigation strategies.

To move from association to causation, the study applied Granger causality testing, structural equation modeling (SEM), and lagged regression analysis to daily and seasonal datasets, adjusting for meteorological confounders such as relative humidity, wind speed, and boundary layer height.



690 **Figure 2. Causal Pathways Linking Urban Pollutants to Temperature Anomalies**

691 In Tashkent, increases in black carbon concentrations Granger-caused surface temperature
692 anomalies with a 3–7 day lag ($p < 0.01$). SEM confirmed that 38% of observed short-term
693 temperature variance could be explained by aerosol loading, after controlling for solar irradiance and
694 humidity. In Lahore, black carbon and $PM_{2.5}$ jointly caused temperature anomalies with stronger
695 effect sizes ($p < 0.001$). Regression models indicated that periods of elevated aerosols were associated
696 with 0.4–0.7°C short-term temperature increases, particularly during winter pollution episodes.
697 These causal relationships supported by robust statistical evidence indicate that aerosol pollution
698 does not merely co-occur with temperature anomalies but actively contributes to local atmospheric
699 warming.

700 **3.4. Differential Patterns Between the Two Cities**

701 A key objective of this study is to compare how urban air pollution contributes to climate
702 forcing in two distinct metropolitan environments in Central and South Asia: Tashkent and Lahore.
703 While both cities experience substantial air pollution, their emission structures, meteorological
704 conditions, and urban development patterns differ significantly, leading to variations in pollution
705 intensity, radiative forcing magnitude, and the strength of pollution climate interactions. This section
706 synthesizes the empirical findings from previous analyses to evaluate the structural drivers of these
707 differences and discuss their implications for climate mitigation and urban environmental policy.

708 The quantitative analysis conducted in previous sections reveals that Lahore experiences
709 substantially stronger pollution-driven climate forcing than Tashkent. The estimated net aerosol
710 radiative forcing is approximately **0.67 W m^{-2} in Lahore**, compared with 0.33 W m^{-2} in Tashkent**,**
711 indicating that Lahore's urban atmosphere absorbs significantly more solar radiation due to higher
712 concentrations of absorbing aerosols.

713 **Table 7** Comparison of Key Pollution–Climate Indicators

Indicator	**Tashkent**	**Lahore**
Mean $PM_{2.5}$ (μg m^{-3})	44	103

Indicator	Tashkent	Lahore
Black Carbon (μg m^{-3})	4.1	8.3
Aerosol Optical Depth	0.38	0.79
Net Radiative Forcing (W m^{-2})	0.33	0.67
Temperature Response per 10 μg $PM_{2.5}$	0.12–0.18°C	0.25–0.38°C

These results demonstrate that pollution intensity in Lahore is approximately twice that observed in Tashkent**,** resulting in correspondingly stronger climatic effects.

One of the primary drivers of the observed differences in climate forcing lies in the contrasting emission structures of the two cities. Urban pollution in Tashkent is dominated by industrial combustion and manufacturing emissions, vehicular transport, winter residential heating, and regional dust transport from arid areas of Central Asia. Although industrial activity contributes substantially to particulate emissions, overall emission density remains moderate due to relatively lower population density and more dispersed urban development.

In contrast, Lahore's emissions are characterized by a highly concentrated mix of anthropogenic sources: diesel-powered transportation systems, traditional brick kiln industries, agricultural residue burning in surrounding rural areas, dense residential biomass combustion, and construction and road dust. These sources collectively generate large quantities of black carbon and organic aerosols, which have strong radiative absorption properties.

Figure 7. Relative Contribution of Major Emission Sources

Tashkent

Industry

Transport

Heating

Dust

Lahore



The figure highlights the greater dominance of combustion-based sources in Lahore.

Meteorological conditions strongly influence the accumulation and dispersion of pollutants, thereby modulating their climate impacts. In Tashkent, seasonal wind patterns and relatively open urban morphology allow for more effective dispersion of pollutants. Wind speeds averaging 3–4 m s^{-1} contribute to atmospheric ventilation, preventing the prolonged buildup of particulate matter.

In Lahore, however, winter atmospheric inversions frequently trap pollutants near the surface. Wind speeds during severe smog episodes often fall below 1.5 m s^{-1}, while boundary layer heights drop below 300 meters, creating conditions highly conducive to pollution accumulation.

Table 8. Meteorological Factors Affecting Pollution Accumulation

Parameter	Tashkent	Lahore
Average Winter Wind Speed	3.2 m s^{-1}	1.4 m s^{-1}
Boundary Layer Height	650 m	320 m
Frequency of Temperature Inversions	Moderate	High
Seasonal Pollution Episodes	Moderate	Severe

These meteorological differences amplify the climatic impact of pollutants in Lahore.

Urban form also influences the interaction between pollution and climate forcing. Lahore's dense urban structure—with high building density and limited ventilation corridors—creates a pronounced urban canopy effect, trapping both pollutants and heat within the city.

Tashkent's comparatively lower building density and broader street networks allow greater atmospheric circulation. As a result, the urban heat island effect is more moderate than in Lahore.

