Airshed-Based Source Apportionment of Delhi Air Pollution Using WRF-Chem and Back Trajectory Analysis

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Abstract: *The intensification of human activities has significantly deteriorated air quality in densely populated urban centers such as Delhi, leading to severe health and urban climate challenges. While ongoing mitigation efforts aim to reduce pollutant concentrations, addressing the sources of pollution remains critical for achieving sustainable improvements. This study investigates the geographical origins and sectoral contributions of CO,* NO_2 *and* $PM_{2.5}$ *in Delhi. Pollutant concentration data and gridded meteorological data were utilized to identify pollution transport pathways and source regions. The study applied back trajectory analysis and the Concentration Weighted Trajectory (CWT) method at 100 meters above ground level for winter, pre-monsoon, monsoon, and post-monsoon season of year 2022. Airshed is delineated using back trajectory frequency analysis which extends across the Indo-Gangetic Plain, from Uttar Pradesh in India to Lahore in Pakistan. Using WRF-Chem model and emission inventories for 2022, pollutant contributions from six major sectors, namely agriculture, energy, industry, residential, transportation, and waste were estimated for 1st November 2022. Outputs were downscaled to a spatial resolution of 5 km for the regional airshed and 1 km for the local airshed. Sectoral contributions were found to be significantly higher than those estimated in earlier studies that were limited by administrative boundaries. The results show that dominant pollution sources vary by scale: for regional airshed, residential emissions contribute most to CO (55.9%), while in local airshed, transportation is the largest contributor (54.2%). Stubble burning contributed 18.01% to* $PM_{2.5}$*, 1.43% to* NO_2*, and 3.6% to CO in the regional airshed, higher than in the local airshed. These findings underscore the importance of adopting a regional airshed-based approach to air pollution management that considers pollutant sources beyond the administrative boundaries of Delhi.*

Keywords: Airshed, Source contribution, Stubble burning, Back trajectory, WRF-Chem

Introduction

Air pollution remains a critical environmental challenge in densely populated urban centers like Delhi, where elevated levels of pollutants such as particulate matter ($PM_{2.5}$), carbon monoxide (CO), and nitrogen dioxide (NO_2) have serious health and climate implications (Park et al., 2024). The complex mixture of emission sources, including vehicular traffic, industrial activities, residential combustion, and agricultural residue burning, coupled with meteorological and topographical conditions, contributes to the persistent deterioration of air quality in the region (Goyal et al., 2019; Kumar et al., 2021). Traditional approaches focusing exclusively on administrative boundaries often underestimate the contribution of pollutant transport from surrounding regions, highlighting the need for airshed-based analyses that consider broader geographical contexts (Kumar et al., 2020).

Airshed delineation, which accounts for meteorological patterns, terrain, and pollutant transport pathways, provides a robust framework for understanding source-receptor relationships and guiding regional air quality management (Dey et al., 2020; Zhang et al., 2023). Previous studies have demonstrated that a significant proportion of Delhi's air pollution originates from outside the city limits, including transboundary contributions from the Indo-Gangetic Plain, requiring multi-scale strategies for effective mitigation (Chowdhury et al., 2022; Sharma & Guttikunda, 2024). Additionally, events such as stubble burning in northern states substantially elevate pollutant loads during specific seasons, further complicating urban air quality dynamics (Singh et al., 2023).

Source apportionment using advanced chemical transport models like WRF-Chem enables quantitative estimation of sectoral contributions and pollutant fluxes across scales (Li et al., 2022; Park et al., 2024). This integrated approach facilitates the design of targeted emission control strategies that address both local and regional sources influencing urban air pollution.

Delhi faces significant challenges, particularly in relation to environmental issues. Air pollution has become a major concern, with the city experiencing severe levels of particulate matter and other pollutants, primarily attributed to vehicular emissions, industrial activities, and crop residue burning in nearby agricultural regions. Currently, the origins pollution in DUA can be identified through atmospheric physics and photochemistry. The distinctive local terrain plays a significant role in this phenomenon. The area's relatively enclosed nature results in a gradual internal temperature change. Additionally, the transport capacity within the planetary boundary layer (PBL) is limited, leading to temperature inversion and frequent stagnation of local air, hindering the dispersion of air pollutants.

Accordingly, this study applies an airshed-based source apportionment methodology using WRF-Chem to examine the spatial origins and sector-wise contributions of key pollutants in Delhi for 1 Nov 2022. The results are expected to provide actionable insights for policymakers to optimize intervention measures beyond administrative lines for comprehensive air quality improvement.

