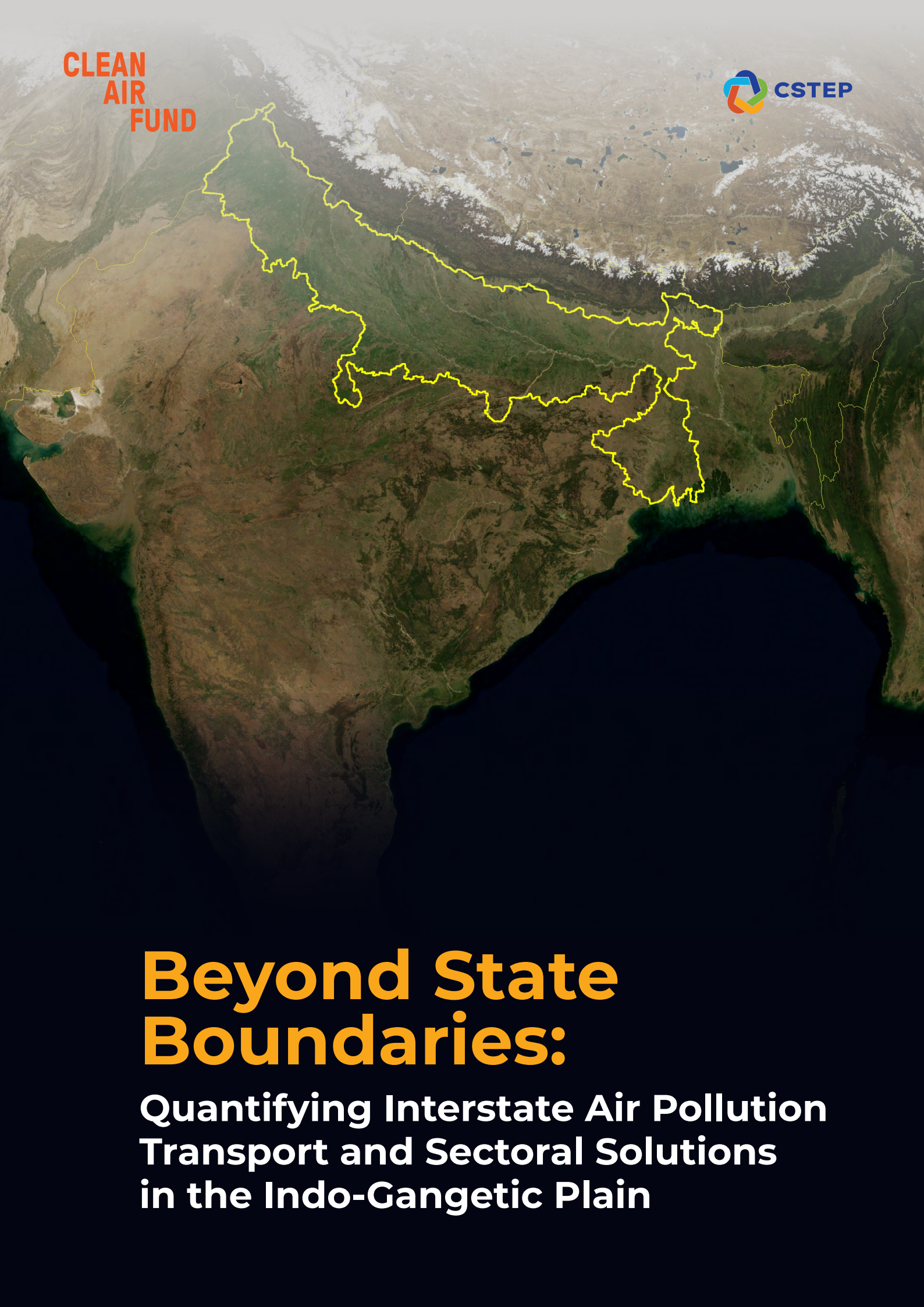


A satellite map of South Asia, with the country of India highlighted by a yellow outline. The map shows the surrounding regions, including Pakistan to the west, China to the north, and Bangladesh to the east. The Indian Ocean is visible to the south.

**CLEAN  
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FUND**



# **Beyond State Boundaries:**

**Quantifying Interstate Air Pollution  
Transport and Sectoral Solutions  
in the Indo-Gangetic Plain**



# **Beyond State Boundaries:**

## **Quantifying Interstate Air Pollution Transport and Sectoral Solutions in the Indo-Gangetic Plain**

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August 2026

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# Executive Summary

The Indo-Gangetic Plain (IGP) is home to about 36% of India's population. People in the region are exposed to high levels of fine particulate matter ( $\text{PM}_{2.5}$ ) pollution, with annual average concentrations more than double the Indian National Ambient Air Quality Standard (NAAQS) of  $40 \mu\text{g m}^{-3}$ . The IGP is an emission-intensive region. Combined with unfavourable meteorological conditions, such as slow wind speeds and a shallow planetary boundary layer (PBL), this leads to the accumulation of pollutants during the post-monsoon and winter seasons.

During these seasons, the National Capital Region (NCR) frequently experiences severe air pollution episodes, attracting significant media and public attention. However, these episodes are not confined to administrative boundaries. City-centric initiatives under the National Clean Air Programme (NCAP) insufficiently address the regional nature of the problem. Tackling this challenge requires an airshed-based framework that enables coordinated action across multiple jurisdictions, as envisaged through institutions such as the Commission for Air Quality Management in the NCR and Adjoining Areas (CAQM).

This study aims to identify the major sources of air pollution across the IGP, the regions from which they originate, and feasible mitigation measures to manage air quality at a regional scale.

The Weather Research and Forecasting model coupled with the Comprehensive Air Quality Model with Extensions (WRF-CAMx) was used, along with multiple global emissions inventories, to apportion sources of  $\text{PM}_{2.5}$  pollution across IGP states for 2019. The model captures  $\text{PM}_{2.5}$  concentrations well, with a low normalised mean bias ( $-2.3\%$ ) and a moderate Pearson correlation ( $0.63$ ) against measurements from the Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network.

The annual average simulated  $\text{PM}_{2.5}$  concentration over the NCR is  $67.9 \mu\text{g m}^{-3}$ . Local sources account for approximately 28% of this total, driven primarily by residential activities, followed by industry, natural and agricultural sources, and transport. About one-third of  $\text{PM}_{2.5}$  pollution in the NCR originates from neighbouring countries.

A similar analysis across seasons shows that Punjab experiences the highest seasonal concentrations— $98.6 \mu\text{g m}^{-3}$  during the post-monsoon months (October–November)—due to agricultural waste burning. These high levels persist during winter (December–February), with  $\text{PM}_{2.5}$  concentrations reaching  $91.2 \mu\text{g m}^{-3}$ . Among local sources in Punjab, the residential sector accounts for about 52% of local  $\text{PM}_{2.5}$  pollution.

The WRF-CAMx setup is also used to test multiple emission reduction scenarios. In a combined scenario comprising a 50% reduction in emissions from residential, energy, industrial, transport, and agricultural waste-burning sources, along with a 90% reduction in emissions from waste incineration, annual average  $\text{PM}_{2.5}$  reduces by 23% in the NCR (from  $67.9$  to  $52.3 \mu\text{g m}^{-3}$ ) and by 20% in Punjab (from  $77.8$  to  $62.2 \mu\text{g m}^{-3}$ ).

Targeted interventions yield limited benefits. For example, a 50% reduction in agricultural waste burning emissions across Punjab and Haryana (excluding NCR districts) leads to a 5% reduction in average  $\text{PM}_{2.5}$  concentration in Punjab from October to November.

## Policy insights

Air quality in the IGP is driven by geographically dispersed, seasonally varying, and multi-sectoral emissions. Modelling results show that standalone state- or sector-specific interventions yield limited gains. In contrast, combined reductions across residential, industrial, energy, transport, and agricultural waste-burning sources deliver substantially higher annual and seasonal benefits. This underscores the need to move from fragmented local implementation to aligned state-level action within an airshed framework.

## Key governance gaps

- » At present, most mitigation measures are implemented at the city level because the jurisdiction of urban local bodies—the key implementing agencies under the National Clean Air Program—is confined to city limits.
- » Sectoral compliance timelines are misaligned. For example, timelines for industrial fuel transitions and end-of-life vehicle (ELV) regulations vary across states. While India's federal structure allows states to design independent policies, the absence of a coordination framework to address cross-border pollution means that emissions from individual states can affect air quality across entire regions.
- » Limited inter-state coordination enables emission sources to shift across borders, such as through freight movement and old-vehicle migration, thereby diluting local gains.
- » Implementation gaps persist in key schemes. For instance, the rapid expansion of access to liquefied petroleum gas (LPG) under the Pradhan Mantri Ujjwala Yojana (PMUY) has not consistently translated into sustained clean fuel use. Continued fuel stacking in rural households remains a challenge.
- » Weak data integration and uneven enforcement, reflected in varying inspection intensity across states, reduce overall regional effectiveness.

## Strategic priorities and actions

- » Accelerating sustained clean cooking transitions by improving last-mile LPG access, rather than focusing solely on the number of LPG connections, and addressing behavioural factors, such as fuel stacking, through awareness campaigns and improved subsidy design, including upfront discounts
- » Aligning crop diversification strategies, ex-situ biomass market mechanisms, and enforcement mechanisms across Punjab, Uttar Pradesh, and Haryana
- » Integrating crop residue management monitoring with real-time satellite-based fire detection to enable field-level verification and targeted enforcement
- » Developing and adopting a common approved clean fuel list across the IGP through coordinated state action
- » Expanding Online/Continuous Emission Monitoring System coverage to include medium-scale industries and strengthen inter-state compliance tracking
- » Implementing stringent and harmonised industrial emission standards across the IGP, similar to CAQM directives in the NCR
- » Aligning vehicle inspection and maintenance programmes, scrappage policies, and electric vehicle adoption strategies across states to prevent cross-border migration of older fleets
- » Eliminating open dumping and waste burning through strengthened grievance redressal systems, enforcement mechanisms (e.g. flying squads), and public awareness programmes.

## Conclusion

An airshed-based framework for the IGP should establish shared regional targets, harmonised enforcement timelines, coordinated funding mechanisms, integrated emission inventories, and robust compliance tracking systems. Such a framework would enable collective emission reductions across the region, ensuring that progress in one state is not offset by weaker action in another and facilitating the exchange of best practices across jurisdictions.



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# Abbreviations

|               |                                                                                          |
|---------------|------------------------------------------------------------------------------------------|
| APCD          | Air Pollution Control Devices                                                            |
| BC            | Black carbon                                                                             |
| CAAQMS        | Continuous Ambient Air Quality Monitoring Stations                                       |
| CAMS-GLOB-BIO | Copernicus Atmosphere Monitoring Service Global Biogenic                                 |
| CAMx          | Comprehensive Air Quality Model With Extensions                                          |
| CAQM          | Commission for Air Quality Management in the National Capital Region and Adjoining Areas |
| CEDS          | Community Emissions Data System                                                          |
| CO            | Carbon monoxide                                                                          |
| CRM           | Crop residue management                                                                  |
| ECMWF         | European Centre for Medium-Range Weather Forecasts                                       |
| EI            | Emissions inventory                                                                      |
| ELV           | End-of-life vehicle                                                                      |
| ERA5          | ECMWF Reanalysis Version 5                                                               |
| EV            | Electric vehicle                                                                         |
| FAME          | Faster Adoption and Manufacturing of Electric Vehicles in India                          |
| FGD           | Flue gas desulphurisation                                                                |
| GFED          | Global Fire Emissions Database                                                           |
| HCV           | Heavy commercial vehicles                                                                |
| IGP           | Indo-Gangetic Plain                                                                      |
| LPG           | Liquefied petroleum gas                                                                  |
| MoEFCC        | Ministry of Environment, Forests and Climate Change                                      |
| NAAQS         | National Ambient Air Quality Standards                                                   |
| NCAP          | National Clean Air Programme                                                             |

|                   |                                                                                                         |
|-------------------|---------------------------------------------------------------------------------------------------------|
| NCR               | National Capital Region                                                                                 |
| NH <sub>3</sub>   | Ammonia                                                                                                 |
| NMB               | Normalised mean bias                                                                                    |
| NMVOC             | Non-methane volatile organic compounds                                                                  |
| NO                | Nitric oxide                                                                                            |
| NO <sub>2</sub>   | Nitrogen dioxide                                                                                        |
| NO <sub>x</sub>   | Oxides of nitrogen (includes NO <sub>2</sub> and NO)                                                    |
| OC                | Organic carbon                                                                                          |
| OCEMS/CEMS        | Online/Continuous Emission Monitoring System                                                            |
| OSAT              | Ozone Source Apportionment Technology                                                                   |
| PBL               | Planetary boundary layer                                                                                |
| PM <sub>10</sub>  | Particulate matter of size 10 µm or less                                                                |
| PM <sub>2.5</sub> | Particulate matter of size 2.5 µm or less                                                               |
| PMUY              | Pradhan Mantri Ujjwala Yojana                                                                           |
| PSAT              | Particulate Source Apportionment Technology                                                             |
| RVSF              | Registered vehicle scrapping facility                                                                   |
| SO <sub>2</sub>   | Sulphur dioxide                                                                                         |
| SPCB              | State pollution control board                                                                           |
| SWM               | Solid waste management                                                                                  |
| ULB               | Urban local bodies                                                                                      |
| VOC               | Volatile organic compounds                                                                              |
| WRF               | Weather Research and Forecasting Model                                                                  |
| WRF-CAMx          | Weather Research and Forecasting model coupled with the Comprehensive Air Quality Model with Extensions |
| WRF-Chem          | WRF model coupled with chemistry                                                                        |



# 1. Introduction

## 1.1. Air quality in the Indo-Gangetic Plain: Background and challenges

The National Capital Region (NCR) is in the news every year for its high levels of air pollution, particularly between October and February. However, this issue is not confined to New Delhi or the NCR. It affects a much broader region, including the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, and West Bengal, as well as neighbouring countries such as Pakistan and Bangladesh. These areas form part of the Indo-Gangetic Plain (IGP), which covers only about 16% of India's area but is home to about 36% of its population, as of 2019.

Given the high population density and the associated emission sources in the region, the IGP emits large quantities of anthropogenic air pollutants. As a result, populations across the region are exposed to persistently high pollution levels year-round. On an annual basis, average concentrations of particulate matter of size 2.5  $\mu\text{m}$  or less ( $\text{PM}_{2.5}$ ) reach  $84 \mu\text{g m}^{-3}$ , which is  $44 \mu\text{g m}^{-3}$  above the National Ambient Air Quality Standard (NAAQS; Central Pollution Control Board, 2009) of  $40 \mu\text{g m}^{-3}$ .

Air pollutant emissions in the IGP originate from a combination of sources, including domestic solid fuel use (for cooking and heating); the transport sector, including a large share of ageing commercial vehicles such as trucks and buses; industrial activities, ranging from heavy industries to informal units such as brick kilns; and agricultural practices, including crop residue burning. In addition, ammonia emissions from agriculture contribute to the formation of secondary particulate matter.

The continued use of readily available, high-emission solid fuels (e.g. firewood, crop residue, cow dung, and coal) for cooking and heating is particularly prevalent in rural and peri-urban areas. These activities emit substantial quantities of pollutants, including  $\text{PM}_{2.5}$ , black carbon (BC), organic aerosols, and dust. Emissions typically peak during the colder months (December–February) due to increased demand for space and water heating (Venkataraman et al., 2018).

Although air pollution is a year-round concern, meteorological conditions during the post-monsoon and winter seasons (October–February) strongly favour the accumulation of pollutants near the surface. Calm winds, shallow boundary layers, and poor ventilation contribute to elevated  $\text{PM}_{2.5}$  concentrations and persistent haze. Temperature inversions act as a 'lid' on the atmosphere, trapping aerosols and precursor gases close to the ground.

Observational and modelling studies consistently link severe winter smog episodes to these meteorological conditions (Ghude et al., 2017). Satellite-based analyses further show that cold air trapped beneath warmer air aloft strongly limits atmospheric dispersion (NASA, 2009). Findings from the Indian Institute of Tropical Meteorology's Winter Fog Experiment indicate that weak turbulent mixing and shallow wintertime boundary layers sustain prolonged fog and haze events over northern India, while coupled aerosol–radiation effects further suppress boundary-layer development (Ghude et al., 2023). In addition, humidity and aerosol–radiation feedbacks intensify and extend winter fog, thereby maintaining high near-surface aerosol loading (Bharali et al., 2019). Together, these processes, combined with persistent emission sources, create a high baseline pollution load that is strongly amplified under unfavourable winter meteorological conditions.

## 1.2. Need for an airshed-level assessment

Air pollution is not restricted to administrative boundaries—it is transported across regions. Ambient pollutant concentrations at any location reflect a complex interplay of local emissions, prevailing meteorology, pollutant transport, and downwind secondary pollutant formation.

The National Clean Air Programme (NCAP), launched in 2019 by the Ministry of Environment, Forest and Climate Change (MoEFCC), provides a structured, city-centric framework for non-attainment cities to improve air quality through enhanced monitoring, accountability, and targeted sectoral interventions. However, city- and state-level action plans have limited regional impact because they do not adequately address pollution originating outside their jurisdictions.

This underscores the need for an airshed-based approach to air quality management. An airshed is a region within which air pollutants are transported, dispersed, and mixed under broadly similar meteorological and topographical conditions. Within such a system, emissions from different sources interact and collectively influence ambient air quality. Managing air quality at the airshed level enables coordinated action across jurisdictions and better reflects the spatial scale of the problem.

This study aims to establish the scientific basis for an airshed-level approach, demonstrate how emissions and meteorology interact to shape regional air quality, and identify actionable solutions across the IGP.

The Commission for Air Quality Management (CAQM) was established to enable coordinated action across states in the National Capital Region (NCR) and adjoining areas, recognising that interventions within the National Capital Territory (NCT) of Delhi alone were insufficient. This represents a shift towards regional governance—acknowledging that effective air quality management is best conducted at the airshed level rather than the city level.

Such an approach enables the quantification of shared emissions, evaluation of cross-boundary contributions, and development of long-term mitigation strategies. It complements city-level actions while ensuring that interventions reflect the true spatial scale of the air pollution problem. In this study, we extend this approach to the broader IGP, drawing on CAQM and the NCR.

### 1.3. Scope of the report and limitations

In this report, the Weather Research and Forecasting model coupled with the Comprehensive Air Quality Model with Extensions (WRF-CAMx) setup is used to identify the major regions and sectors contributing to air pollution across the IGP. The results emphasise the need to move beyond state boundaries and adopt an airshed-based approach to pollution control. The modelling framework demonstrated here can also be adopted for other regions in India.

Due to the lack of a publicly available national emissions inventory (EI) for India, this study relies on a global EI: the Community Emissions Data System (CEDS; McDuffie et al., 2020). However, global EIs do not provide activity-level detail at sectoral or sub-sectoral levels, limiting their usefulness for designing targeted interventions. As a result, this study focuses on sectoral gross reductions and the policy interventions required to achieve them.

These gross-reduction scenarios demonstrate the model's ability to quantify potential reductions in  $PM_{2.5}$  concentrations and the associated improvements in air quality. However, at the time of this study, not all emission inventories had been updated to the most recent base year; therefore, an earlier base year was used. The development of an updated national EI would improve the accuracy of model estimates for interstate transport and the impacts of proposed interventions.