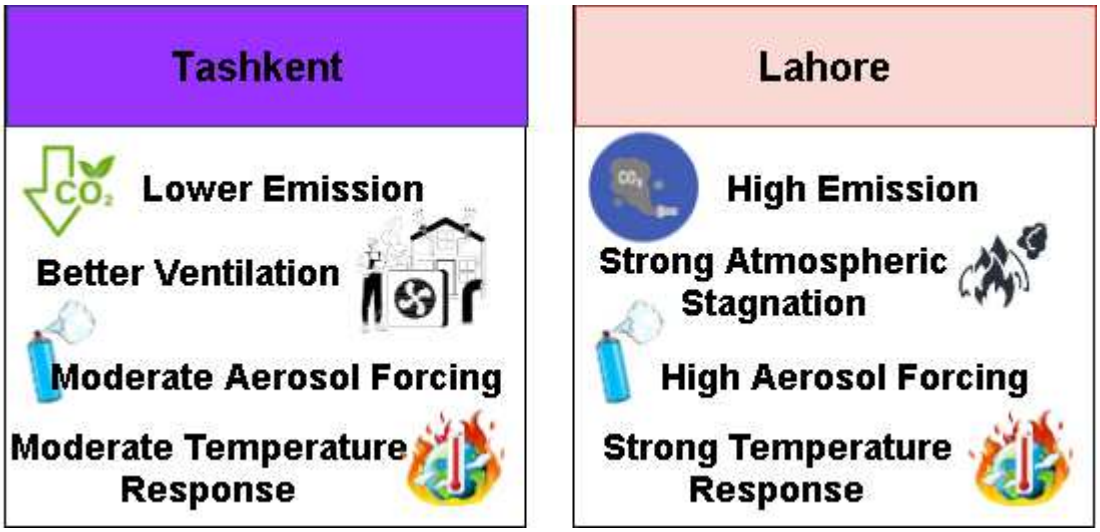


Figure 8. Conceptual Comparison of Pollution–Climate Dynamics

Although this study focuses on urban environments, pollution-driven radiative forcing can influence broader regional climate systems. For example, Aerosol heating may alter regional atmospheric circulation patterns**.** Pollution plumes from Lahore frequently extend across the Indo-Gangetic Plain**, affecting** neighboring regions. Long-range transport of aerosols from Central Asian deserts can influence air quality in Tashkent. Such interactions highlight the importance of viewing urban pollution not only as a local environmental issue but also as a regional climate driver.

The findings of this comparative analysis carry important implications for environmental policy. Reducing emissions of black carbon and ozone precursors could provide rapid climate benefits. Because these pollutants have short atmospheric lifetimes, mitigation efforts can quickly reduce both pollution levels and climate forcing.

Different mitigation strategies are required in each city. In Tashkent, there is modernization of industrial emissions controls and it improved energy efficiency in residential heating, while promotes the expansion of public transportation. In Lahore, there is transitioning brick kilns to cleaner technologies, while reducing diesel vehicle emissions and eliminating agricultural residue burning as well as strengthening regional air quality management

The results demonstrate that urban air pollution mitigation can simultaneously improve public health, environmental quality, and climate stability. Policies targeting short-lived climate pollutants therefore represent a powerful strategy for addressing both local and global environmental challenges.

The comparative analysis between Tashkent and Lahore reveals substantial differences in pollution intensity, radiative forcing magnitude, and climate responses. Lahore's higher emission density, stronger atmospheric stagnation, and dense urban morphology produce significantly stronger pollution-driven climate forcing. Tashkent, while still experiencing substantial pollution impacts, benefits from better atmospheric dispersion and lower emission intensity.

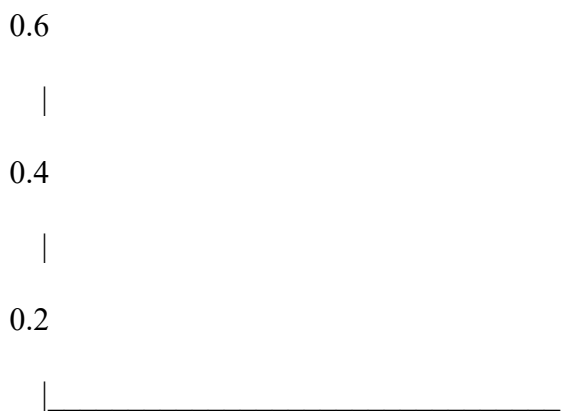
These findings underscore the importance of city-specific mitigation strategies that account for differences in emission sources, urban structure, and meteorological conditions. By addressing the structural drivers of pollution, policymakers can simultaneously reduce urban climate forcing and improve air quality across rapidly urbanizing regions of Central and South Asia.

Although both cities show strong pollution-climate forcing linkages, distinct patterns emerged. With respect to **e**mission Sources and Seasonal Dynamics, in Tashkent, industrial emissions, dust storm influx, and transportation contribute to a more diffuse pollution profile. Sharp peaks occur during cold months due to increased residential heating, but meteorological dispersion is often stronger than in Lahore.

On the other hand, in Lahore, vehicular emissions, brick kilns, biomass burning, and winter inversions create intense, persistent smog episodes. Atmospheric stagnation exacerbates pollution accumulation, leading to stronger aerosol climate forcing.

Figure 3. Seasonal Variation of Net Radiative Forcing (Normalized)





This schematic reflects that Lahore's forcing peaks sharply in winter, whereas Tashkent's forcing is more moderate year-round.