Literature Review

a. Airshed Delineation

Defining an airshed is a fundamental step for effective air quality management and environmental stewardship. Air pollutants disperse across regions called airsheds, shaped by factors such as wind direction and speed, topographic features including vegetation, mountains, and river basins, along with altitude, precipitation, temperature variations, and proximity to the sea (Khan et al., 2024). Recent studies highlight the limitations of focusing air pollution control solely within city boundaries, as substantial portions of urban pollution often originate from beyond city or even state lines. For example, from April 2016 to February 2017, about 24% of $PM_{2.5}$ in the National Capital Region (NCR), 17% from neighbouring upwind states, and 33% from regions outside India contributed to Delhi's air pollution (ARAI & TERI, 2018). This underlines the significant external sources impacting Delhi's air quality. Similarly, stubble burning in Punjab and Haryana contributes to elevated $PM_{2.5}$ in northern India, with wind, low mixing heights, and weak winds during winters causing up to a 50% increase in pre-winter $PM_{2.5}$ in Delhi (Guttikunda et al., 2023). The Air Pollution Knowledge Assessment (APnA) across 20 tier-2 cities demonstrated that 30–40% of $PM_{2.5}$ in cities like Agra (36%) and Coimbatore (32.5%) originates from outside their urban airsheds (Guttikunda et al., 2019). Various studies have delineated airsheds in India using different approaches. According to the World Bank, six principal airsheds in South Asia are influenced by geography, climate, and spatial air quality connectivity, covering regions such as the Central/Eastern Indo-Gangetic Plain, Middle India, Northern/Central Indus River Plain, and the Southern Indus Plain extending into neighbouring countries (World Bank, 2023b). IIT Delhi utilized k-means clustering to identify airsheds seasonally at regional and local scales, incorporating land elevation and wind patterns, revealing broad airsheds overlapping multiple cities (Dey et al., 2020). Guttikunda et al. (2023) proposed 104 micro airsheds covering 164 cities based on urban-rural classifications, land-use, and emissions both within and near city boundaries, expanding from administrative limits to include satellite cities and major emission sources. Additionally, IIT Kanpur developed a 5 km × 5 km emission inventory and airshed delineation for Agra city as part of a WRF-Chem-based source apportionment study presented to the Climate and Clean Air Coalition and UN Environment India. Further, Liu et al. (2018) employed the HYSPLIT model to assess the impact of outdoor biomass burning alongside other sources on air quality in Delhi, Pune, and Bengaluru by estimating seasonal airsheds using backward trajectories converted to spatial density grids, delineating seasonal airsheds for each city.

a. Source Apportionment

Receptor modeling has been used in several studies in Delhi to examine $PM_{2.5}$, PM_{10}, and suspended particulate matter (SPM). A considerable amount of these pollutants are consistently attributed to vehicle emissions, road dust, and coal combustion, according to studies conducted by (Balachandran et al., 2000; Chelani et al., 2010; Chowdhury et al., 2007; Goyal et al., 2010; Pant & Harrison, 2012b; H. Sharma et al., 2007; Shridhar et al., 2010; A. Srivastava et al., 2008)

Several studies have been conducted to identify and analyze the sources of air pollution in different regions of India using various models and methodologies. In a study by (Chelani et al., 2008), the Chemical Mass Balance (CMB) model was used to analyze PM_{10} concentrations. The study found that vehicular sources, resuspension of road dust, and industrial activities were the major contributors to PM_{10} levels. High concentrations of manganese (Mn), magnesium (Mg), iron (Fe), aluminum (Al), vanadium (V), and cobalt (Co) indicated these sources. Additionally, the presence of chlorine (Cl) and sodium (Na) at specific sites, such as Colaba and Chembur, pointed to the influence of marine sources. (Yadav et al., 2019) employed the Positive Matrix Factorization (PMF), Conditional Probability Function (CPF), and HYSPLIT models to study $PM_{2.5}$, PM_{10}, and gaseous pollutants. The findings revealed that vehicular emissions were the main sources of NO, NO_2, NO_x, and CO. The fertilizer industry was identified as the primary source of NH_3 and SO_2, while particulate matters (PM_{10}, $PM_{2.5}$) and ozone were mainly emitted from mining activities. Another study in Mumbai by (Gupta et al., 2012) using the PMF model indicated that most of the sampling sites were dominated by local sources. The study emphasized that action plans for reducing air pollution should prioritize local sources, as their reduction would provide the most significant benefits in terms of lowering exposure to air pollutants.

Study conducted by (Gummeneni et al., 2011) utilized the CMB model to analyze PM_{10} and $PM_{2.5}$. The results showed that suspended dust was a major source of PM_{10} (40%) and $PM_{2.5}$ (31%), with vehicular emissions also significantly contributing to particulate matter emissions. The study noted that vehicular pollutants had a more substantial impact on $PM_{2.5}$ than PM_{10}, and other significant sources included industrial emissions, combustion, and refuse burning. Whereas (Thammadi et al., 2018) combined the CMB receptor model and AERMOD dispersion model to identify sources and improve the performance of the AERMOD model. The study found that fugitive sources, soil, and road dusts were substantial contributors to ambient pollution. The emission inventory was improved by adjusting emissions based on road lengths and the deficit between measured and computed concentrations. Sah et al. (2022) conducted a study using HYSPLIT and Principal Component Analysis (PCA) models to assess $PM_{2.5}$ and heavy metal concentrations. The study revealed that the average annual mass concentration of $PM_{2.5}$ in Agra was above WHO and NAAQS limits, while the average annual concentration of lead (Pb) was below these limits. There were significant seasonal variations, with the highest concentrations of $PM_{2.5}$ and heavy metals observed during winter and the lowest during the monsoon season. Another study in Agra using the Weather Research and Forecasting (WRF) model and AERMOD dispersion model found that road dust was the primary source of $PM_{2.5}$ (64%) and PM_{10}. Vehicles contributed 13%, industrial activities 9%, residential emissions 7%, and hotel operations 3% to $PM_{2.5}$ levels. The majority of NO_x and CO emissions were from vehicles, while SO_2 primarily originated from brick kilns.