This report also highlights the need for a coordinated effort to develop a periodically updated, standardised, and publicly accessible EI. Such an inventory would enhance modelling accuracy, enable granular scenario analysis, and strengthen evidence-based policymaking.

While EIs and source apportionment studies are mandated for non-attainment cities under NCAP, integrating these inventories into air quality models, such as WRF-CAMx can enable the evaluation of mitigation strategies prior to implementation.

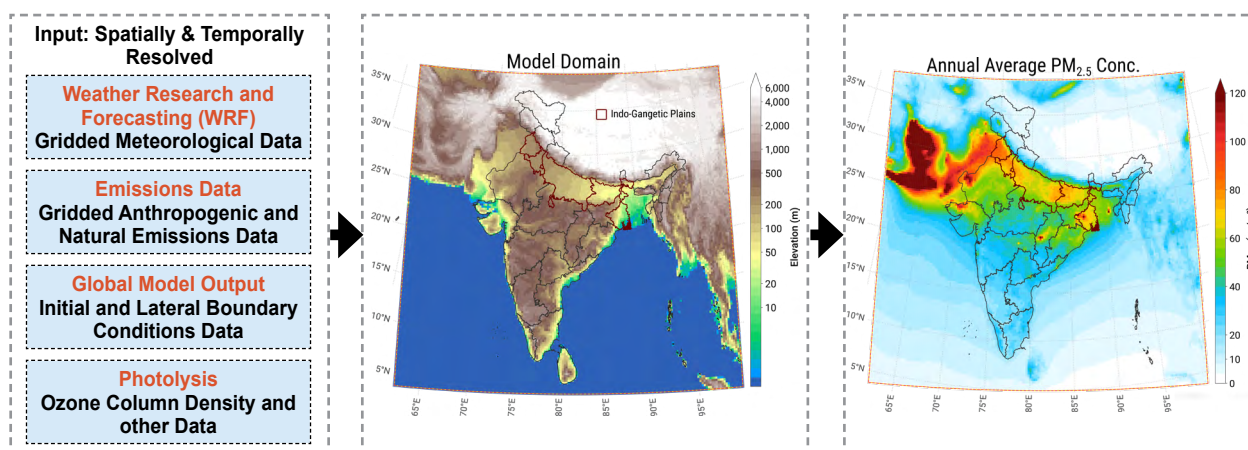
## 2. Modelling Framework

### 2.1. WRF-CAMx model and setup

This chapter describes the WRF-CAMx setup, which combines a meteorological model (WRF) with a photochemical air quality model (CAMx) to simulate the temporal evolution of pollutants emitted from various sources. Emission inputs are derived from multiple global EIs.

The WRF-CAMx framework is widely used in the United States (US) for developing State Implementation Plans mandated by the US Environmental Protection Agency. In this study, it is used to simulate atmospheric composition, estimate interstate transport, and assess the impacts of emission reduction measures across the IGP. A schematic of the modelling system is shown in Figure 1; a detailed description of the model configuration is provided in Appendix A.

*Figure 1. Schematic of the WRF-CAMx setup*



The key inputs to the WRF-CAMx are as follows:

- i. **Meteorological fields:** Three-dimensional fields, such as air temperature, wind speed, and wind direction, generated by the WRF model and initialised using European Centre for Medium-Range Weather Forecasts Reanalysis Version 5 (ERA5) data (Hersbach et al., 2020)
- ii. **Chemical boundary conditions:** Concentrations of key species, including carbon monoxide (CO), sulphur dioxide (SO<sub>2</sub>), oxides of nitrogen (NO<sub>x</sub>), ammonia (NH<sub>3</sub>), non-methane volatile organic compounds (NMVOCs), and aerosols such as PM<sub>2.5</sub> and particulate matter of size less than 10 µm (PM<sub>10</sub>), along with organic carbon (OC) and BC, derived from the Whole Atmospheric Community Climate Model (WACCM; Gettelman et al., 2019). These are used to define initial, lateral, and top boundary conditions for the CAMx model domain.
- iii. **Emissions data:** Sector-wise emissions for major pollutants obtained from multiple EIs, as described in the next section.
- iv. **Photolysis data:** Satellite-derived product datasets used to simulate atmospheric chemical reactions.

### 2.2. Source apportionment tool

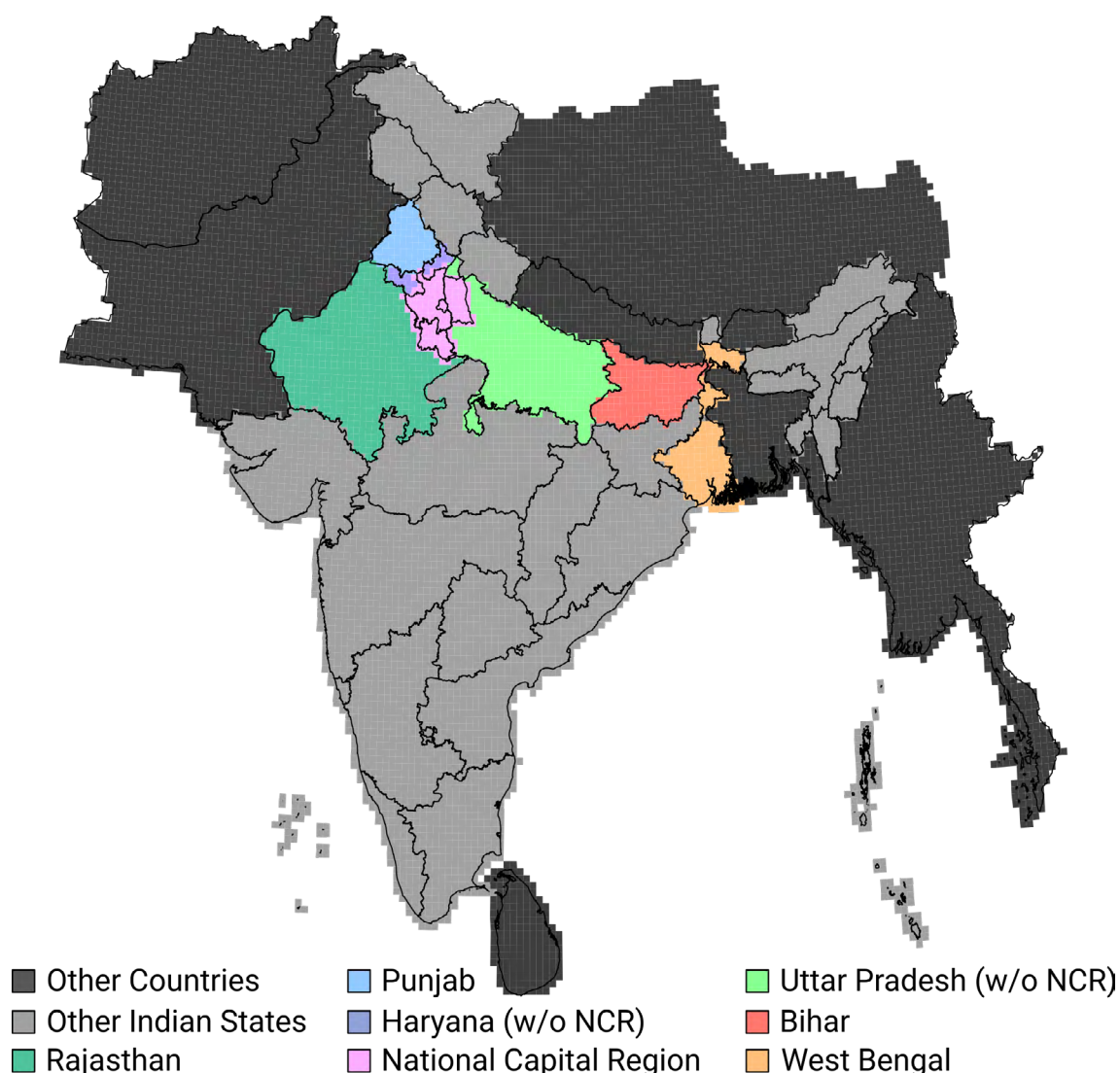
The WRF-CAMx setup includes diagnostic tools for advanced source apportionment and sensitivity analysis, notably the Particulate Source Apportionment Technology (PSAT) and the Ozone Source Apportionment Technology (OSAT). These tools enable quantitative attribution of PM<sub>2.5</sub> components, such as OC, BC, secondary sulphate, nitrate, ammonium, crustal elements (Ca, Si, Mg, Al, etc.), and ozone, to specific emission sectors and geographical regions, making them a valuable tool for assessing air quality policies (Koo et al., 2009).

In this study, we used the PSAT to estimate the interstate transport of  $PM_{2.5}$ . The method employs multiple tracer families to track the fate of primary and secondary pollutants (Yarwood et al., 2007), including sulphur, nitrogen, secondary organic aerosols, primary particulate matter, and particulate mercury. Secondary particulate species are attributed to their precursor emissions. For example, particulate sulphate is apportioned to  $SO_2$  emissions, particulate nitrate to oxides of nitrogen ( $NO_x$ ), and particulate ammonium to  $NH_3$ .

Within PSAT, regions are defined using spatial masks, referred to as 'tags', while emission sources and their groupings form an additional layer of classification. This enables the quantification of both regional and sectoral contributions to air pollution. For instance, the framework can estimate the contribution of domestic biomass burning in Haryana to  $PM_{2.5}$  concentrations in Delhi.

Figure 2 presents the regional domains used in the PSAT setup. As the number of regions and emission categories increases, computational complexity rises significantly. In this study, we have defined nine regions and seven emission categories as PSAT tags.

**Figure 2.** PSAT regions in the current baseline simulation



Additionally, based on the current policy landscape and the potential for strengthening existing policies, several CAMx simulations with sector-specific gross emission reductions were conducted to quantify the potential for air quality improvement across states in the IGP. Details of the scenarios are discussed in Section 4.3 of the report.

## 3. Emission Inventory

An EI defines the magnitude, spatial distribution, temporal variability, and composition of pollutants released into the atmosphere. The fate of these pollutants, including their transport, chemical transformation, and eventual removal through wet or dry deposition, depends on how accurately emissions are represented in the model (Seinfeld & Pandis, 2016).

In regional air quality modelling, uncertainties in the EI are often the largest source of model error, frequently exceeding those associated with meteorology and chemical mechanisms (Gilliland et al., 2003). An example of changes in  $PM_{2.5}$  concentrations in response to differences in emissions estimates across two versions of the same EI is presented in the results chapter. Errors in emission magnitude can lead to systematic biases in simulated pollutant concentrations, while inaccuracies in spatial allocation can distort urban-rural gradients and hotspot locations. Similarly, incorrect temporal profiles (e.g. diurnal or seasonal scaling) can affect the timing and persistence of pollution episodes, particularly during winter, when boundary layer dynamics strongly influence pollutant concentrations (Kumar et al., 2012).

Accurate chemical speciation is also critical, as chemical transport models rely on precursor emissions such as  $SO_2$ ,  $NO_x$ ,  $NH_3$ , and volatile organic carbons (VOCs) to simulate secondary pollutant formation, including sulphates, nitrates, and secondary organic aerosols. Misrepresentation of these species can significantly alter simulated aerosol composition and mass, leading to incorrect attribution of dominant sources in source apportionment analyses using tools such as CAMx-PSAT (Koo et al., 2009).

Emissions in highly polluted regions, such as the IGP, arise from diverse and often poorly characterised sources, including biomass burning for residential cooking and heating; informal industries such as brick kilns; and strong seasonal sources such as agricultural residue burning. In this context, high-resolution, region-specific EIs are particularly important (Venkataraman et al., 2018). Model outputs are typically validated against regulatory observations, such as data from the Central Pollution Control Board's (CPCB) Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network. However, even high-quality EIs may not capture hyper-local emissions occurring at spatial scales below 100 m, which can affect model validation.

### 3.1. Input emissions

The Community Emissions Data System (CEDS; McDuffie et al., 2020) is a global EI developed by the Pacific Northwest National Lab, United States. The version used in this study (v\_2021\_02\_05) provides sector-wise emission estimates for the base year 2019. CEDS classifies emissions into eight broad categories (McDuffie et al., 2020):

1. **Agriculture:** Emissions from soil, manure management, enteric fermentation, and related processes
2. **Energy:** Emissions from electricity and heat production, fuel production and transformation, oil and gas fugitive emissions, and fossil fuel fires
3. **Industry:** Emissions from industrial combustion and processes across sectors such as iron, steel, and other metal industries; chemical, mining, and food industries; and industrial processes and product use, such as cement, metal, lime, and other processes
4. **Transport:** Emissions from road and non-road transport, including rail and domestic navigation
5. **Residential (including commercial and other):** Emissions from biomass burning for cooking and heating, as well as commercial and other activities, such as agriculture, forestry, and fishing
6. **Solvent production and application:** Emissions from paint application, chemical manufacturing, degreasing, and other solvent-related activities



7. **Waste:** Emissions from solid waste disposal, waste incineration, and wastewater treatment
8. **International shipping:** Emissions from shipping goods on large ships, which often use heavy fuel oil, as well as from loading and unloading tankers.

The CEDS EI provides emissions in both flux and mass units for major species, including BC, OC, CO, NH<sub>3</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and speciated NMVOCs. However, it does not include emissions of fine and coarse mineral matter, which are required inputs for CAMx. These are obtained from the Emissions Database for Global Atmospheric Research–Hemispheric Transport of Air Pollution (EDGAR-HTAP v3; Crippa et al., 2023).

For sources not included in CEDS, the following additional datasets were used:

1. **Biogenic sources of emissions:** Copernicus Atmosphere Monitoring Service Global Biogenic (CAMS-GLOB-BIO) VOC emissions (version 3.1; Sindelarova et al., 2022)
2. **Agricultural waste burning and forest fires:** Global Fire Emissions Database (GFED, version 4.1; Randerson et al., 2017)
3. **Aviation emissions:** EDGAR (v6.1; Crippa et al., 2022)
4. **Natural dust:** Emissions from the arid regions of India and neighbouring countries were derived from a separate WRF–Chem simulation with a dust-only configuration (Singh et al., 2021).
5. **Oceanic emissions:** Species such as dimethyl sulphide (DMS), particulate sulphate, sodium, and chloride from large water bodies were estimated using the ‘oceanic’ module provided with CAMx (Lana et al., 2011).

## 3.2. Emissions of key pollutant species: Spatial and seasonal patterns

This section discusses emissions of key pollutant species, focusing on their spatial distribution, seasonal variability, and source contributions from anthropogenic and biogenic processes.

### Particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>)

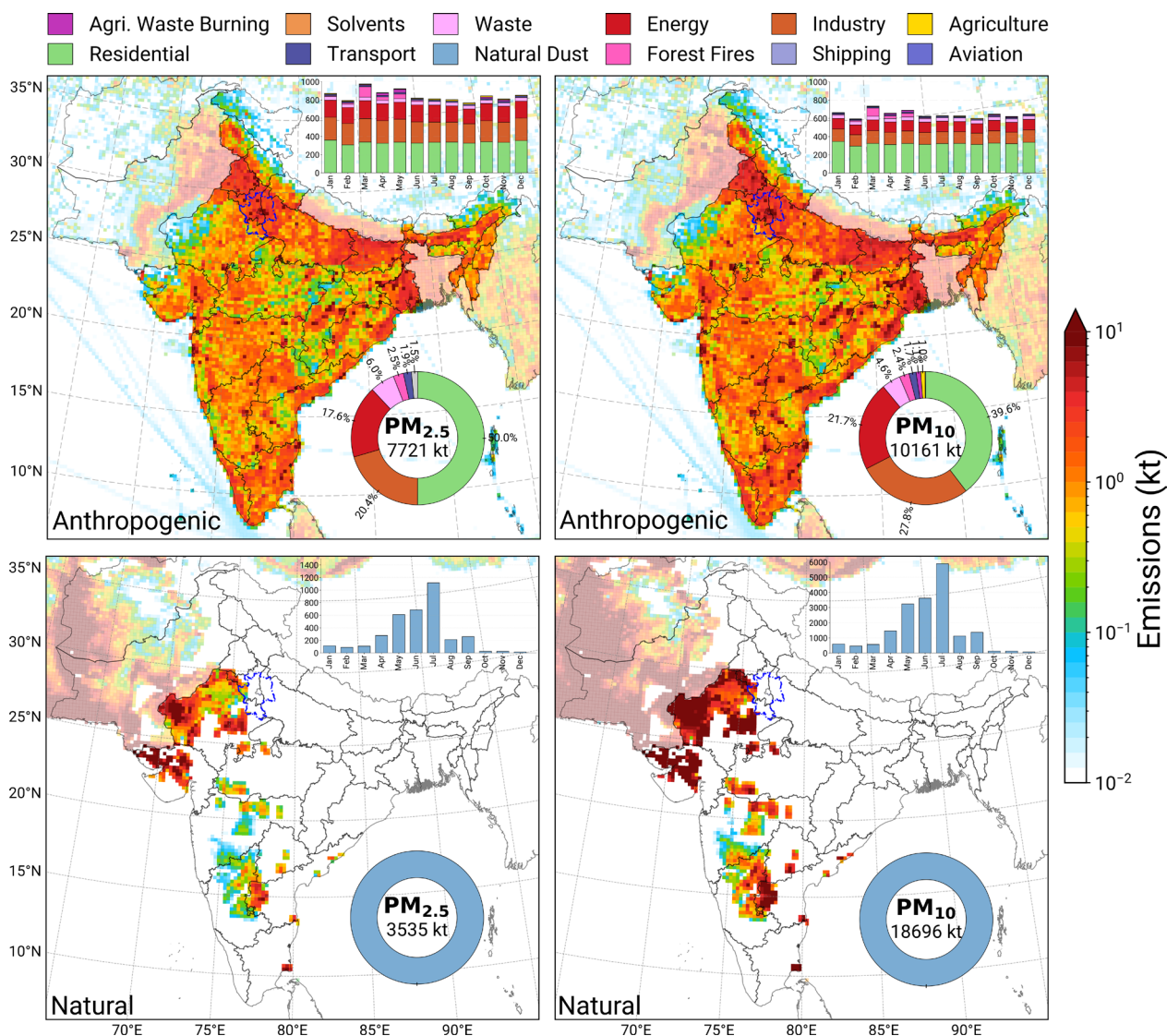
Figure 3 presents the spatial distribution of anthropogenic and natural emissions of PM<sub>2.5</sub> and PM<sub>10</sub>. Anthropogenic sources, primarily residential, industrial, and energy-related activities, dominate PM<sub>2.5</sub> emissions, while natural sources, particularly dust from arid regions such as the Thar Desert, the Rann of Kutch, and parts of peninsular India, contribute significantly to natural PM<sub>2.5</sub> emissions.

Anthropogenic PM<sub>2.5</sub> emissions are more than twice of those from natural sources; however, PM<sub>10</sub> emissions are largely dominated by natural sources. On a monthly scale (as shown in the inset of each spatial plot), anthropogenic PM<sub>2.5</sub> and PM<sub>10</sub> emissions remain consistent, with deviations driven by episodic or seasonal events such as agricultural waste burning and forest fires. In contrast, natural PM<sub>2.5</sub> and PM<sub>10</sub> emissions peak during the dry months (April–July) and decline thereafter.