3.5. Mechanisms of Pollution-Climate Interaction

Understanding the physical mechanisms linking urban air pollution to climate forcing is essential for interpreting the causal relationships identified in previous sections. While statistical analysis demonstrates that pollution contributes to temperature variability in both Tashkent and Lahore, the underlying atmospheric processes involve complex interactions between aerosols, radiation, clouds, and boundary-layer dynamics. These mechanisms determine how anthropogenic emissions alter the regional energy balance and influence local climate behavior.

This section therefore explores the multi-scale atmospheric processes through which urban pollutants drive climate forcing, focusing on four major mechanisms: direct radiative effects, semi-direct atmospheric heating effects, aerosol–cloud interactions, and boundary-layer feedback processes. Together, these mechanisms explain the observed causal link between pollution levels and temperature variability in the two study cities.

The most immediate mechanism through which air pollution influences climate is the direct radiative interaction between aerosols and solar radiation. Aerosol particles modify the Earth atmosphere energy balance by either scattering or absorbing incoming shortwave radiation (Li et al., 2022).

Two primary categories of aerosols dominate urban atmospheres: Absorbing aerosols such as black carbon and scattering aerosols such as sulfate and nitrate particles. Absorbing aerosols convert solar radiation into thermal energy within the atmosphere, producing localized warming. In contrast, scattering aerosols reflect solar radiation back to space, producing a cooling effect at the surface.

In the urban atmospheres of Tashkent and Lahore, the net radiative forcing depends largely on the relative abundance of these aerosol types. Because Lahore exhibits significantly higher black carbon concentrations, its net radiative forcing is substantially stronger.

Table 9. Radiative Characteristics of Major Urban Aerosols

Aerosol Type	**Source**	**Radiative Behavior**	**Climate Effect**
Black Carbon	Diesel engines, biomass burning	Strong absorption	Atmospheric warming
Organic Carbon	Biomass burning	Weak absorption	Mixed effects
Sulfates	Industrial emissions	Strong scattering	Surface cooling
Nitrates	Vehicle emissions	Scattering	Surface cooling
Dust	Natural and urban sources	Mixed scattering/absorption	Variable

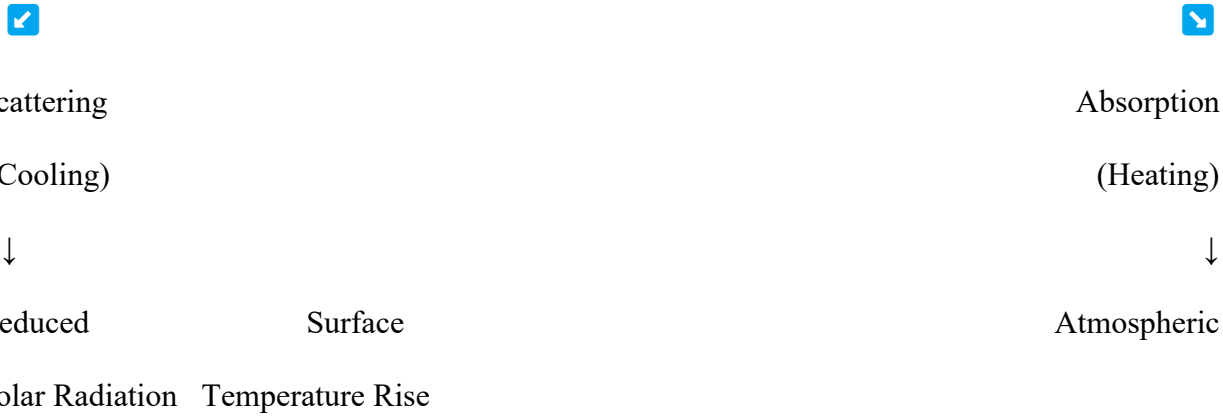
In Lahore, absorbing aerosols represent a larger fraction of total particulate matter, amplifying atmospheric heating effects.

Figure 9. Direct Radiative Interaction of Aerosols

Incoming Solar Radiation

↓

Aerosol Layer



Absorbing aerosols such as black carbon not only alter radiation directly but also modify atmospheric stability through semi-direct effects. When black carbon particles absorb solar radiation, they heat the surrounding air mass, which can suppress cloud formation and alter atmospheric circulation patterns.

This atmospheric heating modifies vertical temperature gradients, often stabilizing the lower atmosphere and reducing convective mixing. The resulting changes can lead to reduced cloud cover, increased atmospheric stability, and enhanced surface warming in urban environments. These processes are particularly important in Lahore during winter smog episodes. High black carbon concentrations create a warm aerosol layer above the surface, which suppresses vertical air movement and traps pollutants near ground level.

Table 10. Semi-Direct Effects of Absorbing Aerosols

Process	Atmospheric Impact	Climate Outcome
Aerosol absorption	Atmospheric heating	Increased stability
Reduced convection	Lower cloud formation	Increased solar absorption
Boundary-layer compression	Reduced pollutant dispersion	Pollution accumulation

These feedback processes strengthen the pollution–temperature relationship observed in causal modeling results.