Spatially, emissions are concentrated over the IGP and major urban centres, as indicated by the deep red colour on the spatial map. The IGP accounts for about 2,290 kt (30%) and 2,915 kt (29%) of total anthropogenic PM<sub>2.5</sub> and PM<sub>10</sub> emissions, respectively. Considering both anthropogenic and natural sources, total emissions are estimated at 11,256 kt for PM<sub>2.5</sub> and 28,857 kt for PM<sub>10</sub>.



**Figure 3.** Anthropogenic and natural emissions of  $PM_{2.5}$  (left column) and  $PM_{10}$  (right column) species in kilotonnes from the CEDS EI (top row) and dust emissions (bottom row), respectively.



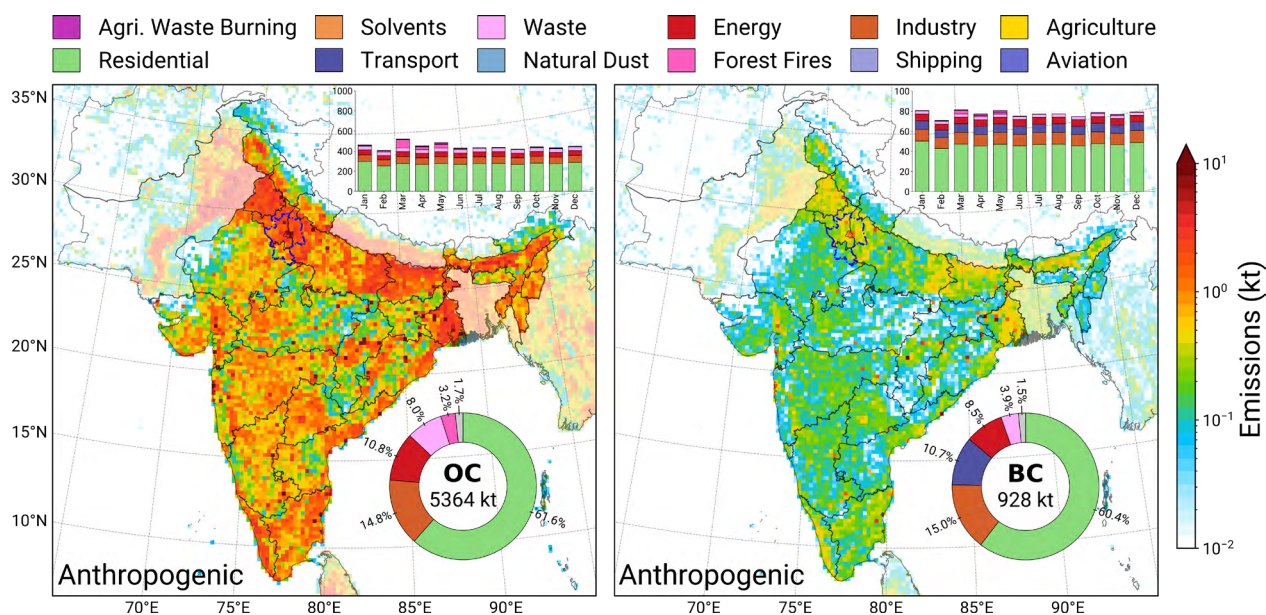
## Carbonaceous aerosols

Figure 4 shows emissions of OC and BC, which together constitute major components of  $PM_{2.5}$ . These species account for about 81.5% of anthropogenic  $PM_{2.5}$  emissions, with the remaining 18.5% attributed to mineral matter, often from sources such as road dust, mining activity, industrial processes, and coal combustion, as well as crustal metals, ash, and heavy metals.

Temporal patterns for OC and BC are broadly similar to those of  $PM_{2.5}$ , with relatively stable emissions year-round and increases during biomass burning and forest fire events. As evident from the monthly plot, emissions also rise during winter months (December–January), driven by increased demand for cooking, water heating, and space heating.

The IGP contributes about 35% and 34% of India's total OC and BC emissions, respectively. These species are primarily associated with residential biomass use and other solid fuels.

**Figure 4.** Anthropogenic emissions of OC (left) and BC (right) species in kilotonnes from the CEDS EI.

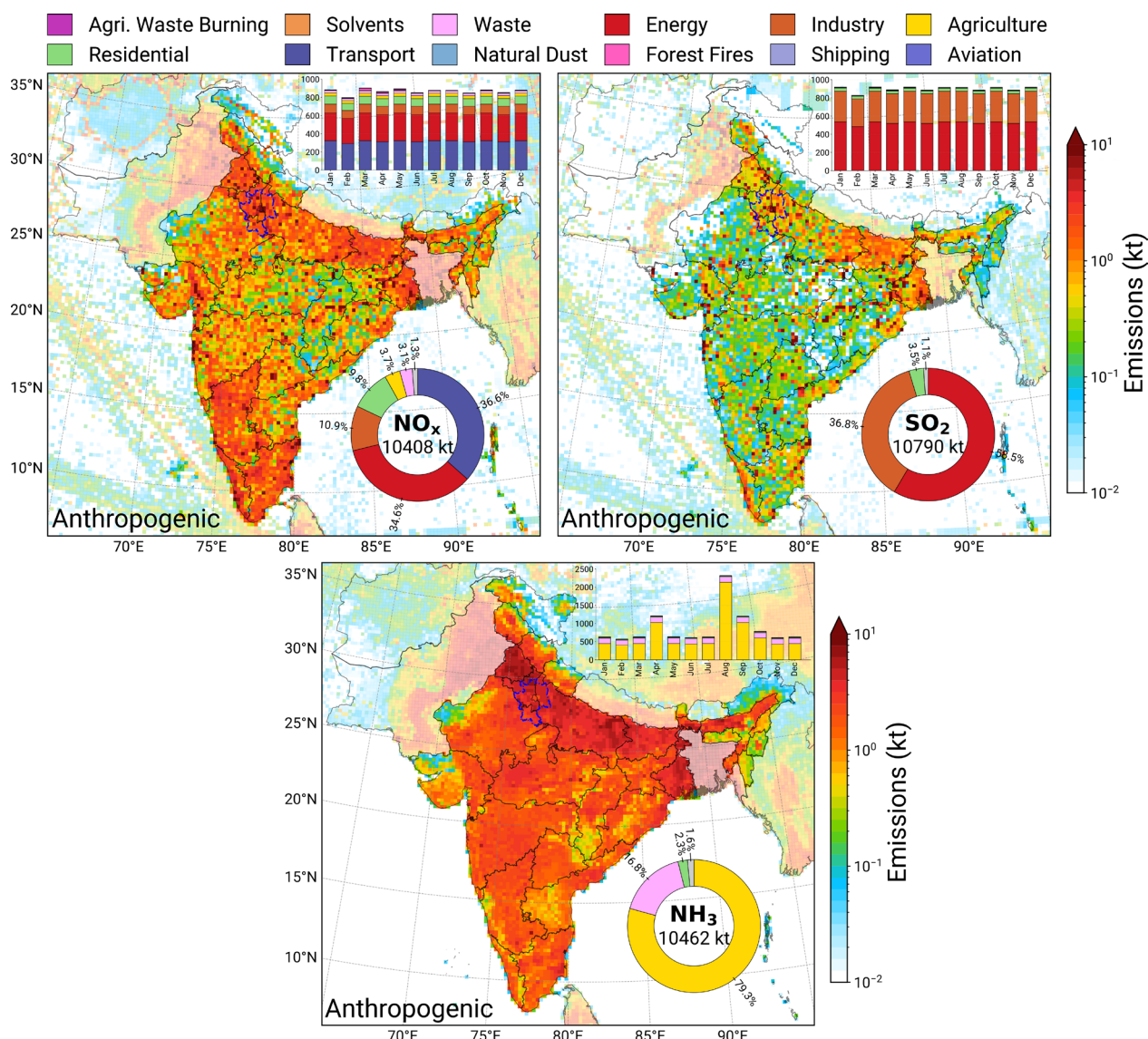


## Gaseous emissions

Figure 5 illustrates the spatial and temporal distribution of NO<sub>x</sub>, SO<sub>2</sub>, and NH<sub>3</sub> emissions. These gases act as precursors to the formation of secondary particulate matter, forming compounds such as ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) and ammonium sulphate ((NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>), which contribute significantly to PM<sub>2.5</sub> concentrations.

NO<sub>x</sub> (NO + NO<sub>2</sub>) emissions are dominated by the transport sector, followed by thermal and captive power generation. SO<sub>2</sub> emissions are concentrated in the energy and industrial sectors, with localised hotspots associated with thermal power plants and clusters of coal-based industries, such as brick kilns. Small amounts are also emitted from residential sources that use coal rather than biomass. On a monthly scale, both NO<sub>x</sub> and SO<sub>2</sub> emissions remain consistent throughout the year.

**Figure 5.** Anthropogenic emissions of  $\text{NO}_x$  (top row, left),  $\text{SO}_2$  (top row, right), and  $\text{NH}_3$  (bottom row) species in kilotonnes from the CEDS EI.



## Ammonia emissions

India's  $\text{NH}_3$  emissions are substantial, driven largely by agricultural activities, including urea-based fertiliser use and animal husbandry. The IGP accounts for about 37% of national  $\text{NH}_3$  emissions. Emissions typically peak in April, August, and September, about 6–8 weeks after sowing seeds for various crops (Kuttippurath et al., 2020), reflecting fertiliser application cycles. These cycles vary with monsoon trends in India, as rainfall accounts for a large share of crop water demand.

Waste-related sources, such as landfills and open burning, are the second-largest contributors to  $\text{NH}_3$  emissions.

## Non-methane volatile organic compounds (NMVOCs/VOCs)

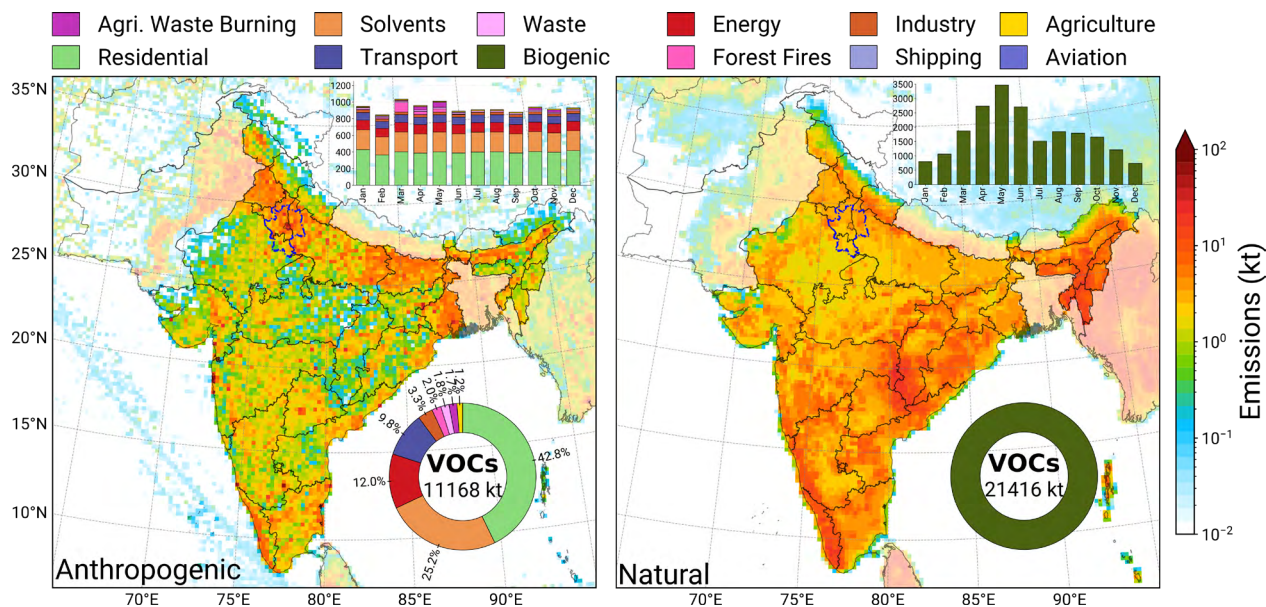
Figure 6 presents the spatial distribution and sectoral contributions of monthly NMVOC emissions. These compounds play a key role in the formation of ozone and secondary organic aerosols.

Anthropogenic NMVOC emissions arise from residential activities, solvent use, energy production, and transport, and remain relatively stable throughout the year, except during episodic or seasonal events such as agricultural waste burning and forest fires. In contrast, natural emissions, primarily from plants and forests, exhibit strong seasonal variability driven by meteorological conditions and biological activity.



According to the CAMS-GLOB-BIO EI, natural NMVOC emissions are approximately twice those from anthropogenic sources and show pronounced seasonal cycles.

**Figure 6.** Anthropogenic emissions of  $\text{NO}_x$  (top row, left),  $\text{SO}_2$  (top row, right), and  $\text{NH}_3$  (bottom row) species in kilotonnes from the CEDS EI.



## 4. Results

The WRF-CAMx modelling setup and EI, described in the preceding sections, were used to run a baseline CAMx-PSAT simulation, along with multiple CAMx-only simulations to evaluate emission-reduction scenarios. These simulations were used to quantify interstate pollution transport across the IGP and identify the most feasible emission-reduction scenarios for achieving cleaner air.

A list of simulations performed for this study, with a detailed rationale for selecting these scenarios, is discussed in Section 4.3. The baseline CAMx-PSAT runs were validated against observational data, as described in the following section. The accuracy of the baseline simulation is critical, as it directly influences estimates of interstate transport and the interpretation of scenario outcomes.

### 4.1. Model validation

The baseline run generated both meteorological and chemical outputs, which were evaluated against observations from surface weather stations and the CPCB's CAAQMS network. The validation of meteorological outputs is presented in Appendix B; this section focuses on air quality model validation.

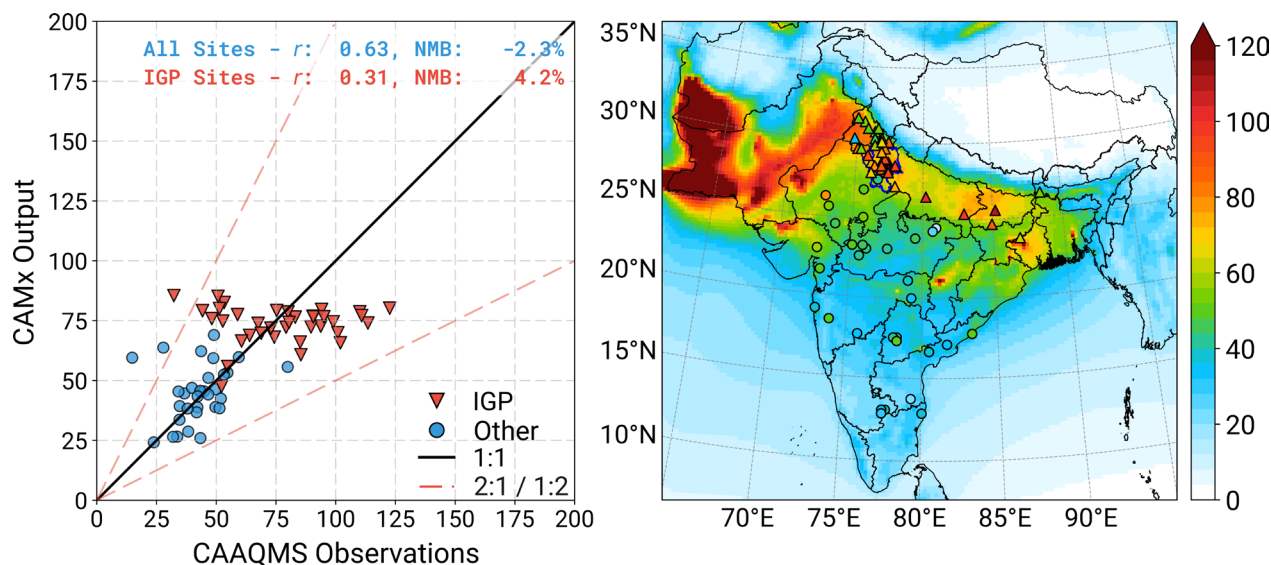
The CAAQMS network provides continuous measurements of key pollutants, including  $PM_{2.5}$ ,  $PM_{10}$ , and several gaseous species. These measurements were used to validate CAMx-derived concentrations. Discrepancies between modelled and observed concentrations may arise from inconsistencies in EIs, chemical mechanisms, aerosol modules, or boundary conditions.

The CAMx model provides hourly pollutant concentrations, which are aggregated to daily averages for comparison with daily average  $PM_{2.5}$  measurements from CAAQMS stations. To ensure data quality, the CAAQMS observations were filtered using the following criteria:

1. **Daily:** At least 75% data availability (i.e. 18 hours), with no repeated values for more than four consecutive hours
2. **Monthly:** At least 80% valid daily data
3. **Seasonal:** At least two valid months within a season
4. **Annual:** Valid data across all seasons.

Of the 338 monitoring sites with  $PM_{2.5}$  data, 158 met these criteria and were classified as 'valid' sites. The data were then checked for spatial consistency. Where a model grid contains multiple valid CAAQMS sites, the daily average of the measurements was used for further analysis. Figure 7 presents a comparison of simulated and observed annual average  $PM_{2.5}$  concentrations as a scatter plot and a spatial map.

**Figure 7.** Annual average of  $PM_{2.5}$  from CAMx vs CPCB's CAAQMS network, represented using a scatter plot (left) and a spatial map (right).



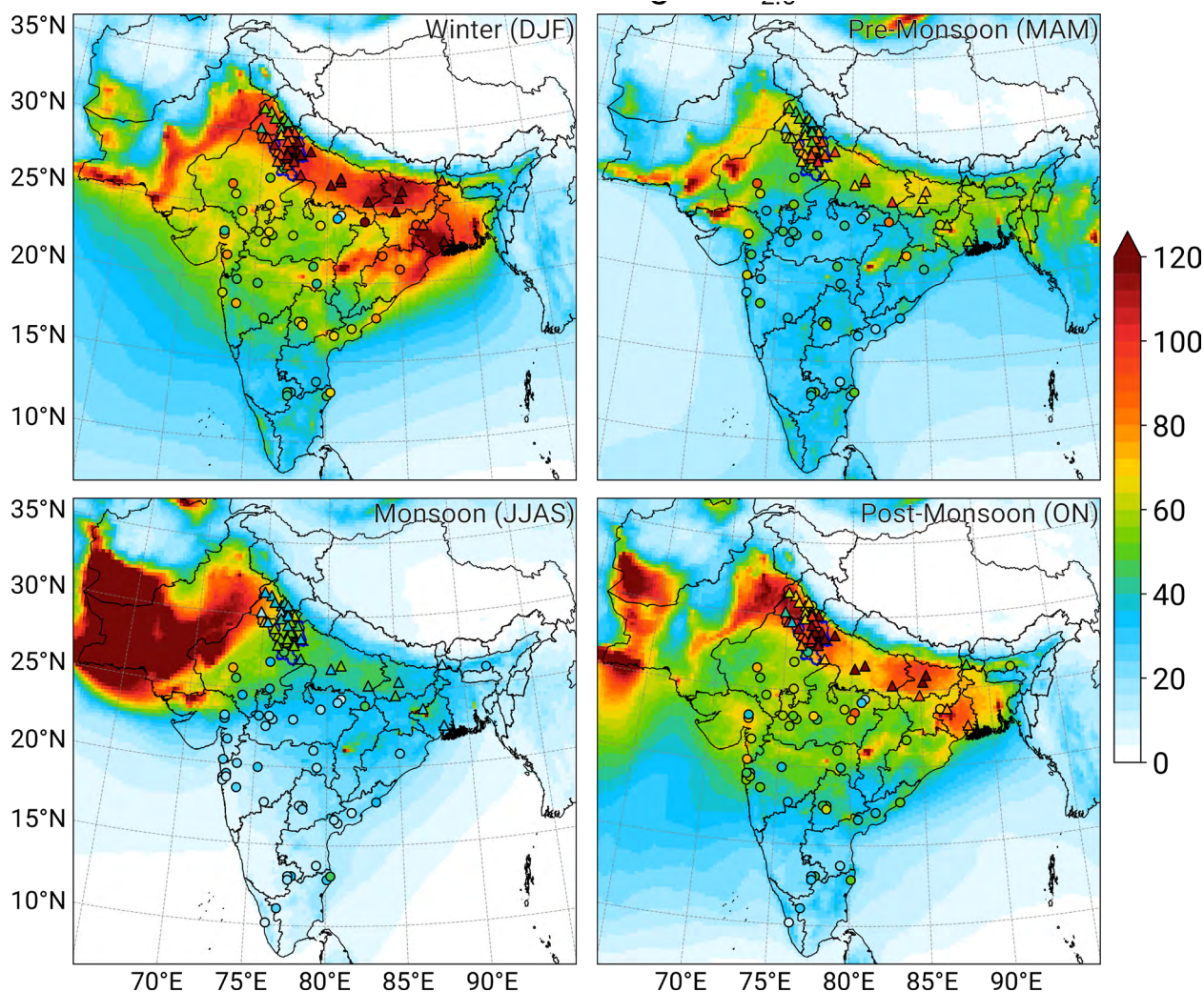
At the annual level, model performance is satisfactory, with a Pearson correlation of 0.63 and a low normalised mean bias (NMB) of 2.3%. However, when evaluated over the IGP, model performance decreases ( $r = 0.31$ , NMB = 4.2%); the model overestimates  $PM_{2.5}$  pollution in Punjab and Haryana and underestimates it in Uttar Pradesh and Bihar. This could be due to inaccuracies in global EIs over this region.

Seasonal comparisons (Figure 8 and Figure 9) show elevated  $PM_{2.5}$  concentrations across the IGP from October to February, consistent with observed pollution patterns. The region is also influenced by transboundary dust during June–July, prior to the onset of monsoon in northern India.

Model performance remains acceptable across seasons, with correlation coefficients of around 0.6 or higher across all seasons. However, NMB values increase during the pre-monsoon and monsoon periods. This is partly attributable to biases in simulated wind speeds, underestimated during the pre-monsoon season and overestimated during the monsoon (see Appendix A).



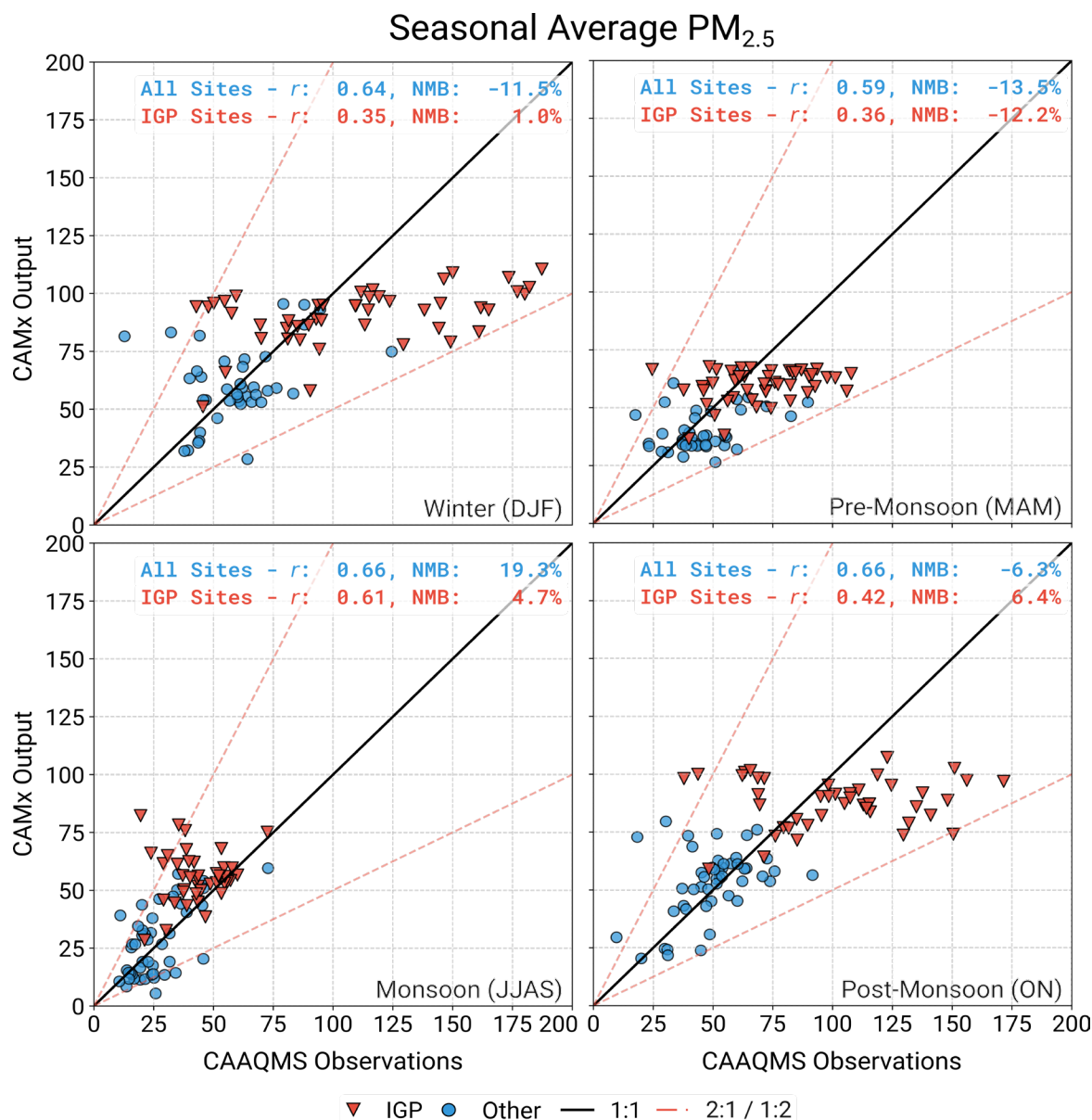
**Figure 8.** Seasonal average  $PM_{2.5}$  concentration from CAMx vs CPCB's CAAQMS network, represented using a spatial plot.



Note: DJF: December, January, February; MAM: March, April, May; JJAS: June, July, August, September; ON: October, November.

Additional uncertainties arise because global EIs, which are typically available at monthly temporal resolution, do not capture diurnal variations in emissions. By assuming uniform emissions for every hour of every day within a given month, they fail to represent localised or episodic emissions, such as open burning, construction activities, or festival-related emissions (e.g. Diwali, Baisakhi, Holi, and Durga Pooja). They also inadequately capture diurnal emission patterns associated with activities such as cooking and traffic, potentially leading to the underestimation of  $PM_{2.5}$  concentrations during specific time periods.

**Figure 9.** Seasonal average  $PM_{2.5}$  concentration from CAMx vs CPCB's CAAQMS network, represented using a scatter plot



## 4.2. Interstate transport

The baseline CAMx simulation, configured with the PSAT tool, is used to quantify the contribution of emission sources in one region to  $PM_{2.5}$  concentrations in another. Because the emission sources in the EIs were diverse, they were grouped into broader emission categories to reduce unnecessary computational costs while retaining analytical relevance. These groupings, obtained by combining different emission sources, are shown in Table 1. Additionally, the nine regions used for the CAMx-PSAT simulation are discussed in Section 2.2 and shown in Figure 2. Results from the baseline CAMx-PSAT runs for Punjab and the NCR are discussed below, while visualisations of results for other regions are included in Appendix C.

**Table 1.** Emission groups used in the baseline CAMx-PSAT simulation

| No | Emission group                   |  | Emission sources combined                                          |
|----|----------------------------------|--|--------------------------------------------------------------------|
| 1  | Residential                      |  | Residential (domestic cooking and heating), commercial, and others |
| 2  | Energy                           |  | Energy (including thermal power plants)                            |
| 3  | Industry                         |  | Industry; solvent production and application                       |
| 4  | Natural and agricultural sources |  | Biogenic, dust, agricultural sources, oceanic sources              |
| 5  | Transport                        |  | Transport, international shipping, aviation                        |
| 6  | Open burning                     |  | Waste, forest fires                                                |
| 7  | Agricultural waste burning       |  | Agricultural residue burning                                       |

Source: Adapted from CEDS EI (McDuffie et al., 2020), EDGAR v6.1 and EDGAR-HTAP v3 (Crippa et al., 2022, 2023), CAMS-GLOB-BIO (Sindelarova et al., 2022), GFED v4.1 (Randerson et al., 2017), Singh et al. (2021), and Lana et al. (2011).

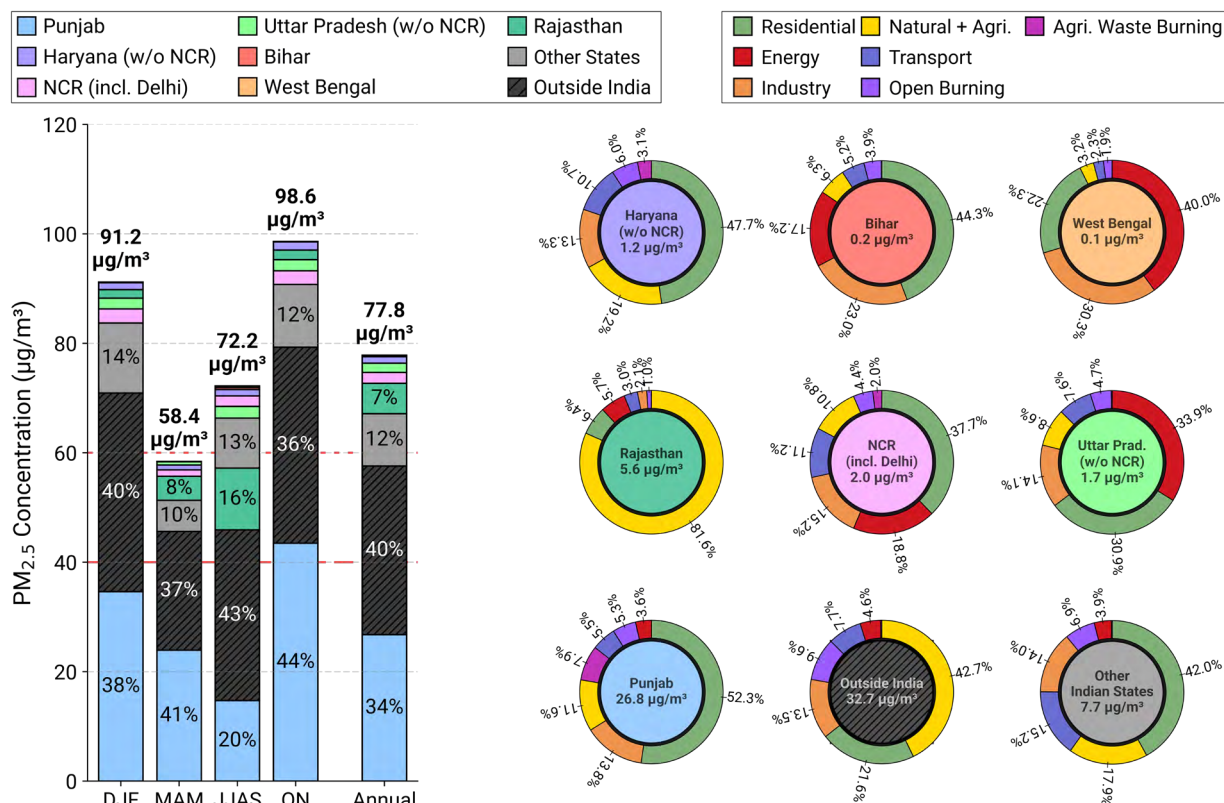
### 4.2.1. Contribution to Punjab's air quality

The baseline CAMx-PSAT simulation indicates that the annual average  $PM_{2.5}$  concentration in Punjab is  $77.8 \mu g m^{-3}$ , exceeding both the annual ( $40 \mu g m^{-3}$ ) and daily ( $60 \mu g m^{-3}$ ) limits prescribed under India's NAAQS, as shown in Figure 10.  $PM_{2.5}$  concentrations remain persistently elevated from October to February, with the seasonal mean concentration exceeding  $90 \mu g m^{-3}$ , highlighting the severity of wintertime pollution.

Local sources contribute about 34% ( $26.8 \mu g m^{-3}$ ) of the annual  $PM_{2.5}$  concentration. Within this, the residential sector is the dominant contributor (52.3%), followed by industry (13.8%), natural and agricultural sources (11.6%), and agricultural waste burning (7.9%). Although agricultural waste burning contributes only 7.9% annually, it is concentrated over a short period—15 days in May and 15–20 days during the winter season—resulting in a disproportionately high short-term impact, given that it is active for only about 10% of a year.

The dominance of residential emissions underscores that rural households still rely heavily on biomass for cooking, water heating, and space heating, highlighting the need for targeted interventions in the household energy sector.

**Figure 10.** Regional and sectoral contributions to Punjab's air quality from other regions in India. The stacked bar chart (left) shows the seasonal and annual contributions of various regions to Punjab; the pie charts (right) show the sectoral emission breakdown within each contributing region at the annual level.



Beyond local sources, Punjab's air quality is strongly influenced by transboundary pollution from Pakistan, which accounts for approximately 40% of Punjab's annual PM<sub>2.5</sub> concentration, exceeding the contribution from local sources. This transboundary influence is driven primarily by natural and agricultural sources, followed by residential, industrial, and other burning sources, such as waste and forest fires. Notably, this contribution remains relatively consistent at around 40% throughout the year.

Other regions contributing to Punjab's air quality include neighbouring Indian states, Rajasthan, the NCR, and even lower IGP states; however, their contributions are comparatively less on an annual scale. At the same time, emissions from Punjab significantly affect downwind regions, contributing about 17% to the non-NCR districts of Haryana, 8% to the NCR region, 4% to Uttar Pradesh, and less than 2% to Bihar and West Bengal.

These results demonstrate the directionality of air pollution transport: regions may be affected by upwind emissions while also contributing to downwind pollution.

#### 4.2.2. Contribution to the NCR's air quality

The NCR, including Delhi, experiences severe air pollution episodes, particularly from October to February. Poor air quality results from a combination of factors, such as a shallow planetary boundary layer, stagnant air (i.e. a low ventilation coefficient), and increased emissions from residential heating and open burning, including agricultural waste burning.

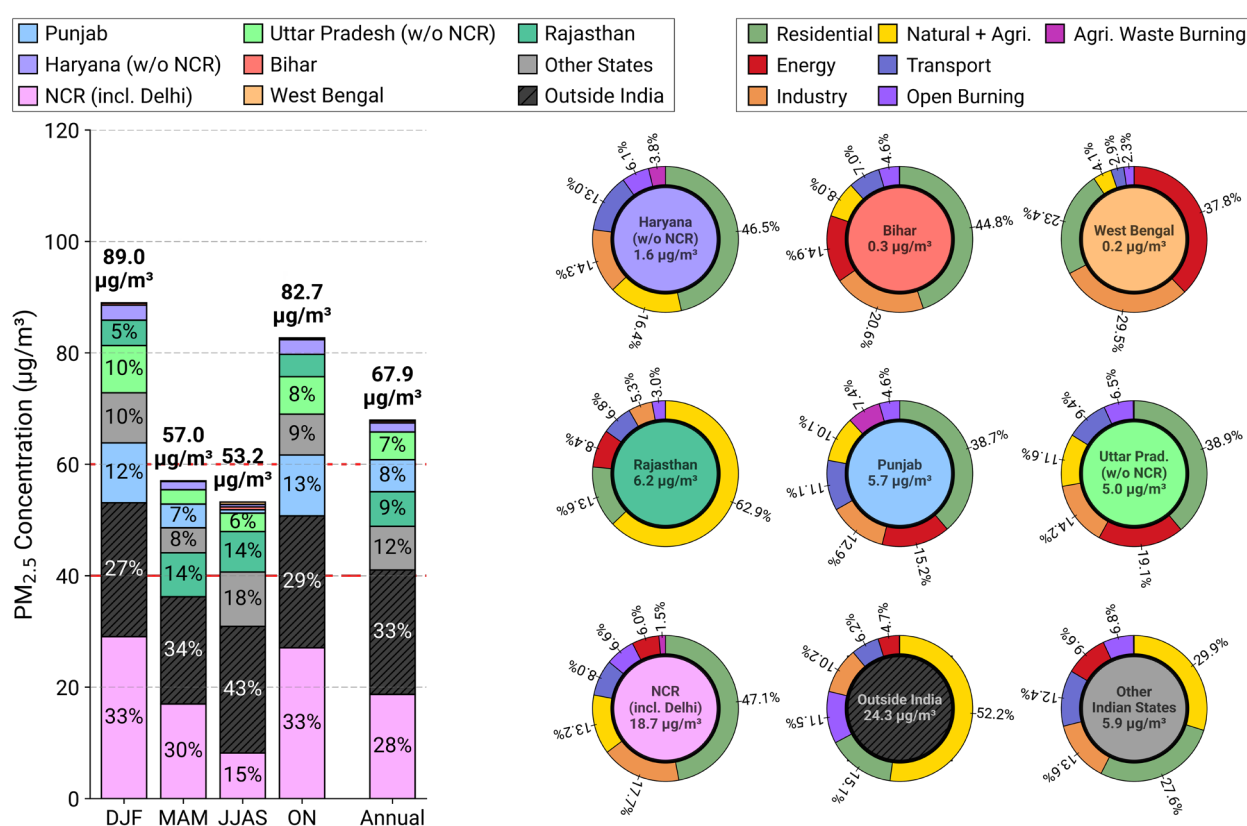
The baseline CAMx-PSAT simulation indicates an annual average PM<sub>2.5</sub> concentration of 67.9 µg m<sup>-3</sup> in the NCR. As in the case of Punjab, this exceeds both the annual (40 µg m<sup>-3</sup>) and daily (60 µg m<sup>-3</sup>) NAAQS limits (Figure 11). Several districts in the NCR are still rural (around 40% according to Census 2011) and rely heavily on fossil fuels for cooking, water heating, and space heating. Of the average annual PM<sub>2.5</sub> concentration of 67.9 µg m<sup>-3</sup>, 28% is attributed to local sources. Among these, the residential sector is the largest contributor (47%), followed by industry, natural and agricultural sources, transport, and open burning (including waste burning).