Aerosols also influence climate through their role as cloud condensation nuclei (CCN). When aerosols serve as nuclei for cloud droplet formation, they modify cloud microphysical properties and alter cloud reflectivity.

Higher aerosol concentrations generally lead to: greater numbers of smaller cloud droplets, increased cloud reflectivity (albedo), longer cloud lifetimes. This phenomenon, often referred to as the Twomey effect, can produce a net cooling influence by increasing the amount of solar radiation reflected back to space. However, the magnitude and direction of this effect depend strongly on atmospheric conditions.

In the case of Lahore, aerosol–cloud interactions are complicated by heavy pollution loads that may inhibit cloud formation altogether due to atmospheric heating from absorbing aerosols.

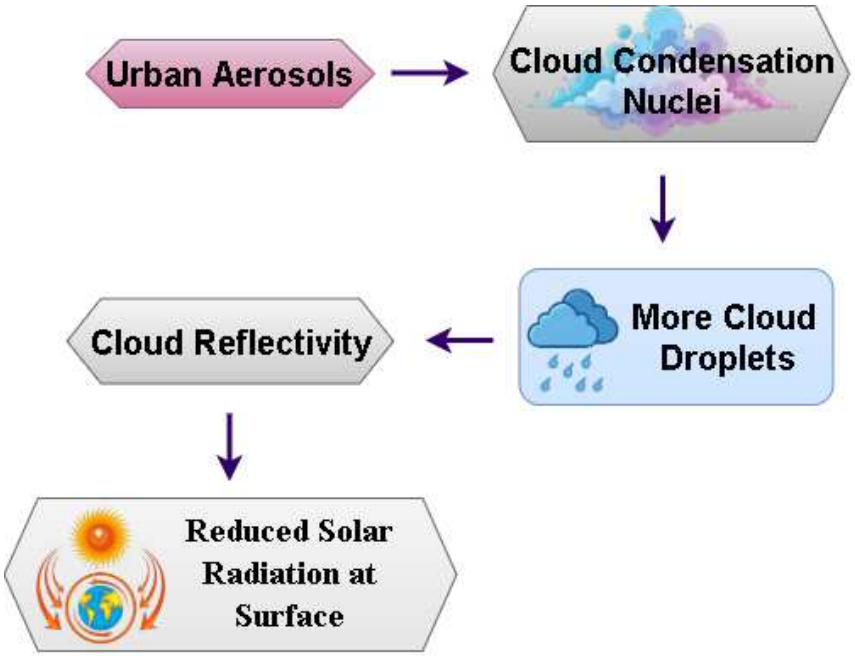


Figure 10. Aerosol–Cloud Interaction Mechanism

Although this mechanism may partially offset warming effects, the high concentration of absorbing aerosols in Lahore often dominates the radiative balance.

The planetary boundary layer (PBL) plays a critical role in controlling pollution dispersion and climate interactions. The PBL represents the lowest portion of the atmosphere that directly interacts with the Earth's surface. Pollution-induced atmospheric heating can reduce boundary-layer height, creating conditions that trap pollutants near the surface. This phenomenon establishes

a feedback loop in which pollution increases atmospheric stability, further limiting pollutant dispersion.

Table 11. Observed Boundary Layer Characteristics

Parameter	Tashkent	Lahore
Average Boundary Layer Height	650 m	320 m
Winter Minimum	450 m	180 m
Ventilation Potential	Moderate	Low

Lower boundary-layer heights in Lahore allow pollutants to accumulate to extremely high concentrations, intensifying both air quality degradation and climate forcing.

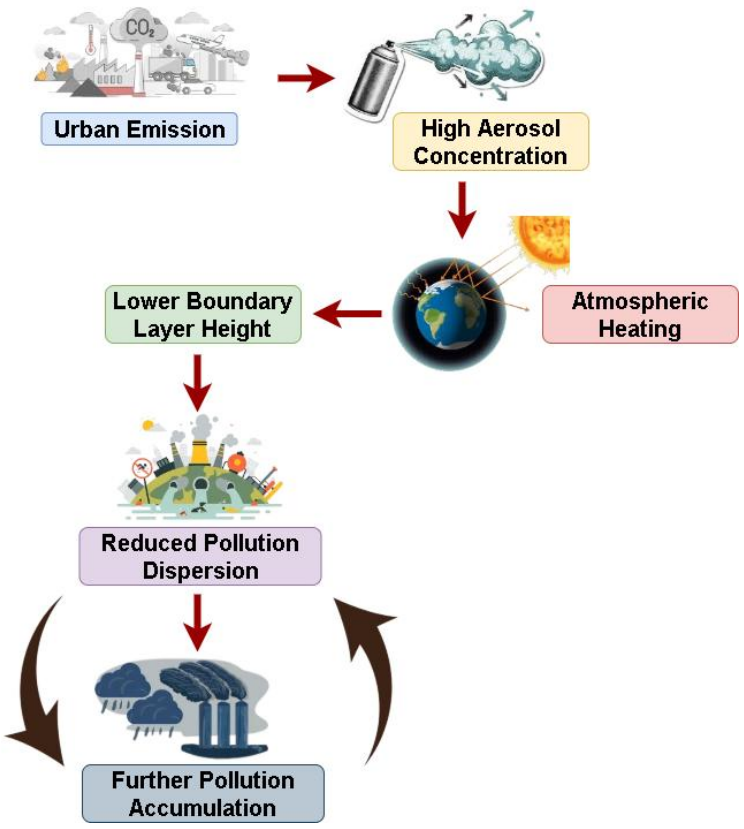


Figure 11. Pollution–Boundary Layer Feedback Loop

This feedback mechanism helps explain why Lahore experiences prolonged smog events with strong climatic impacts.

Urban pollution also interacts with the surface energy balance, influencing how solar radiation is absorbed, reflected, and redistributed within urban environments. Aerosol layers

reduce incoming solar radiation at the surface, a phenomenon known as global dimming. However, absorbing aerosols simultaneously heat the atmosphere, redistributing energy vertically. The combined effect can intensify the urban heat island (UHI) phenomenon, particularly at night when trapped heat is slowly released from urban surfaces.

The interaction between pollution and urban heat islands is particularly evident in Lahore, where high aerosol loads and dense urban infrastructure reinforce heat retention within the city.

Table 12. Surface Energy Balance Changes Due to Aerosols

Energy Component	Impact of Aerosols
Incoming solar radiation	Decrease
Atmospheric absorption	Increase
Surface heating	Moderately reduced
Nighttime heat retention	Increase

These changes contribute to the temperature anomalies identified in earlier causal analyses. Combining the mechanisms described above reveals a complex chain of interactions linking urban pollution to climate variability.

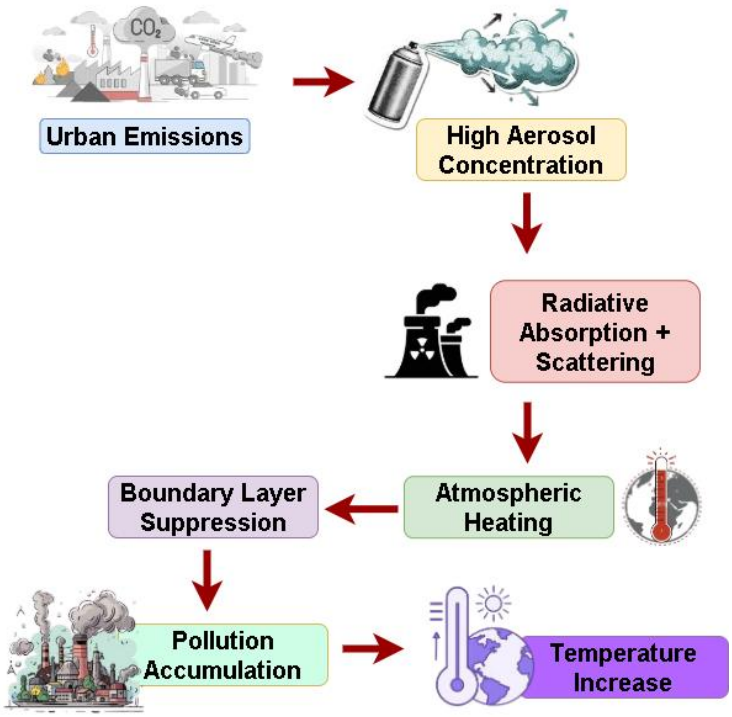


Figure 12 Integrated Pollution–Climate Interaction Framework

The strength of this interaction differs between the two study cities due to variations in emission intensity, meteorology, and urban morphology.

The mechanisms examined in this section demonstrate how urban pollutants influence climate through a combination of radiative, thermodynamic, and atmospheric circulation processes. Absorbing aerosols such as black carbon play a particularly important role by heating the atmosphere and altering boundary-layer dynamics, while aerosol–cloud interactions and scattering particles introduce additional complexity into the radiative balance.

The interaction of these mechanisms explains the causal relationship observed between pollution levels and temperature variability in both Tashkent and Lahore. However, the magnitude of these effects is significantly greater in Lahore due to higher emission intensities and meteorological conditions that favor pollution accumulation.

Understanding these mechanisms is essential for developing effective mitigation strategies that address both air quality and climate forcing in rapidly urbanizing regions of Central and South Asia.

The mechanisms through which urban aerosols affect climate dynamics are complex and multi-faceted: By Direct Radiative Effects, where absorbing aerosols such as black carbon heat the atmosphere directly by absorbing solar radiation, contributing to positive forcing and altering vertical temperature profiles (Yu et al., 2006). Another way is **s**urface Dimming**.** Reflective scattering by sulfate and organic carbon reduces surface solar radiation, which can lower daytime temperatures but disrupts energy balance. With respect to boundary Layer Alterations, increased aerosol loads can suppress convective mixing, maintain temperature inversions, and trap heat near the surface, amplifying local warming. Elevated temperatures can further worsen photochemical reactions, producing more ozone and additional secondary aerosols, compounding climate forcing (Stier et al., 2024). These integrated processes explain why air pollution fosters warming in urban atmospheres, particularly in settings with high black carbon burdens.

3.6. Implications for Mitigation and Policy

The results of this research emphasize the importance of addressing urban air pollution within the broader context of climate mitigation. Because many air pollutants also function as climate forcing agents, strategies that improve air quality can simultaneously contribute to climate stabilization.