Similar to Punjab, the NCR is substantially affected by transboundary pollution from Pakistan, which accounts for about 33% of total pollution annually. Transboundary pollution is dominated by natural sources, including transported dust from arid regions of Pakistan and Afghanistan, followed by residential and open-burning sources.

Indian states in north and central India contribute about 12% of NCR's  $PM_{2.5}$  concentrations, with major contributions from natural and agricultural sources, as well as residential, industrial, and transport emissions. Contributions from Rajasthan, Punjab, and Uttar Pradesh are 9%, 8%, and 7%, respectively. Natural sources, including dust, dominate contributions from Rajasthan, while emissions from Punjab and Uttar Pradesh are driven primarily by residential, energy, and industrial sources. As large parts of Haryana fall within the NCR, their emissions are classified as local. Contributions from non-NCR districts of Haryana remain relatively small at the annual scale.

**Figure 11.** Regional and sectoral contributions to NCR's air quality from other regions in India. The stacked bar chart (left) shows seasonal and annual contributions from various regions to the NCR, while the pie charts (right) show the sectoral breakdown of emissions within each contributing region at the annual level.



Overall, these results highlight that regional and transboundary sources play a dominant role in shaping air quality in the NCR. As regions both receive pollution from upwind sources and contribute to downwind air quality degradation, these findings highlight the need for coordinated regional and international action. While local interventions can reduce urban concentrations, sustained improvement in air quality across this region will require aligned efforts across regions to address regional pollution transport.

### 4.2.3. Differences between versions of the same EI

As discussed earlier, uncertainties in EIs are often the largest source of error in air quality modelling, frequently exceeding uncertainties associated with meteorology and chemical mechanisms (Gilliland et al., 2003).

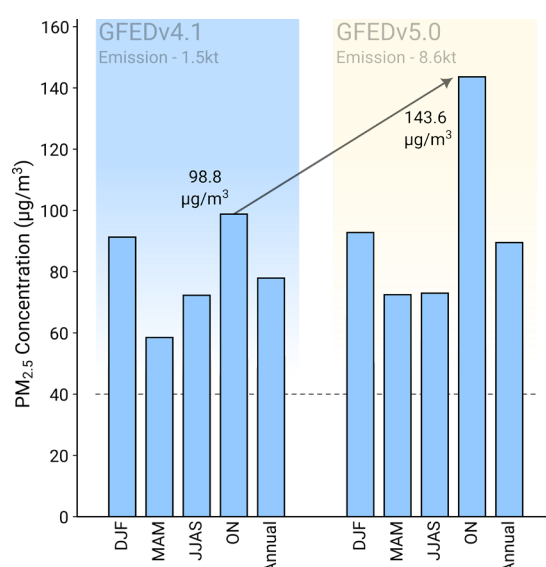
To assess the sensitivity of the WRF-CAMx model setup to input emissions, analyses were conducted using two versions of the agricultural waste burning emission inventory, GFED: GFEDv4.1 and GFEDv5.0. The latter incorporates improved small-fire detection and updated fuel consumption estimates, resulting in substantially higher reported emissions.



A comparison of the raw emission numbers shows that GFEDv4.1 estimates approximately 1.5 kt of  $PM_{2.5}$  emissions, while GFEDv5.0 reports 8.6kt. This approximately five-fold increase in GFEDv5.0 emissions leads to substantially higher simulated  $PM_{2.5}$  concentrations, particularly in October and November. As shown in Figure 12, seasonal average  $PM_{2.5}$  concentrations in Punjab increase approximately 1.5-fold during the post-monsoon season (October–November), from 98.6  $\mu g\ m^{-3}$  to 143.6  $\mu g\ m^{-3}$ . A similar, though smaller, increase is observed during the pre-monsoon months (March–May), with concentrations rising from 58.4  $\mu g\ m^{-3}$  to 72  $\mu g\ m^{-3}$ .

Although GFEDv5.0 is expected to provide a more representative estimate of emissions due to changes made to the algorithm, including enhanced small-fire detection and improved fuel consumption data, model performance deteriorates under these higher emission levels. Therefore, GFEDv4.1 is used in this study for agricultural waste burning emissions. Further analysis is required to assess the suitability of GFEDv5.0 for future model simulations.

**Figure 12.** Seasonal average  $PM_{2.5}$  concentration over Punjab with two different agricultural waste burning EIs



### 4.3. Emission reduction potential

The baseline CAMx-PSAT run identifies the regions and sectors influencing air quality in Punjab and the NCR. However, as discussed earlier, the global EIs used for the simulations lack activity-level information, making targeted interventions difficult.

To address this limitation, the modelling approach is used to present sectoral gross emission reductions, supported by the policy interventions needed to achieve them. The emission-reduction scenarios considered in this study, along with their rationales, are presented in Table 2. The rationale for these reductions is discussed next, followed by the results from these scenarios for Punjab and the NCR. Results for IGP states and regions, such as Haryana and Uttar Pradesh (excluding NCR districts), Bihar, and West Bengal, are discussed in Appendix C.

**Table 2.** List of CAMx emission reduction scenarios and rationale

| No | Scenario                                                                                | Rationale                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----|-----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1. | IGP – 50% reduction in transport emissions                                              | States across the IGP have adopted electric vehicle (EV) policies with ambitious targets. Additionally, India has leapfrogged from Bharat Stage (BS) IV to BS VI emission standards, resulting in reduced emissions (Ministry of Road Transport and Highways, 2016). While actions have been most pronounced in Delhi, more needs to be done across the IGP. This may be treated as an ambitious emissions reduction scenario.                                                                                                                                                                                                                                                   |
| 2. | IGP – 50% reduction in residential emissions                                            | Most global EIs identify residential energy use as a major source of pollution in the region. There has been considerable political will and policy push for clean cooking initiatives; hence, we are considering a combined impact of 50% reduction across these states.                                                                                                                                                                                                                                                                                                                                                                                                        |
| 3. | IGP – 50% reduction in energy sector emissions                                          | Existing mandates for flue gas desulphurisation (FGD) installation in NCR plants (CPCB, n.d.) and co-firing using agricultural residue (5%-10%; CAQM, 2021), as well as the presence of multiple biomass-fired power plants in the region, support potential reductions in energy sector emissions.                                                                                                                                                                                                                                                                                                                                                                              |
| 4. | IGP – 50% reduction in industrial emissions                                             | <p>The IGP hosts a wide range of industries, including several large and medium-scale enterprises that rely on the region's rich agricultural output. These include brick kilns, agro-based industries, chemicals, textiles, sugar mills, rice mills, steel processing, rolling mills, and jute mills in the eastern parts of the region. While almost all states have an approved fuel policy (Delhi Pollution Control Committee, 2018) and there is substantial CNG penetration, most of these industries remain dependent on fossil fuels.</p> <p>We propose this scenario based on current rates of CNG and PNG adoption and approved fuel policies across these states.</p> |
| 5. | IGP – 90% reduction in waste emissions                                                  | Policies under the Swachh Bharat Mission and MSW regulations aim to eliminate open burning. All non-attainment cities (37) have bylaws for municipal waste management (MoEFCC, 2026). This is an achievable target, as enabling conditions are already in place.                                                                                                                                                                                                                                                                                                                                                                                                                 |
| 6. | IGP – combined reductions (Scenarios 1-5) + 50% reduction in agricultural waste burning | This represents a coordinated regional emission reduction measure that assesses the cumulative impact of the individual measures listed in Scenarios 1 to 5 above, along with a 50% reduction in agricultural waste burning across the IGP.                                                                                                                                                                                                                                                                                                                                                                                                                                      |

| No  | Scenario                                                                                                                             | Rationale                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-----|--------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 7.  | IGP – combined reductions (Scenarios 1–5) + 50% reduction in agricultural waste burning sources over the IGP (October–February only) | Similar to Scenario 6 but restricts agricultural waste burning reductions to the peak pollution months of October to February.                                                                                                                                                                                                                                                                                                                                                                                                       |
| 8.  | Uttar Pradesh – 50% reduction in residential emissions                                                                               | Similar to Scenario 2, a focused assessment based on the dominant role of residential emissions and ongoing clean cooking initiatives in the state.                                                                                                                                                                                                                                                                                                                                                                                  |
| 9.  | Bihar – 50% reduction in residential emissions                                                                                       | There has been considerable political will and policy push for clean cooking initiatives; hence, we are assessing the impact of 50% reduction. Similar to Scenarios 2 and 8, it reflects the importance of residential energy transitions in Bihar.                                                                                                                                                                                                                                                                                  |
| 10. | Punjab + Haryana (excluding NCR) – 50% reduction in agricultural waste burning                                                       | This scenario is supported by policies promoting ex-situ and in-situ crop residue management (CRM), financial incentives, and mandates for biomass co-firing. The CAQM has issued seven notifications. Additional enabling policies include mandating 5%–10% co-firing in power plants (CAQM, 2021). CAQM and other stakeholders have reported a 70% reduction in Punjab alone and larger reductions in NCR districts (PIB, 2025a, 2025b). Thus, this scenario assumes a net 50% reduction in crop residue burning across the region |
| 11. | NCR – 50% reduction in transport emissions                                                                                           | The CAQM and the Government of NCT of Delhi have notified and implemented numerous measures to reduce transport emissions. These include restrictions on older vehicles (Transport Department, Govt of NCT of Delhi, 2024; CAQM, 2025a), limits on freight entry (CAQM, 2025b), electrification of the bus fleet, and the near-elimination of diesel buses and auto-rickshaws. In addition, only BS VI vehicles are permitted under the Graded Response Action Plan.                                                                 |

### 4.3.1. Effect of scenarios on Punjab's air quality

As outlined in Table 2, the effect of multiple state- and region-specific emission-reduction scenarios is evaluated using CAMx simulations. These scenarios are broadly classified into two categories:

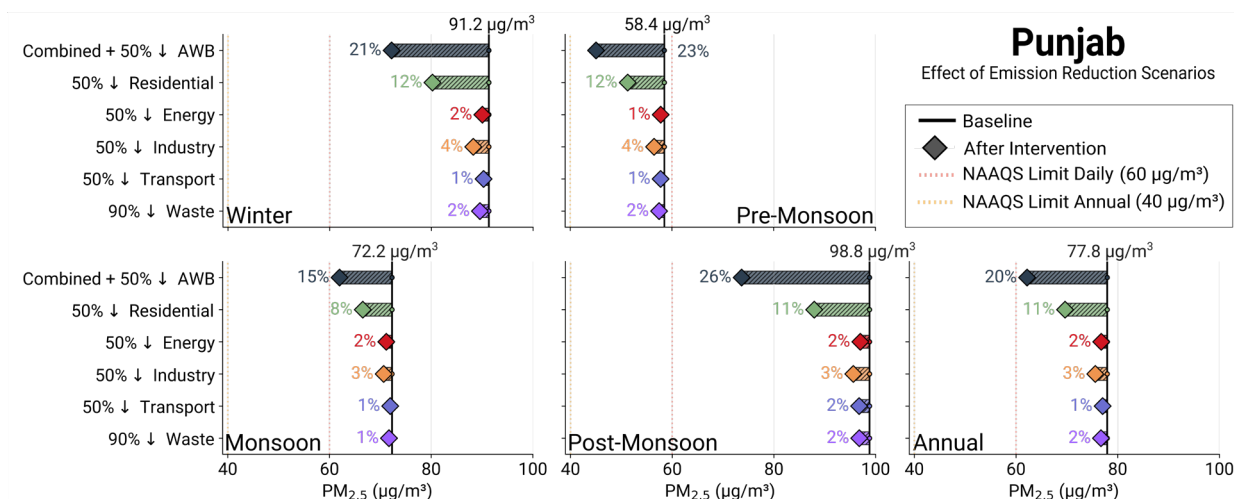
1. emission reductions applied across the entire IGP, and
2. targeted reduction within specific states or regions.

Figure 13 presents the effects of uniform, sector-specific emission reductions across the IGP on the air quality in Punjab. In addition to individual sectoral reduction scenarios, a combined scenario representing simultaneous reductions across all sectors is also evaluated. Reducing residential emissions by 50% yields the largest decrease in seasonal and annual mean  $PM_{2.5}$  concentrations across Punjab, lowering the annual average from  $77.8 \mu g m^{-3}$  to  $69.2 \mu g m^{-3}$ .

This reflects the dominant contribution of residential energy use, particularly solid fuels such as firewood, agricultural waste, cow dung, and coal for cooking and heating, in driving emissions across the IGP.

Compared with residential emissions, reductions in other sectors yield smaller benefits. However, the combined scenario comprising 50% reductions in residential, transport, energy, industry, and agricultural waste burning, along with a 90% reduction in waste emissions from waste emissions yields a substantially larger reduction in  $PM_{2.5}$  concentrations over Punjab. Under this scenario, the annual average  $PM_{2.5}$  concentrations decreases to  $62.2 \mu g m^{-3}$ .

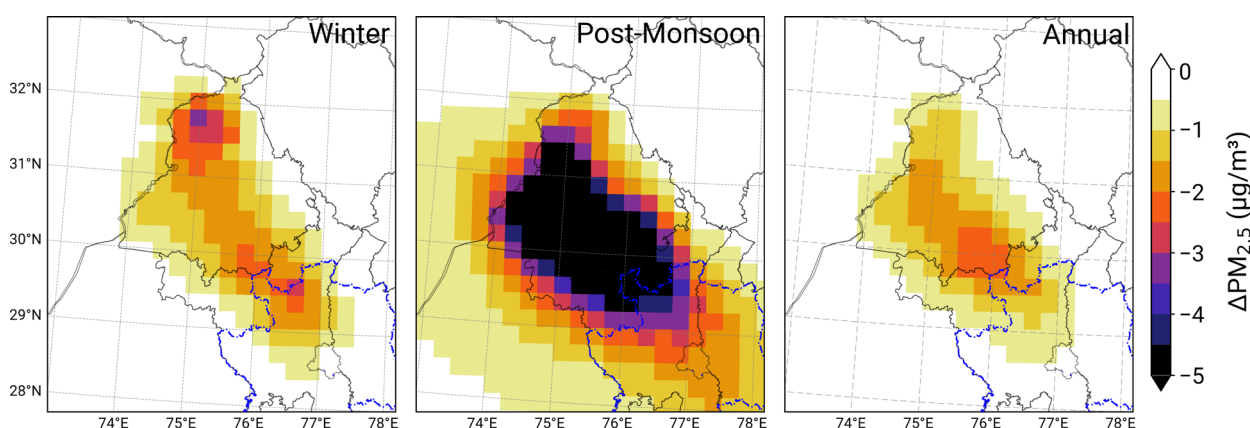
**Figure 13.** Seasonal and annual reductions in  $PM_{2.5}$  concentrations over Punjab relative to the baseline for major emission reduction scenarios across the IGP



When emissions from agricultural residue burning in Punjab and Haryana (excluding the NCR) are reduced by 50%, a noticeable improvement in ambient air quality is observed. Specifically, as shown in Figure 14, seasonal average  $PM_{2.5}$  concentrations decrease by approximately 5% ( $4.5 \mu g m^{-3}$ ) during the post-monsoon months of October and November, when crop residue burning is most intense and meteorological conditions favour the accumulation of atmospheric pollutants.

In contrast, reductions during the pre-monsoon season (March–May) are modest, at approximately 2%, due to relatively enhanced atmospheric ventilation during these hot months. While the reduction is marginal, these results highlight the air quality benefits from mitigating agricultural waste burning at the local scale and underscore the need for targeted mitigation measures during peak burning periods.

**Figure 14.** Seasonal (winter and post-monsoon) and annual spatial map showing reduction in  $PM_{2.5}$  concentration for the scenario in which emissions from agriculture waste burning are reduced by 50% over Punjab and Haryana, excluding the NCR



### 4.3.2. Effect of scenarios on NCR's air quality

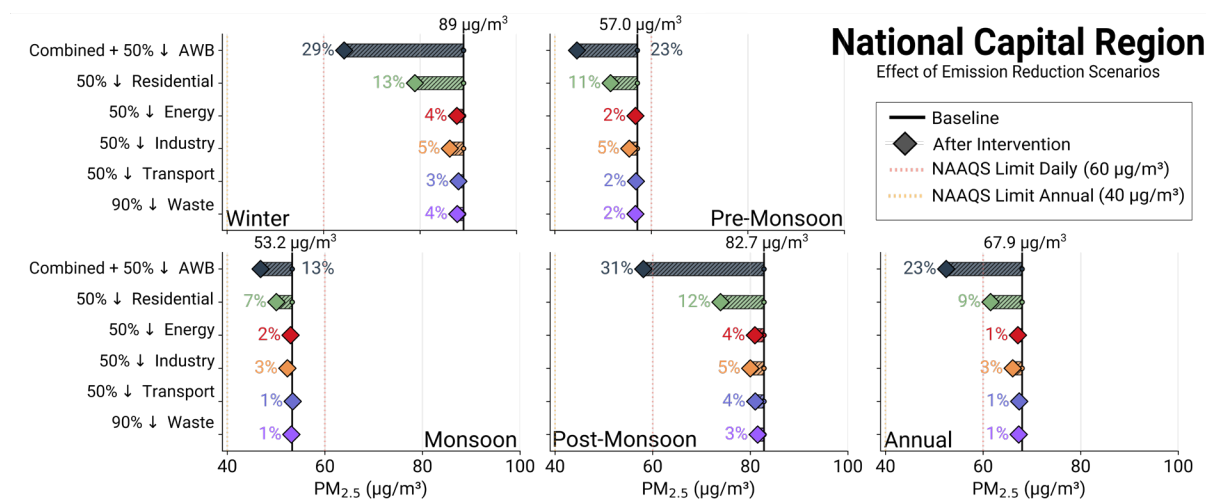
Figure 15 presents the impact of uniform, sector-specific emission reduction scenarios across the IGP on air quality in the NCR.

As in Punjab, reductions in residential emissions contribute significantly to reducing overall  $PM_{2.5}$  emissions in the NCR. A 50% reduction in residential emissions yields the largest decrease in seasonal and annual mean  $PM_{2.5}$  concentrations across the NCR, lowering the annual average from  $67.9 \mu g m^{-3}$  to  $61.8 \mu g m^{-3}$ . The largest reductions occur during the winter and post-monsoon seasons, reflecting the increased use of solid fuels for space and water heating during this period.

The combined scenario with 50% reductions in residential, transport, energy, industrial, and agricultural waste burning emissions, along with a 90% reduction in emissions from waste burning, yields a substantially larger reduction in  $PM_{2.5}$  concentrations over the NCR. Annual average  $PM_{2.5}$  concentrations decrease from 67.9 to  $52.3 \mu g m^{-3}$ , with reductions of 31% and 29% during the winter and post-monsoon seasons, respectively. Although individual contributions from sectors such as energy, industry, transport and waste are relatively small, their combined effects add up to significant overall reductions.