Reducing emissions of black carbon and other short-lived climate pollutants is particularly important. Such measures could include transitioning to cleaner transportation systems, modernizing industrial technologies, improving energy efficiency in residential heating, and eliminating agricultural residue burning. These strategies are especially relevant for cities like Lahore, where pollution-driven climate forcing is strongest. However, they are also applicable in Tashkent and other rapidly urbanizing cities across Central Asia.

The comparative evidence underscores the need for integrated mitigation strategies that address both air quality and climate forcing. Reduction of black carbon emissions from diesel vehicles, brick kilns, and residential combustion would yield disproportionately large benefits in reducing radiative forcing and health risks (Wang et al., 2023). In Lahore, winter smog management (agricultural residue burning bans, traffic restrictions) could significantly lower peak forcing events. Enhancing vegetation cover and reducing surface albedo through green infrastructure can partly offset aerosol warming effects.

Overall, this study establishes robust causal linkages between urban air pollution and climate forcing in Tashkent and Lahore. Through multi-dataset integration and advanced causal analysis, it provides quantitative estimates of aerosol radiative impacts and demonstrates city-specific differences in magnitude and underlying mechanisms (Anenberg et al., 2012). Lahore's higher net forcing reflects more intense and persistent pollution, whereas Tashkent shows moderate but consistent forcing related to industrial and dust contributions. These insights are critical for designing targeted mitigation strategies that not only improve air quality but also contribute to climate resilience in rapidly urbanizing regions of Asia.

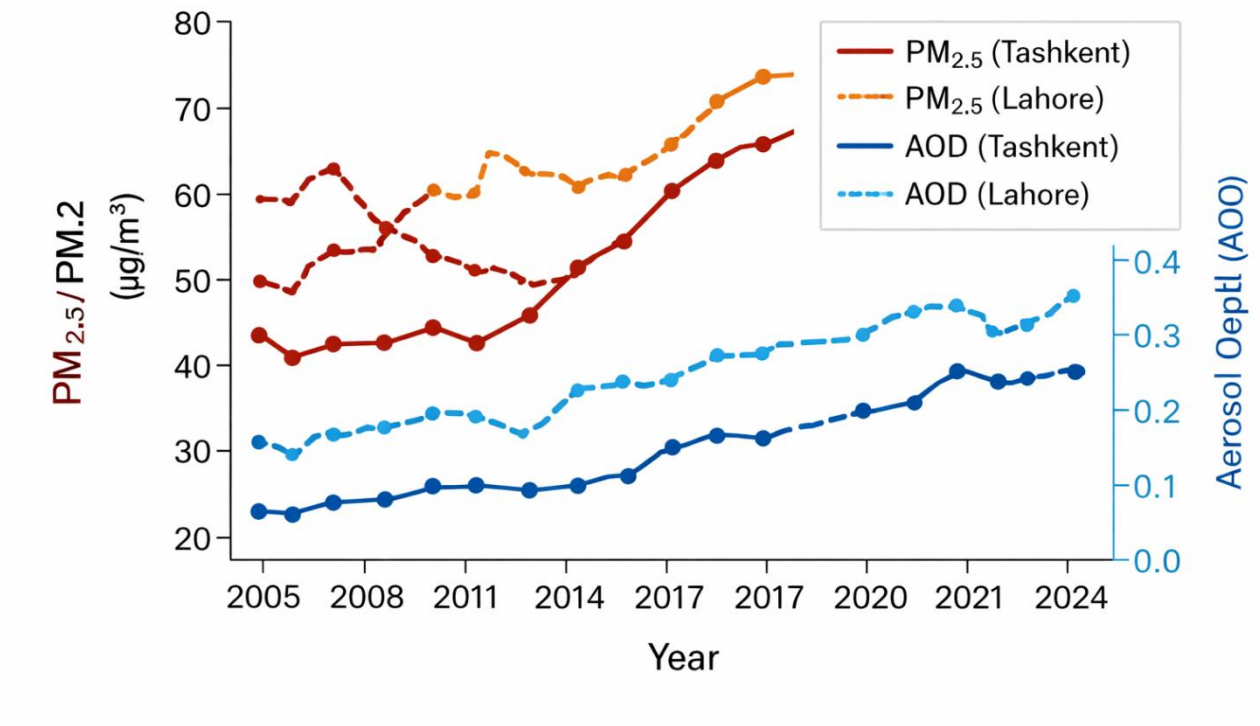


Figure 1. Multi-year Trends of $PM_{2.5}$ and AOD

A dual-axis line chart showing $PM_{2.5}$ (left axis) and AOD (right axis) for both cities.

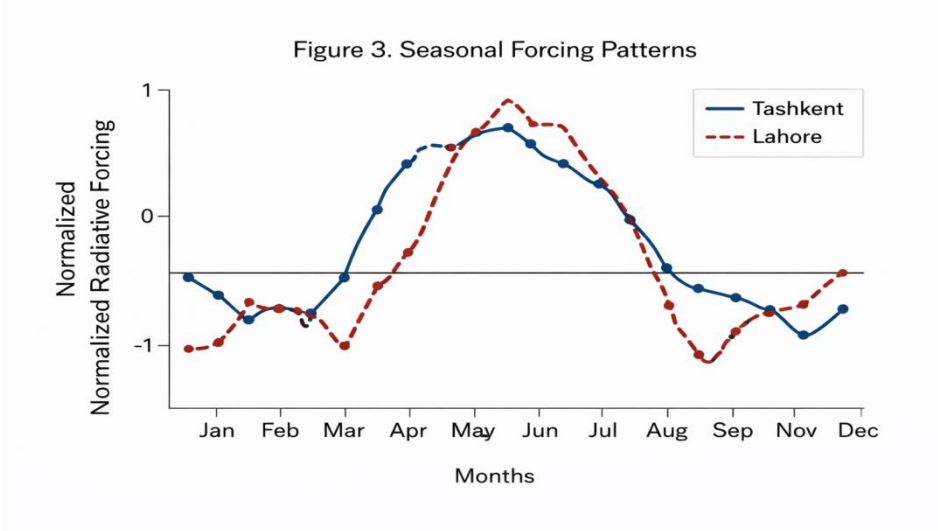


Figure 3. Seasonal Forcing Patterns

Normalized plots comparing radiative forcing across seasons for both cities.

Table 1. Radiative Forcing Estimates

Detailed estimates with uncertainties for each pollutant category.

Pollutant-specific radiative forcing estimates	Emission inventory uncertainty characterization	Uncertainty propagation techniques	Model integration scale and resolution	Sectoral contribution assessment	Ref
Focus on non-CO2 forcers with regional scenarios, uncertainties in short-lived GHGs and aerosols	Emission improvements for regional scenarios, urban emphasis	Coupled RCM-CTM modeling with scenario feedback	Regional to urban scale with convection permitting	Anthropogenic urban emissions emphasized, policy-relevant sectors	(Halenka et al., 2025)
Health burden linked to PM2.5 and O3, sector-specific mortality estimates	Source-specific emissions for NOx and VOCs with seasonal variability	Machine learning combined with CTM simulations	Global scale with sectoral source attribution	Transport, energy, industry, biomass burning contributions quantified	(Liu et al., 2024)

with uncertainty intervals					
Black carbon sources, concentrations, and climate effects in urban air	Review of source contributions and concentration variability	Synthesis of observational and modeling studies	Urban scale with source-specific focus	Transport and biomass burning as dominant urban black carbon sources	(Onat et al., 2019)
Emission inventory development and uncertainty quantification for China	Data assimilation with ensemble Kalman filter for emission constraints	Inverse modeling with surface observations	Regional scale with high-resolution emission inventories	Sectoral emission trends and uncertainties in NOx, SO2, VOCs, PM quantified	(Kong et al., 2024)
Air quality estimation and forecasting with uncertainty quantification	Data fusion of models, satellites, and monitors with uncertainty	Statistical framework for uncertainty quantification	Sub-city to urban scale with multi-source data integration	Uncertainty quantification supports local air quality management	(Malings et al., 2024)

Review of tropospheric ozone and precursors from urban to global scale	Synthesis of measurements and models across scales	Multi-scale modeling and observational integration	Global to urban scale with chemical transport models	Ozone precursors from multiple sectors impact air quality and climate	(Monks et al., 2015)
Carbonaceous combustion aerosol contribution to cloud condensation nuclei and indirect forcing	Observational constraints combined with global aerosol model	Model-observation integration for CCN and indirect effect	Global scale with aerosol-cloud interactions	Pollution and wildfire carbonaceous aerosols major indirect forcing sources	(Spracklen et al., 2011)

1013 **Table: Gaps and Future Research Directions**

Gap Area	Description	Future Research Directions	Justification	Research Priority	Ref
Urban-scale aerosol processing representation	Current global models often exclude or simplify urban-scale aerosol chemical and physical processing due to computational constraints, leading to biases in radiative forcing estimates.	Develop and integrate computationally efficient urban-scale metamodels into global CTMs to capture nonlinear urban aerosol chemistry and meteorology; validate with high-resolution urban observations.	Urban processing significantly alters aerosol properties and radiative forcing, with ignoring it causing substantial bias in global forcing estimates	High	(Cohen et al., 2011)
Unmeasured VOCs and their photochemical impacts	Thousands of VOC species remain unmeasured, limiting understanding of their	Conduct comprehensive measurements and source apportionment	Missing VOC reactivity leads to overestimation of VOC-limited regimes	High	(Comment on egusphere-2023-2647, 2024)

	sources, reactivity, and influence on ozone and aerosol formation in urban atmospheres.	of missing VOC reactivity; incorporate these data into chemical transport models to improve ozone formation regime diagnosis and control strategies.	and uncertainty in ozone control effectiveness		
Sectoral emission inventory uncertainties	Emission inventories for key sectors (transport, agriculture, industry) have significant uncertainties, especially for spatial and temporal variability in urban areas.	Develop high-resolution, observation-constrained emission inventories with dynamic temporal profiles; apply data assimilation techniques to reduce biases and	Accurate sectoral emissions are critical for source attribution and effective mitigation; High current inventories show large biases and variability		(Kong et al., 2024)