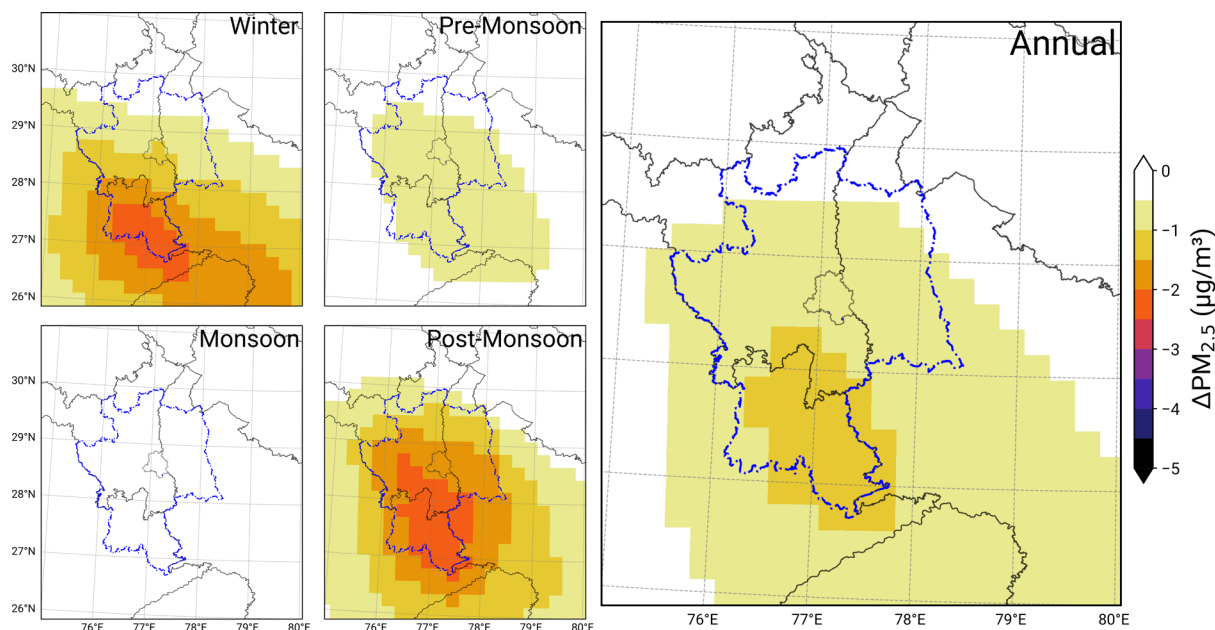
For a region-specific scenario in which emissions from the transport sector in the NCR are reduced by 50%, the annual average  $PM_{2.5}$  concentration decreases by about 1%. However, this average is calculated across the entire NCR; as a result, spatial variations within the region may be obscured, including areas where the effect of a 50% reduction in traffic emissions is high. As shown in Figure 16, reductions exceed  $2 \mu g m^{-3}$  in the southern NCR districts during winter and post-monsoon periods.

**Figure 15.** Seasonal and annual reductions in  $PM_{2.5}$  concentrations over the NCR relative to the baseline for major emission-reduction scenarios across the IGP





**Figure 16.** Seasonal and annual spatial map showing reduction in  $PM_{2.5}$  concentration for the scenario in which transport emissions are reduced by 50% over the NCR



#### 4.4. Policy implications of sector-specific solutions

The modelling results demonstrate that  $PM_{2.5}$  concentrations in the NCR are also influenced by regionally distributed emissions rather than local emissions alone. This is reflected in the scenarios analysis, which shows that state- or sector-specific interventions yield limited annual improvements, as both baseline concentrations and seasonal peaks arise from multi-sectoral emissions distributed across the IGP.

In contrast, the combined multi-sectoral scenario, involving simultaneous reductions across residential, energy, industry, transport, waste, and agricultural waste burning, delivers substantially larger improvements in both annual and seasonal air quality. These findings highlight the need to expand beyond city-level actions, as effective mitigation requires re-scaling strategies for the entire IGP. This includes shifting planning and implementation from municipal jurisdictions to coordinated state-level strategies across the IGP airshed.

Operationally, this requires integrating city-level clean air action plans into comprehensive state-level frameworks that explicitly account for cross-boundary emission sources. State-level action plans should clearly define coordinated sectoral interventions with neighbouring states and set sectoral reduction pathways informed by regional modelling. Implementation timelines must be synchronised across states to ensure that progress in one jurisdiction is not offset by delays or weaker enforcement elsewhere. This does not imply replacing city-level action with state-level action; rather, it calls for reorienting isolated local measures towards coordinated state-level strategies, executed within a shared airshed framework, to complement and strengthen existing city-level efforts.

**Table 3.** Sector-wise policy gaps and coordinated actions

| Scenario: Residential emissions (50% reduction)        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|--------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Modelled annual reduction (range across IGP states, %) | 9%–14%                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Policy status                                          | Expansion of LPG access under the Pradhan Mantri Ujjwala Yojana (PMUY) has improved coverage across IGP states                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| Key gaps                                               | <ul style="list-style-type: none"> <li>» Low LPG refill frequency and affordability constraints</li> <li>» Continued fuel stacking in rural households across states. In India, 39% of households use both LPG and solid fuels, while 14% rely exclusively on free biomass.</li> <li>» Access does not translate into sustained clean fuel use</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| IGP-level actions required                             | <ul style="list-style-type: none"> <li>» Shift from connection-based targets to refill-consumption performance metrics, especially in low consumption districts.</li> <li>» Expand last-mile LPG delivery in rural and hilly areas.</li> <li>» Pilot electric cooking in highly electrified states, such as Delhi, Punjab, and Haryana.</li> <li>» Establish region-wide clean cooking performance benchmarks.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Scenario: Energy emissions (50% reduction)             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Modelled annual reduction (range across IGP states, %) | 1%–4%                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Policy status                                          | <ul style="list-style-type: none"> <li>» National emission norms in place</li> <li>» Air pollution control devices installed</li> <li>» Electrostatic precipitators widely installed</li> <li>» FGD installation underway; as of Feb 2025, 537 of 600 units had been identified for FGD installation, with 49 units commissioned and 211 units under implementation (Ministry of Power, 2025), while the remaining units were in the tendering or pre-tendering stages. Compliance timelines vary by plant category, with deadlines of 2027, 2028, and 2029 for Categories A, B, and C, respectively (Ministry of Power, 2026). Plants scheduled to retire before 2030 may be exempted from installing FGDs.</li> <li>» Biomass co-firing mandates (5%–7%) exist for coal-based thermal power plants; Continuous Emissions Monitoring Systems (CEMS) are installed in large plants.</li> </ul> |
| Key gaps                                               | <ul style="list-style-type: none"> <li>» Misaligned compliance timelines</li> <li>» Lack of transparency in implementation status</li> <li>» Delays in operationalisation despite installation</li> <li>» Uneven enforcement across state pollution control boards (SPCBs)</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| IGP-level actions required                             | <ul style="list-style-type: none"> <li>» Accelerate FGD installation across the IGP.</li> <li>» Expand biomass co-firing mandates beyond the NCR, Punjab, and Haryana.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |

| Scenario: Industrial emissions (50% reduction)         |                                                                                                                                                                                                                                                                                                                                                                                                   |
|--------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Modelled annual reduction (range across IGP states, %) | 3%-7%                                                                                                                                                                                                                                                                                                                                                                                             |
| Policy status                                          | <ul style="list-style-type: none"> <li>» National emission standards for key industrial sectors are in place.</li> <li>» Conversion of traditional brick kilns to zig-zag brick kilns is underway.</li> <li>» CEMS are mandated for highly polluting industries.</li> <li>» Fuel bans are in place in select NCR districts, and PNG expansion is underway in some industrial clusters.</li> </ul> |
| Key gaps                                               | <ul style="list-style-type: none"> <li>» Continued use of coal and pet coke in several clusters</li> <li>» Non-uniform enforcement across states</li> <li>» Absence of a common approved cleaner fuels list across the IGP.</li> </ul>                                                                                                                                                            |
| IGP-level actions required                             | <ul style="list-style-type: none"> <li>» Adopt a common 'approved cleaner fuel list'</li> <li>» Inter-state real-time CEMS monitoring and complete transition to zig-zag brick kiln across the IGP</li> </ul>                                                                                                                                                                                     |
| Scenario: Transport emissions (50% reduction)          |                                                                                                                                                                                                                                                                                                                                                                                                   |
| Modelled annual reduction (range across IGP states, %) | 1%-3%                                                                                                                                                                                                                                                                                                                                                                                             |
| Policy status                                          | <ul style="list-style-type: none"> <li>» National Vehicle Scrappage Policy (2021)</li> <li>» State-wise scrappage policies</li> <li>» State-wise EV policies</li> <li>» PM E-DRIVE scheme, Faster Adoption and Manufacturing of Electric Vehicles in India scheme, etc</li> </ul>                                                                                                                 |
| Key gaps                                               | <ul style="list-style-type: none"> <li>» Inconsistent definitions and age thresholds for ELVs (10 vs 15 years) across states</li> <li>» Scrappage is not regionally synchronised and is currently only voluntary.</li> <li>» Delhi restricts ELVs, but neighbouring states absorb the displaced fleet.</li> <li>» Interstate fleet mobility dilutes city-only restrictions.</li> </ul>            |

|                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|--------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Key gaps (contd)                                       | <ul style="list-style-type: none"> <li>» India currently lacks a formal regulatory definition and framework for identifying and managing super-emitters (SEs), which contribute disproportionately to tailpipe emissions. Enforcement largely relies on periodic Pollution Under Control testing and visual inspections, with limited deployment of remote-sensing technologies for real-time detection. In a study conducted by CSTEP in 2025, a large pool of SEs was found in the heavy commercial vehicle (HCV) category in the IGP (4,705 in Delhi, 63,029 in Haryana, 27,136 in Punjab, 76,072 in UP, and 51,406 in Rajasthan). Although registered vehicle scrapping facilities (RVSFs) have been established, infrastructure remains uneven across IGP states. There are only 2 operational RVSFs in Delhi, 5 in Punjab, 3 in Rajasthan, 21 in Haryana, and 45 in UP. Each facility can typically process 10,000–20,000 vehicles annually across all vehicle categories, indicating a potential constraint in scaling the removal of SEs.</li> <li>» Additionally, the informal scrapping industry provides greater financial incentives for scrapping vehicles (around INR 100/kg of truck weight) compared with authorised scrappage centres (around INR 25/kg), discouraging vehicle owners from using regulated scrappage channels. Automated Testing Station (ATS) infrastructure remains insufficient to support more frequent emission and fitness testing of HCVs (Ministry of Road Transport and Highways, n.d.). Only 32 of 178 ATSS nationwide are located in the IGP region (2 in Rajasthan, 8 in Bihar, and 22 in Uttar Pradesh), with none currently operational in Punjab, Haryana, and Delhi.</li> </ul> |
| IGP-level actions required                             | <ul style="list-style-type: none"> <li>» Align ELV age caps and interoperable deregistration across IGP states</li> <li>» Implement corridor-based enforcement for commercial vehicles</li> <li>» Deny interstate entry to non-compliant fleet</li> <li>» Establish region-wide super-emitter detection</li> <li>» Scale up ATS infrastructure and integrate with VAHAN database to enable automated identification of non-compliant vehicles and penalties.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <b>Scenario: Waste emissions (90% reduction)</b>       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Modelled annual reduction (range across IGP states, %) | 1%–3%                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Policy status                                          | <ul style="list-style-type: none"> <li>» Solid Waste Management (SWM) Rules, 2026</li> <li>» CPCB graded criteria and standards (2024) are in place.</li> <li>» CAQM mandates monthly reporting of waste burning incidents (Ministry of Environment, Forest and Climate Change, 2025).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Key gaps                                               | <ul style="list-style-type: none"> <li>» Persistent open dumping and burning of garbage despite bans.</li> <li>» Challenges in real-time monitoring and enforcement; compliance reporting is monthly, and there is no geo-tagged hotspot monitoring tied to enforcement.</li> <li>» Large untreated waste pools: West Bengal treats approximately 4.9% of generated waste, Punjab treats around 43.6%, and Rajasthan treats only about 17.6% only, leaving a large mass of waste susceptible to open dumping and burning (Government of India, 2025).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |

|                                                                                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Key gaps (contd)                                                                            | <ul style="list-style-type: none"> <li>» Most SWM rules and infrastructure focus on urban local bodies (ULBs), leaving rural areas with poor infrastructure, limited waste collection, and inadequate processing.</li> <li>» Legacy dumpsites not fully remediated.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| IGP-level actions required                                                                  | <ul style="list-style-type: none"> <li>» IGP states must close the treatment gap.</li> <li>» Enable real-time enforcement and monitoring by integrating satellite hotspot detection (e.g. Visible Infrared Imaging Radiometer Suite data) for landfill and dump fires with geo-tagged enforcement inspections.</li> <li>» Link detections to time-bound action by local nodal officers.</li> <li>» Operationalise the updated graded criteria under the revised SWM rules at the ULB level, with performance incentives and penalties.</li> <li>» Move beyond monthly compliance reporting towards near real-time dashboards.</li> <li>» Ensure scientific closure of legacy dumpsites .</li> <li>» Extend SWM frameworks to rural areas and gram panchayats.</li> </ul>                                                                                                                           |
| <b>Scenario: Combined reductions + agricultural waste burning emissions (50% reduction)</b> |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Modelled annual reduction (range across IGP states, %)                                      | 20%–32%                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Policy status                                                                               | <ul style="list-style-type: none"> <li>» CRM machinery has been deployed.</li> <li>» Super Straw Management System mandate is in place for combine harvesters.</li> <li>» A 5% biomass co-firing mandate is in place for thermal power plants.</li> <li>» Ex-situ utilisation channels exist.</li> <li>» State-specific action plans and CAQM oversight are in place.</li> <li>» Satellite monitoring is being used.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Key gaps                                                                                    | <ul style="list-style-type: none"> <li>» The wheat and rice cropping cycle, characterised by a short interval between paddy harvest and wheat sowing, creates a short sowing window that incentivises rapid field clearance, making burning the least-cost option unless alternatives are subsidised and logistically viable.</li> <li>» CRM deployment may not yet match peak harvesting intensity across districts.</li> <li>» Ex-situ markets have finite uptake capacity relative to total residue generation in the current set-up.</li> <li>» Crop diversification intensity, subsidy structures, and market mechanisms for procurement vary across Punjab, Haryana, and Uttar Pradesh.</li> <li>» Machinery for ex-situ management becomes outdated after a few seasons. This discourages sustained investment by farmers in these machines without continued financial support.</li> </ul> |
| IGP-level actions required                                                                  | <ul style="list-style-type: none"> <li>» Align procurement and harvesting cycles across states to reduce peak residue load concentration.</li> <li>» Develop district-level aggregation and transport systems linked to biomass-based industries.</li> <li>» Develop public real-time dashboards showing CRM availability per cropped hectare.</li> <li>» Harmonise subsidy per hectare for residue management to prevent cross-border behavioural leakage.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                             |



## 4.5. Institutional coordination and airshed governance

The sector-specific measures outlined above require an institutional mechanism capable of coordinating implementation across states. The CAQM provides a statutory framework for supra-jurisdictional coordination across parts of the IGP, but its jurisdiction is currently limited to the NCR and adjoining areas.

Extending similar institutional arrangements across the broader IGP, either by expanding existing mandates or by establishing a parallel coordination mechanism covering Bihar, West Bengal, and Jharkhand, would enable more effective governance across the geographic extent of the airshed.

An effective airshed governance framework for the IGP should include the following:

- region-wide emission-reduction targets within airshed boundaries, differentiated by season where necessary;
- coordinated sectoral implementation and compliance tracking across states;
- integrated technical and data management systems; and
- aligned fiscal and incentive mechanisms.

City-level action plans should be nested within state-level strategies, which in turn should align with regional targets. States should retain sectoral authority but operate within agreed timelines and reporting protocols. Implementation schedules and compliance tracking should be coordinated across states to prevent offset effects arising from uneven enforcement. Standardised data reporting from SPCBs, integrated CEMS data sharing, and harmonised use of satellite-based monitoring for seasonal burning can improve transparency and comparability across states and help address the effects of uneven enforcement.

Some sectors, such as agricultural residue management and residential energy transition, require continued financial support to ensure sustained adoption. Although financial support mechanisms are already in place (i.e. PMUY), the challenge lies in ensuring sustained adoption and continued use, reducing fuel stacking, and coordinating implementation across states.

Overall, the objective is not to centralise sectoral regulation but to institutionalise structured inter-state alignment so that emission reductions in one state reinforce, rather than dilute, regional outcomes. The challenge in the IGP is not the absence of sectoral policies but the fragmentation of their implementation.

## 5. Way Forward

This report demonstrates the value of modelling-based approaches in quantifying regional and sectoral contributions to air pollution, thereby supporting evidence-based policymaking. The current study considers gross emissions reductions from various anthropogenic sources, but the use of a global EI provides an incomplete picture.

India currently lacks a comprehensive, granular national EI developed using locally derived emission factors and activity-level data. The development of such an EI would enable the identification of the most polluting activities within regions and support the adoption of newer technologies.

For example, replacing solid fuels used for cooking and water heating with cleaner alternatives, such as LPG, can be costly, limiting widespread adoption. However, when activity-level data from a national EI are available, models can quantify the air pollution caused by solid fuel use and estimate the costs associated with reducing it. Similar analyses can be performed across EI activities, enabling the cost per activity, expressed as INR per  $\mu\text{g m}^{-3}$  reduction, to be mapped. This can help identify the most beneficial and cost-effective policy interventions to prioritise.

The choice of model resolution is another critical factor in decoupling local source contributions from regional background pollution. While the current 25 km grid configuration is effective for capturing interstate and transboundary pollution transport, it lacks the spatial granularity required to resolve subgrid-scale variations within smaller administrative units, such as the NCT of Delhi. This limitation is compounded by the lack of an updated, high-resolution EI, at the scale of a few kilometres. Global EIs often fail to represent the spatial heterogeneity of localised sources, including fugitive dust from construction and demolition activities, road dust resuspension, and non-exhaust vehicular emissions (e.g. brake, tyre, and engine wear). Consequently, while the model provides robust estimates of regional contributions, source apportionment for localised hotspots should be interpreted as area-wide averages rather than precise, site-specific values.

### 5.1. Recommendations for government stakeholders

#### 5.1.1. Development of a national EI

Developing a periodically updated, high-resolution national EI is a key step in identifying and quantifying air pollution sources. Given the scale and complexity of this effort, establishing a multi-institutional consortium would enable scientific rigour while ensuring timely implementation. This EI should incorporate a city-level layer to better resolve urban emission sources.

#### 5.1.2. Development of a $\text{PM}_{2.5}$ composition monitoring network

A critical requirement for model validation is the comparison of simulated pollutant concentrations with observed data. While several air quality modelling frameworks in India perform reasonably well in estimating total  $\text{PM}_{2.5}$  mass concentrations, they often struggle to accurately simulate the constituents of  $\text{PM}_{2.5}$ . Establishing a comprehensive  $\text{PM}_{2.5}$  composition monitoring network would help improve model representation of gas-aerosol chemistry. Furthermore, such measurements can also help determine whether key emission sources are being correctly represented.

#### 5.1.3. Adoption of air quality modelling for regulatory purposes

An accurate and well-validated EI enables the evaluation of current and future policy interventions on regional air quality. At present, the NCAP primarily focuses on city-level action, requiring individual cities to undertake source apportionment and EI studies. However, this approach does not adequately account for transported pollution, which can contribute up to 80% of ambient concentrations (Lal et al., 2025).

Adopting airshed-based modelling as a regulatory tool would enable more effective quantification of regional and transboundary pollution contributions than a city-level approach alone. It would also enable more accurate identification of dominant sources and support model-based evaluation of policy scenarios. This, in turn, would allow policymakers to quantify the effectiveness of different mitigation strategies and design more impactful, evidence-based interventions.





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# Annexures

## A. Details about model setup

### A1. Meteorological model configuration

Meteorological fields were generated using the Weather Research and Forecasting (WRF) model (version 4.7.1.) For this study, the WRF simulation was run from 1 December 2018 to 1 January 2020. The air quality simulation using the Comprehensive Air Quality Model with Extensions (CAMx) began on 16th December 2018; therefore, the preceding 15 days of the WRF run were used as a meteorological spin-up period before the chemistry simulation. This allows land surface variables (e.g. soil moisture and temperature) to reach physically consistent states before the analysis period.

A single modelling domain was configured over South Asia using a Lambert conformal conic projection, consistent with the CAMx air quality model grid. The spatial resolution is 25 km, ensuring direct compatibility with CAMx without interpolation artefacts.

The model includes 49 vertical layers extending from the surface to a top pressure of 50 hPa. A hybrid sigma-pressure coordinate system is employed, transitioning from terrain-following sigma coordinates near the surface to isobaric levels aloft, thereby reducing pressure-gradient force errors over steep terrain. The vertical resolution (represented by eta levels) was explicitly defined in the namelist file, with the highest vertical resolution concentrated near the surface to resolve boundary-layer processes. The lowest model layer is approximately 60 m thick, and about 15–20 layers lie within the typical daytime boundary layer. CAMx used 20 of these 49 layers, with appropriate layer collapsing applied during the WRF–CAMx meteorological preprocessing.

Initial and lateral boundary conditions were derived from fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis of the global climate, with 38 atmospheric pressure levels and 4 soil levels, provided at 6-hourly intervals.

To represent sub-grid-scale processes, the physics parameterisation schemes for the 25 km domain were selected from previous modelling studies over this region (Bhardwaj et al., 2021; Gunwani et al., 2023). Grid-based four-dimensional data assimilation (FDDA) nudging is applied to all active domains to constrain the simulation towards reanalysis fields.

Wind fields are nudged across the full model depth, including the boundary layer. In contrast, temperature and moisture nudging are excluded within the planetary boundary layer (PBL) to allow the boundary-layer scheme to develop realistic thermodynamic profiles. Nudging is applied at 6-hourly intervals, consistent with the boundary condition update frequency, with a 60-minute ramp-down period at the end of each nudging window to avoid abrupt adjustments.

The model is run in fully non-hydrostatic mode using a third-order Runge–Kutta time integration scheme. Fifth-order horizontal and third-order vertical advection schemes are used for momentum and scalar transport. Model outputs are generated at hourly intervals (with one output time per file for the outer domain) in netCDF format. These are subsequently processed into CAMx-compatible inputs using the WRF–CAMx meteorological preprocessor.

## A2. Air quality model configuration (CAMx)

Air quality simulations are conducted using CAMx version 7.20. The simulation period spans 16 December 2018 to 1 January 2020, with a 15-day spin-up period. This is consistent with the WRF meteorological simulation, which was employed to allow chemical concentrations to equilibrate before the analysis period. The first day was initialised from a cold start using gridded initial condition fields, and all subsequent days were run in restart mode using instantaneous concentration fields from the preceding day.

The CAMx domain covers approximately 4,375 km × 3,875 km, encompassing all of South Asia and surrounding regions; it is identical to the WRF domain. The CAMx-ready meteorological files include three-dimensional fields, such as temperature, pressure, wind, humidity, cloud and rainwater; two-dimensional fields, such as surface parameters, precipitation, PBL height; land-use classifications; and vertical diffusivity ( $k_v$ ) fields.

Vertical diffusivity is parameterised using the Yonsei University (YSU) PBL scheme. All meteorological inputs were provided at hourly temporal resolution. The 49 WRF layers are collapsed to 20 layers for CAMx to balance computational efficiency while retaining adequate vertical resolution in the boundary layer and lower free troposphere.

Gas-phase chemistry is represented using the Carbon Bond 6 revision 5 (CB6r5) mechanism, a widely used lumped-structure mechanism that treats the oxidation of volatile organic compounds (VOCs) and the formation of secondary inorganic and organic species. CB6r5 includes updated rate constants and improved isoprene chemistry relative to earlier revisions. The gas-phase reactions are solved using the Euler Backwards Iterative (EBI) solver.

Photolysis rates are computed using the tropospheric ultraviolet-visible (TUV) model with a pseudo-spherical two-stream radiative transfer approximation and were supplied as daily gridded input files. Ozone column maps for the photolysis calculations were provided as separate daily input files. Aerosol processes are treated using the CF2 two-mode aerosol scheme, which tracks both coarse and fine particles. This scheme tracks inorganic aerosols, including sulphate, nitrate, ammonium; condensable secondary organic aerosol (SOA); primary organic and elemental carbon; crustal material; and sea salt.

## B. Meteorological validation

Meteorological validation assesses WRF's ability to realistically represent key drivers of air quality, including wind speed and direction, temperature, planetary boundary layer (PBL) height, humidity, and precipitation. These parameters strongly influence pollutant transport, dispersion, chemical transformation, and deposition. Even with accurate emission data and chemistry, errors in meteorology can propagate non-linearly into CAMx, leading to substantial biases in simulated pollutant concentrations.

In this study, meteorological variables, such as temperature and wind speed, are evaluated against Meteorological Aerodrome Reports (METAR). The meteorological fields simulated by WRF are converted to a CAMx-compatible grid using the wrfcamx utility.

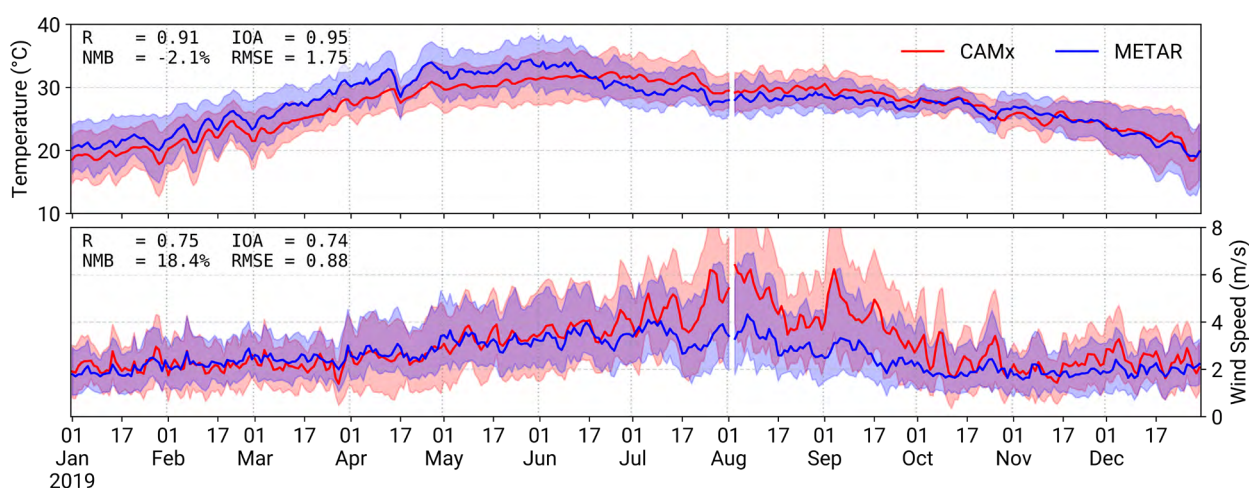
The utility's output consists of time-varying two- and three-dimensional fields required by CAMx to estimate the transport and chemical transformation of pollutants. Figure B-1 presents the time series of the wrfcamx-generated daily averages of 2 m temperature (T2) and 10 m wind speed (computed from U10 and V10 variables) used for annual-scale model validation.

The model simulates temperature with high accuracy, yielding a correlation coefficient (R) of 0.91, an index of agreement of 0.95, and a bias of -2.1%. Although minor seasonal biases are evident—cold biases during the summer and winter months and warm biases during the monsoon season—the simulated values are in good agreement with observations.

In contrast, wind speed is overestimated during the monsoon season—a widely observed pattern in such studies, often attributed to parameterisation choices and uncertainties in surface roughness representation. This overestimation of wind speed during the monsoon can influence model-simulated pollutant concentrations, particularly for wind-blown dust. The model nevertheless simulates wind speeds well in other seasons, with an overall R value of 0.75, an index of agreement of 0.74, and a bias of 18.4%. When the monsoon season (June–September) is excluded, model performance improves significantly, with the R value increasing to 0.8, the index of agreement rising to 0.86, and bias reducing to 6.5%. Notably, the model captures wind speed more accurately during high-pollution periods, which are of interest for air quality assessments.

Biases in surface variables, including temperature and wind speed, are sensitive to PBL schemes and land surface models, as well as the accurate representation of terrain.

**Figure B-1.** Meteorological validation of temperature and wind speed using daily average time series, with the minimum–maximum range shown in the shaded region.



## C. Interstate transport: Results for other states in the Indo-Gangetic Plain

### C1. Haryana (excluding National Capital Region districts)

Figure C-1 shows that the annual average  $PM_{2.5}$  concentration from the baseline CAMx-PSAT over Haryana (excluding National Capital Region [NCR] districts) is  $69.9 \mu g m^{-3}$ , exceeding both the prescribed daily and annual limits under India's National Ambient Air Quality Standards (NAAQS). Similar to Punjab, concentrations remain elevated in Haryana from October to February, with seasonal values exceeding  $80 \mu g m^{-3}$ .

At the annual scale, only 14% of  $PM_{2.5}$  concentration originates from local sources, with residential emissions as the dominant contributor. Other local sources include agriculture, industry, open burning, transport, and agricultural waste burning. Transboundary pollution contributions are substantially higher at 34%, driven primarily by natural dust and agricultural emissions.

**Figure C-1.** Regional and sectoral contributions to Haryana's air quality, excluding NCR, from contributing regions. The stacked bar chart (left) shows the seasonal and annual contribution of various regions to Haryana (excluding NCR), and the pie charts (right) show the sectoral emission breakdown within each contributing region at the annual level.

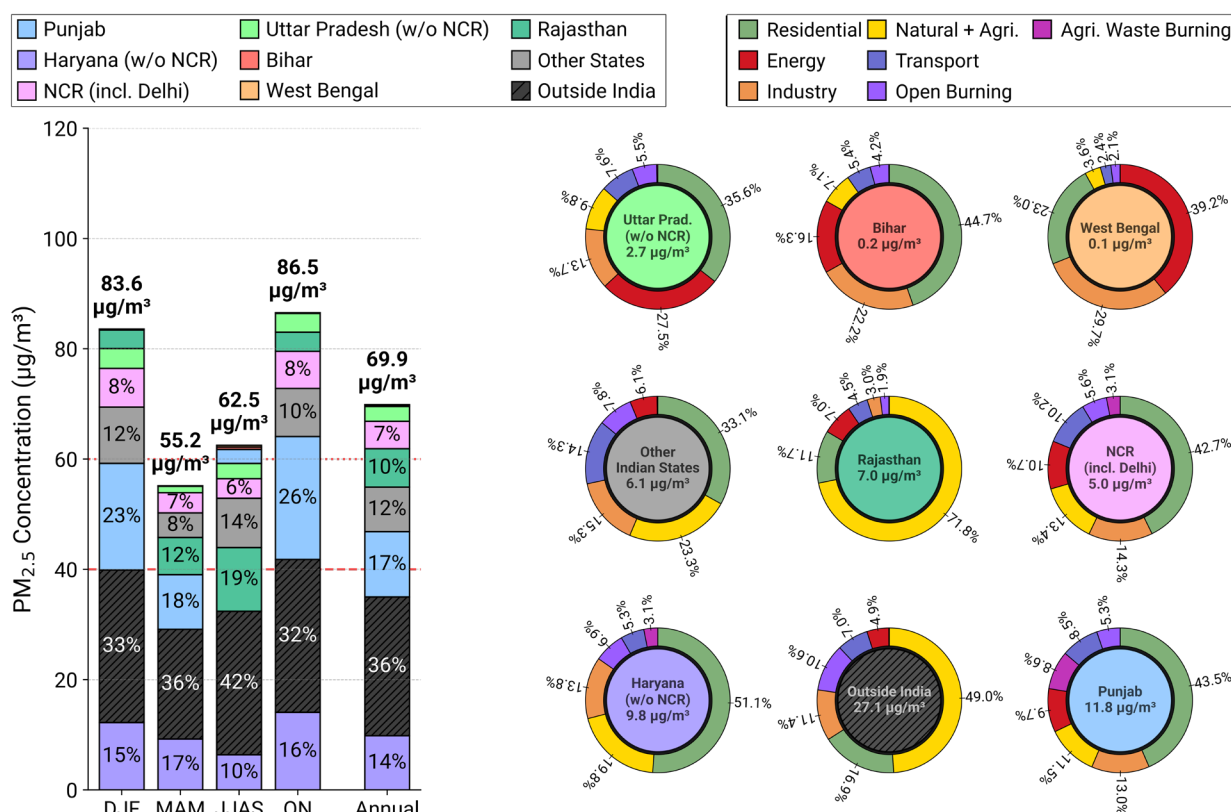
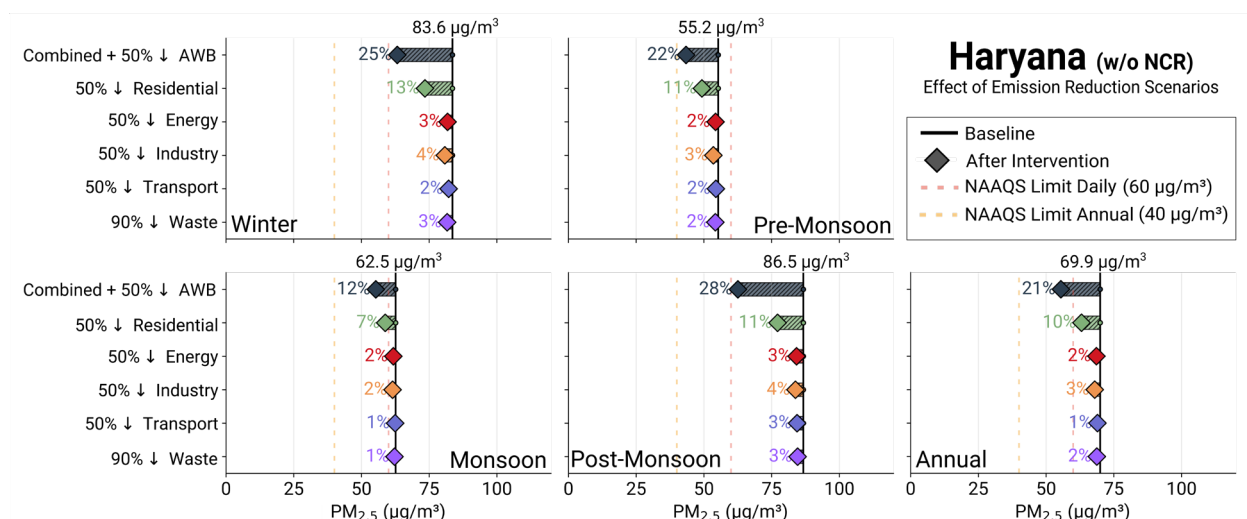


Figure C-2 shows the impact of various emission reduction scenarios on the air quality over Haryana (excluding NCR). The combined emission-reduction scenario results in a 21% reduction in annual  $PM_{2.5}$  concentrations, from  $69.9 \mu g m^{-3}$  to  $55.2 \mu g m^{-3}$ . The reduction is highest during the winter and post-monsoon seasons. An additional scenario in which emissions from agricultural waste burning are reduced by 50% in Punjab and Haryana results in a marginal 4% reduction in  $PM_{2.5}$  concentrations during the post-monsoon (October–November) season.



**Figure C-2.** Seasonal and annual reductions in  $PM_{2.5}$  concentrations over Haryana (excluding NCR) relative to the baseline for major emission-reduction scenarios across the Indo-Gangetic Plain (IGP)



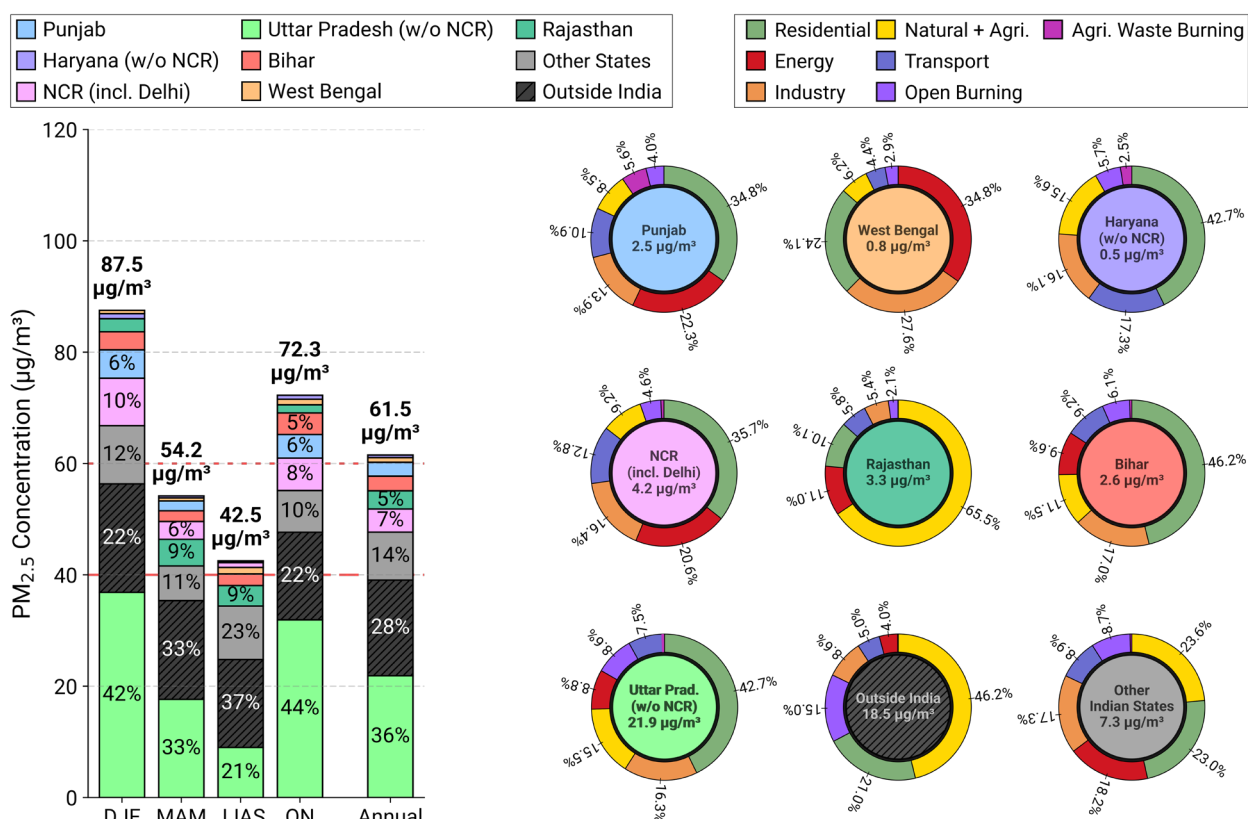
## C2. Uttar Pradesh (excluding NCR districts)

Figure C-3 shows that the annual average  $PM_{2.5}$  concentration from the baseline CAMx-PSAT over Uttar Pradesh (excluding NCR) is  $61.5 \mu\text{g m}^{-3}$ , which exceeds both the daily and annual prescribed limits under NAAQS. The  $PM_{2.5}$  concentrations remain elevated from October to February, exceeding  $80 \mu\text{g m}^{-3}$  in December–February and  $70 \mu\text{g m}^{-3}$  in October–November.