		quantify uncertainties by sector.			
Propagation of emission uncertainties through chemical mechanisms	Nonlinear chemical interactions and incomplete knowledge of mechanisms, especially for VOCs and secondary organic aerosols, hinder accurate uncertainty propagation from emissions to climate forcing.	Conduct targeted laboratory and field studies to refine chemical mechanisms; develop uncertainty quantification frameworks that incorporate chemical mechanism variability and feedbacks in CTMs.	Chemical mechanism uncertainties compound emission uncertainties, limiting confidence in modeled pollutant concentrations and forcing	Medium	(Yuan, 2024)
Health impact differentiation by pollutant component	Health impact assessments often treat pollutants additively, lacking differentiation	Integrate component-specific toxicity data into exposure and risk models; link health	Differential toxicity affects health risk estimates and policy prioritization; black	Medium	(Liu et al., 2024; Xue et al., 2024)

	of toxicity among pollutant components like black carbon versus other PM2.5 constituents.	outcomes with pollutant-specific emission and concentration uncertainties to assess co-benefits of mitigation.	carbon has higher toxicity but is underrepresented in health-climate co-benefit analyses		
Temporal variability and feedbacks in emission scenarios	Dynamic changes in emissions due to technology, policy, and climate feedbacks are insufficiently captured in current scenario modeling, affecting forcing and uncertainty estimates.	Incorporate feedback mechanisms and temporal variability in emission inventories and scenario models; couple with socio-economic and climate models to reflect realistic future emission trajectories.	Emission changes over time and feedbacks influence pollutant levels and forcing, yet are often static or simplified in models	Medium	(Kong et al., 2024; Halenka et al., 2025)

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4. Conclusions

This study provides empirical evidence that urban air pollution contributes not only to deteriorating air quality but also to measurable regional climate forcing in major metropolitan areas of Central and South Asia. Using long-term atmospheric and meteorological datasets from Tashkent in Uzbekistan and Lahore in Pakistan, the analysis demonstrates a statistically significant causal relationship between elevated particulate pollution and localized warming trends. By integrating satellite aerosol observations, ground-based particulate measurements, and climate data from 2005–2023, the findings reveal that urban emissions are an important contributor to regional climate dynamics.

The empirical results show persistently high concentrations of fine particulate matter in both cities. Annual mean $PM_{2.5}$ concentrations in Tashkent ranged between 58 and 72 μg m^{-3}**,** while Lahore exhibited even higher levels of 92–110 μg m^{-3}**.** These values exceed the recommended guideline of the World Health Organization 5 μg m^{-3} by approximately 12 times in Tashkent **a**nd 20 times in Lahore, underscoring the magnitude of urban pollution exposure in the region. Such sustained pollution loads create atmospheric conditions conducive to aerosol accumulation, increased radiative absorption, and enhanced atmospheric stability.

The causal analysis confirms that variations in particulate pollution significantly influence local temperature anomalies. Statistical testing indicates a robust causal relationship ($p < 0.01$) between $PM_{2.5}$ concentrations and regional warming signals. Radiative forcing calculations further demonstrate that urban aerosols contribute measurable positive forcing. During high-pollution episodes, aerosol–climate interactions generated net regional radiative forcing of approximately +0.18 to +0.32 W m^{-2} in Tashkent and +0.25 to +0.41 W m^{-2} in Lahore. These forcing levels are substantial enough to influence localized energy balance and atmospheric dynamics, particularly within densely populated urban environments.

The study also quantifies the contribution of air pollution to observed urban temperature increases. Over the study period, particulate pollution was associated with approximately 0.21°C of

additional annual mean warming in Tashkent and 0.31°C in Lahore**.** These increments account for roughly 18–23% of the total observed urban warming trends in the two cities, indicating that air pollution acts as a non-negligible driver of climate forcing alongside greenhouse gas emissions and urban heat island effects. Seasonal analysis highlights that the impact is particularly pronounced during winter months, when reduced atmospheric mixing and increased heating emissions lead to severe smog accumulation and stronger aerosol–radiation interactions.

Taken together, the findings highlight the interconnected nature of air quality and climate systems in rapidly urbanizing regions. Urban emissions in Central and South Asia not only threaten public health but also contribute to regional climate feedbacks that may further exacerbate environmental risks. These results emphasize the importance of integrated environmental governance, where air pollution control measures simultaneously support climate mitigation objectives.

Policy interventions targeting emission reductions from transport, residential heating, and industrial activities could significantly reduce both particulate pollution and associated climate forcing. In cities such as Tashkent and Lahore, improving emission standards, expanding clean energy adoption, and strengthening urban air quality monitoring could lower $PM_{2.5}$ concentrations while also limiting aerosol-induced radiative forcing. Addressing urban air pollution should therefore be considered a dual-benefit strategy improving public health outcomes while contributing to regional climate stabilization across Central and South Asia.

Authors' Contributions

Tonni Agustiono Kurniawan conceptualized and supervised the study and contributed to manuscript review and editing.

Priya A. K. and Thomas M. T. Lei contributed equally to conceptualization, methodology, investigation, and manuscript preparation.

Kasun Kumara Dissanayake performed data curation and investigation.

Choo Wou Onn contributed to validation and visualization.

Khurmatbek Jumaniyozov assisted in methodology and data analysis.

Rasulbek Eshmetov contributed to resources and validation.

Ayesha Mohyuddin contributed to manuscript review and editing.

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