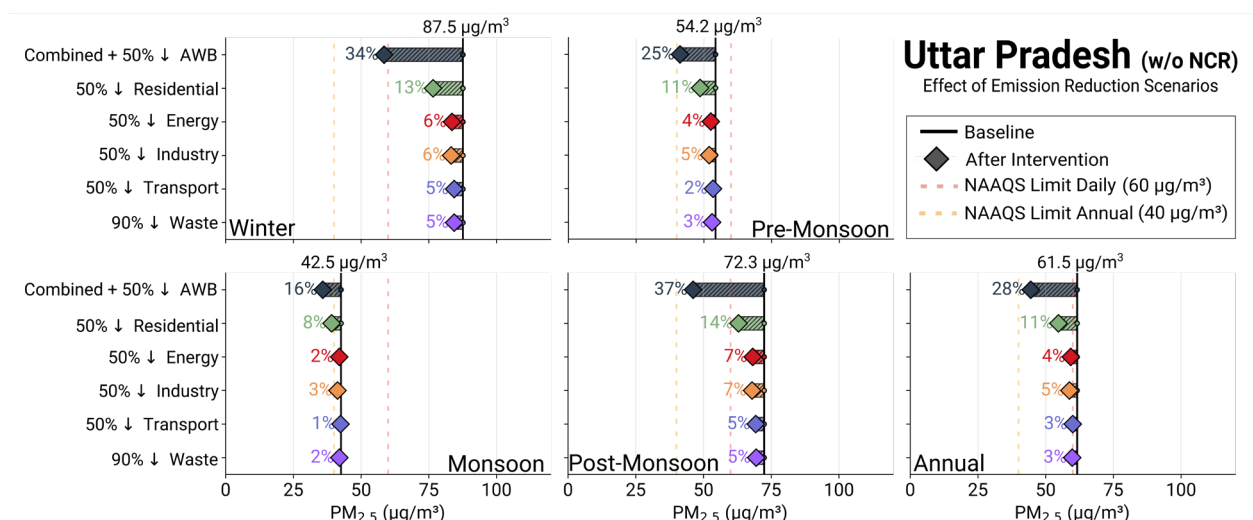
At the annual level, 36% of  $PM_{2.5}$  concentrations originate locally, with residential, industrial, and agricultural sources as the dominant contributors. Transboundary pollution accounts for 28% of the total and is driven by natural dust, agriculture, residential emissions, and open burning.

Figure C-4 shows the effect of various emission reduction scenarios on the air quality over Uttar Pradesh (excluding NCR). The combined emission-reduction scenario results in a 28% reduction in annual  $PM_{2.5}$  concentrations, from  $61.5 \mu\text{g m}^{-3}$  to  $44.3 \mu\text{g m}^{-3}$ . The reduction is highest during the winter (34%) and post-monsoon (37%) seasons. An additional scenario in which emissions from residential sources are reduced by 50% across Uttar Pradesh results in an 11% reduction in annual  $PM_{2.5}$  concentrations, highlighting those mitigating residential emissions can yield substantial reductions.

**Figure C-3.** Regional and sectoral contributions to Uttar Pradesh's (excluding NCR) air quality from contributing regions. The stacked bar chart (left) shows the seasonal and annual contribution of various regions to Uttar Pradesh (excluding NCR), and the pie charts (right) show the sectoral emission breakdown within each contributing region at the annual level.



**Figure C-4.** Seasonal and annual reductions in PM<sub>2.5</sub> concentrations over Uttar Pradesh (excluding NCR) relative to the baseline for major emission-reduction scenarios across the IGP.



## C3. Bihar

Figure C-5 shows that the annual average  $PM_{2.5}$  concentration from the baseline CAMx-PSAT over Bihar is  $65.8 \mu g m^{-3}$ , which exceeds both the daily and annual prescribed limits under NAAQS. The  $PM_{2.5}$  concentrations remain elevated from October to February, touching  $100 \mu g m^{-3}$  in December-February and over  $80 \mu g m^{-3}$  in October-November.

At the annual level, 34% of the  $PM_{2.5}$  concentrations originate locally, with residential, industrial, and agricultural sources as the dominant contributors. Transboundary pollution is the second-most significant contributor, accounting for 24% and driven primarily by residential emissions, natural dust, agriculture, and open burning.

**Figure C-5.** Regional and sectoral contributions to Bihar's air quality from contributing regions. The stacked bar chart (left) shows the seasonal and annual contribution of various regions to Bihar, and the pie charts (right) show the sectoral emission breakdown within each contributing region at the annual level.

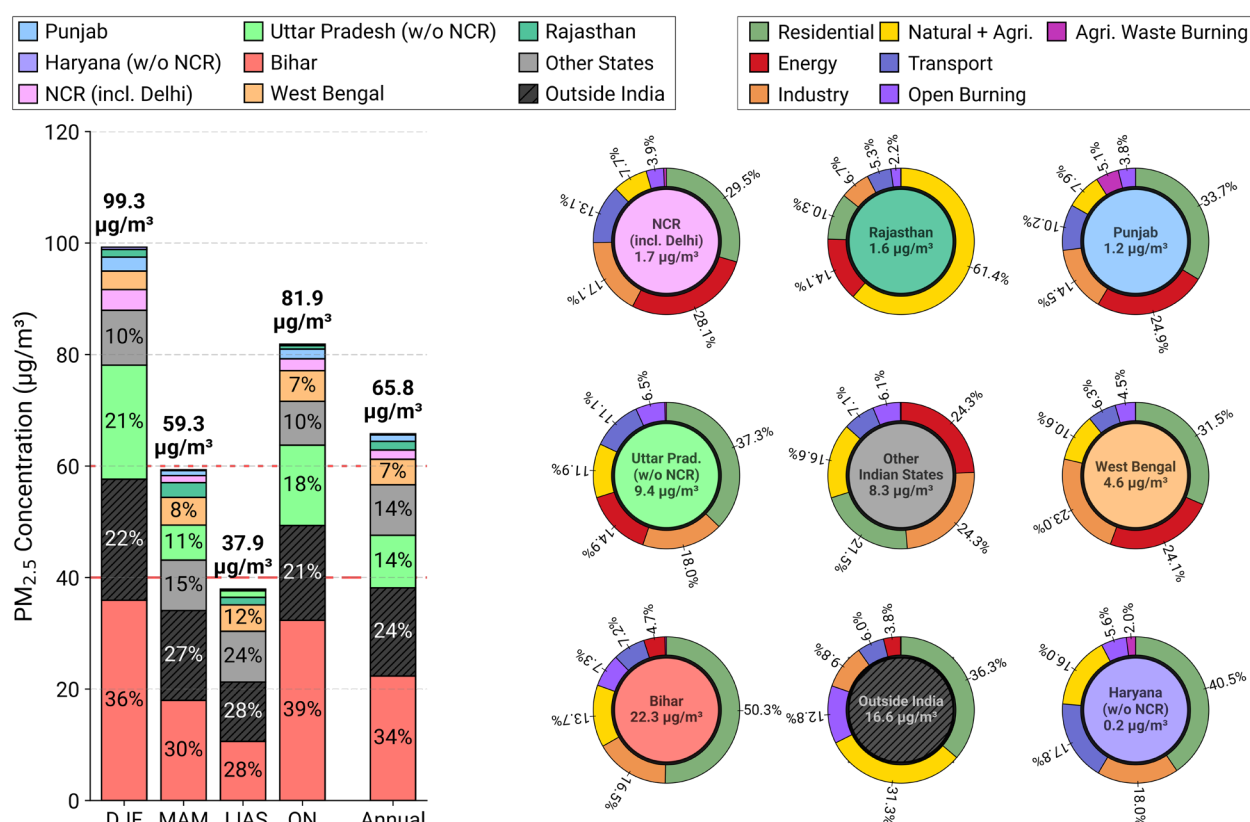
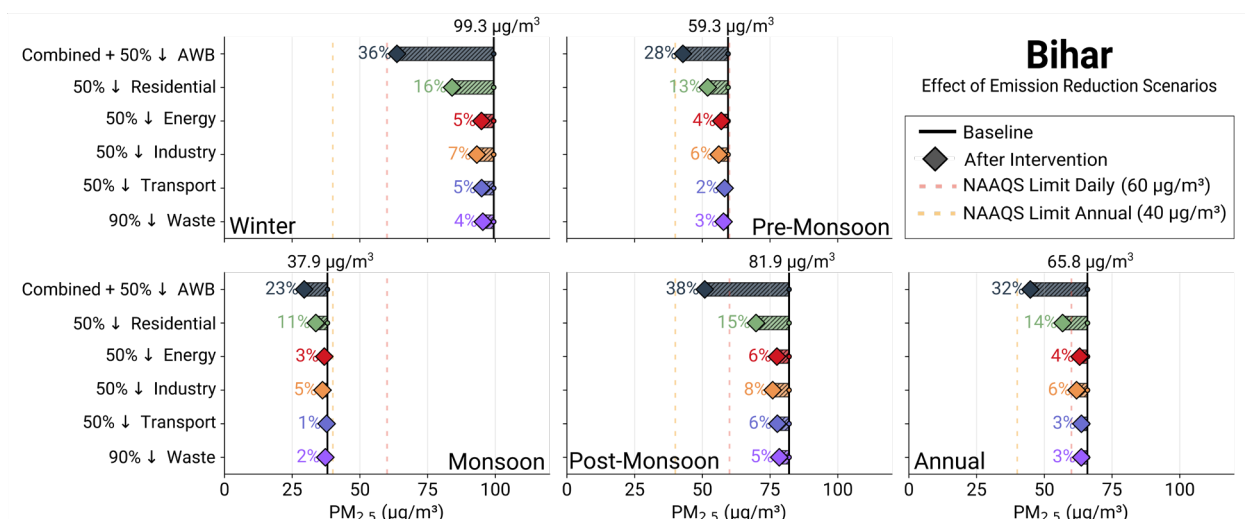


Figure C-6 shows the effects of various emission-reduction scenarios on air quality in Bihar. The combined emission-reduction scenario results in a 32% reduction in annual  $PM_{2.5}$  concentrations, from  $65.8 \mu g m^{-3}$  to  $44.7 \mu g m^{-3}$ . The reduction is highest during the winter (36%) and post-monsoon (38%) seasons. An additional scenario in which emissions from residential sources are reduced by 50% across Bihar results in a 11% reduction in annual  $PM_{2.5}$  concentrations, showing that mitigating residential emissions will yield a drastic reduction.

**Figure C-6.** Seasonal and annual reductions in  $PM_{2.5}$  concentrations over Bihar relative to the baseline for major emission-reduction scenarios across the IGP

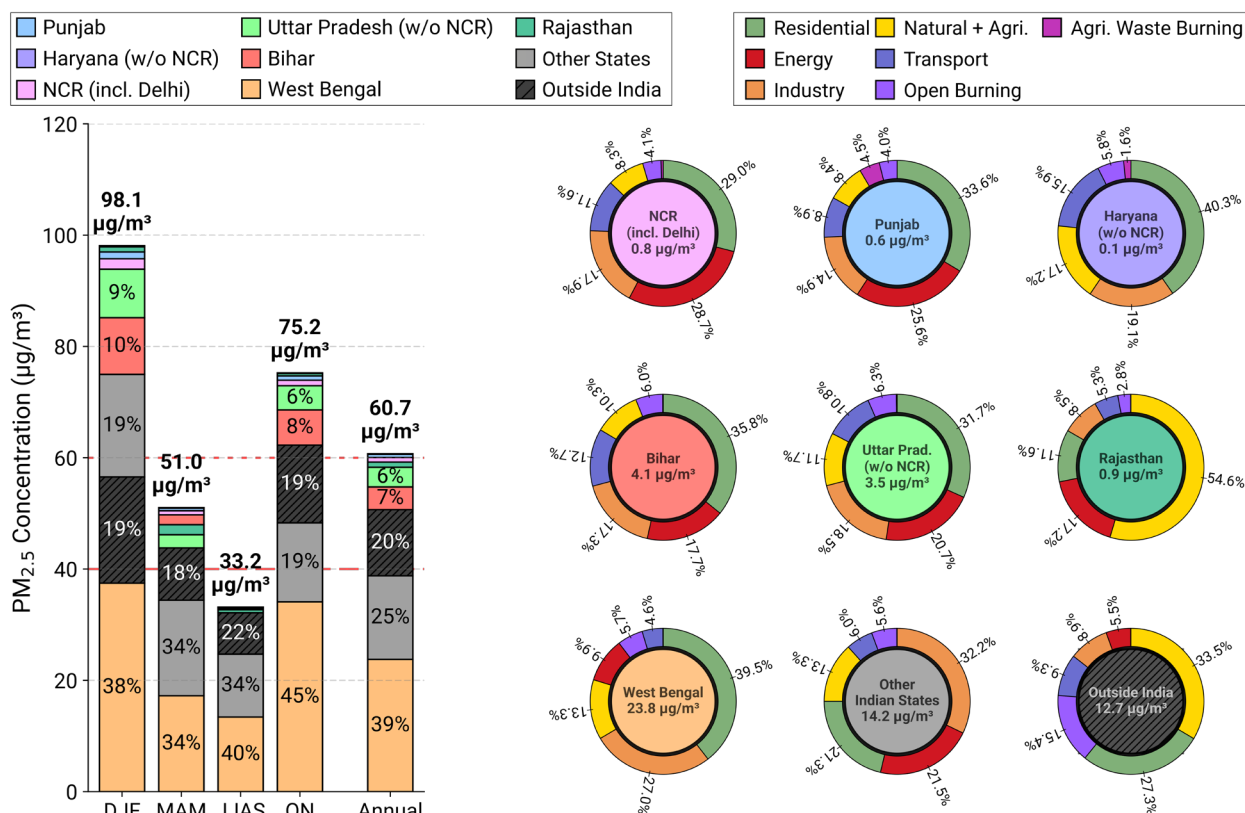


## C4. West Bengal

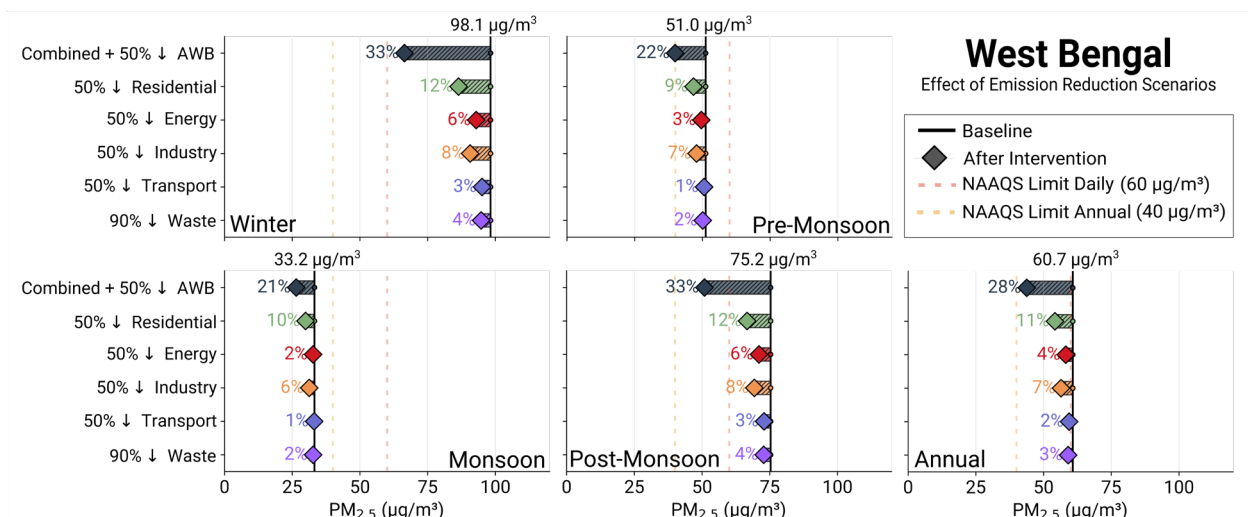
Figure C-7 shows that the annual average  $PM_{2.5}$  concentration from the baseline CAMx-PSAT over West Bengal is  $60.7 \mu\text{g m}^{-3}$ , which exceeds both the daily and annual prescribed limits under NAAQS. The  $PM_{2.5}$  concentrations remain elevated from October to February, with values touching  $100 \mu\text{g m}^{-3}$  in December–February and over  $70 \mu\text{g m}^{-3}$  in October–November. At the annual level, 39% of the concentration originates locally, with residential, industrial, and agricultural sources as the dominant contributors. Pollution transported from nearby Indian states is the second-largest contributor, accounting for 25%, with industry, energy, and residential sources as the largest contributors.

Figure C-8 shows the effects of various emission-reduction scenarios on air quality in West Bengal. The combined emission-reduction scenario results in a 32% reduction in annual  $PM_{2.5}$  concentrations, from  $60.7 \mu\text{g m}^{-3}$  to  $43.7 \mu\text{g m}^{-3}$ . The reduction is highest during the winter (33%) and post-monsoon (33%) seasons.

**Figure C-7.** Regional and sectoral contributions to West Bengal's air quality from contributing regions. The stacked bar chart (left) shows the seasonal and annual contribution of various regions to West Bengal, and the pie charts (right) show the sectoral emission breakdown within each contributing region at the annual level.



**Figure C-8.** Seasonal and annual reductions in PM<sub>2.5</sub> concentrations over West Bengal relative to the baseline for major emission-reduction scenarios across the IGP





# The Authors



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Dr Nirav Lakinwala is a Senior Associate at CSTEP with expertise in air quality modelling, data analysis, and machine learning. He led report writing with a focus on the modelling aspects, performed model simulations, analysed the results, and developed visualisations.



**Dr Nidhi Malik**

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Dr Nidhi Malik is a Senior Associate at CSTEP with expertise in air quality assessment, techno-economic analysis, and policy-oriented applied research. She contributed to the Introduction and Results sections, with a particular focus on policy analysis.



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Swagata Dey is a Policy Specialist and Group Head of the Air Quality Policy and Outreach group at CSTEP, leading air quality policy research and programme design. She served as the Principal Investigator for this project. She provided policy expertise and reviewed the report.



**Dr Piyush Bhardwaj**

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Dr Piyush Bhardwaj is a Research Scientist and Group Head of the Air Quality Observations and Modelling group at CSTEP. He planned the study design, helped set up the model domain, interpreted the modelling results, and provided a technical review of the report.







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