These studies highlight the diverse sources of air pollution across different regions in India, including vehicular emissions, industrial activities, road dust, and more localized sources, indicating the need for region-specific strategies to mitigate air pollution effectively.

Study Area

Delhi, located in northern India at coordinates 28° 36′ 36″ N and 77° 13′ 48″ E, sits at an elevation of 216 meters above sea level. As the capital territory and a major metropolitan area, Delhi occupies a strategic position on the banks of the Yamuna River, which flows north-south, bisecting the city. It is bordered by the states of Haryana and Uttar Pradesh and lies within the extensive Indo-Gangetic Plain, an alluvial plain formed by the Indus, Ganges, and Brahmaputra rivers. The city is flanked to the west by the Thar Desert and to the south by the Aravalli hill ranges. Delhi's topography is largely flat, except for a low ridge extending in a NNE-SSW direction, considered an extension of the Aravalli hills from Rajasthan. The Delhi Airshed encompasses the entire area where pollutants disperse due to meteorological and geographical factors.

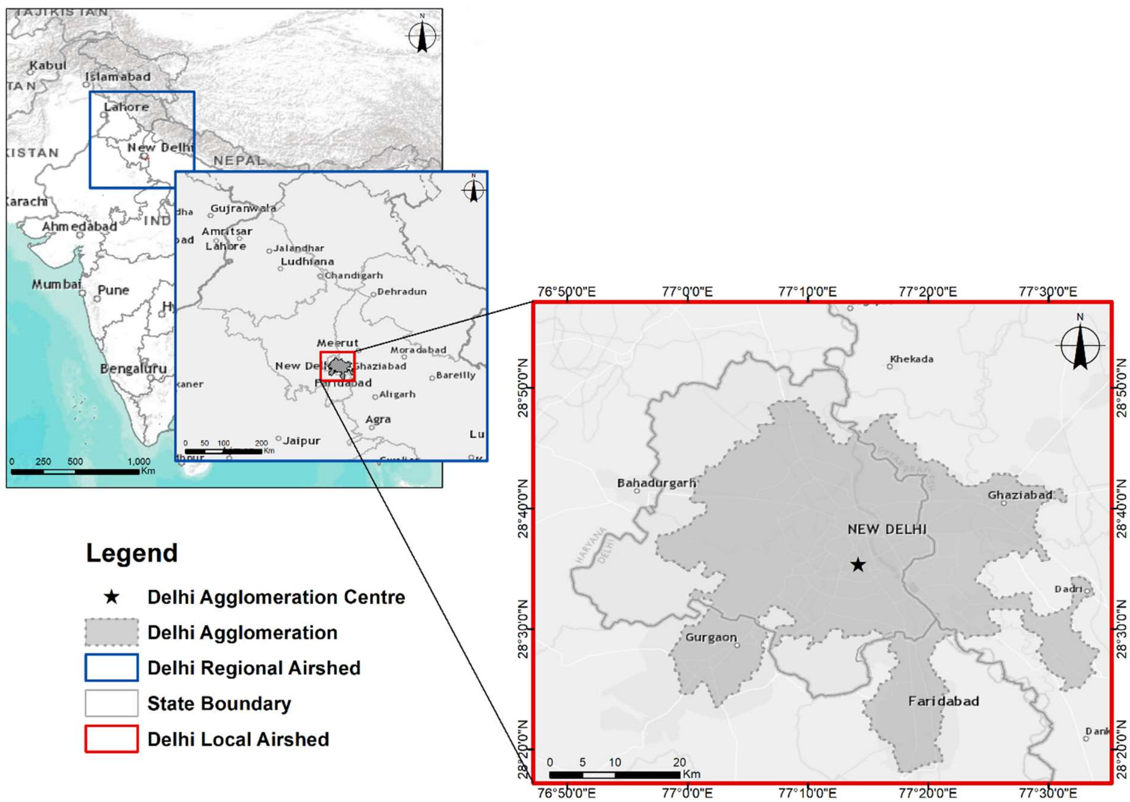

Figure 1: Study Area

The local airshed includes the entire National Capital Territory (NCT) region and the urban agglomeration of Delhi, which comprises the built-up area and surrounding suburbs connected by continuous urban development. This area is characterized by high population density, significant economic and social integration, and continuous expansion of the built environment. The regional airshed extends beyond Delhi, covering Punjab, Haryana, Uttarakhand, Himachal Pradesh, parts of Uttar Pradesh, Rajasthan, a portion of Pakistan, and a very small part of Madhya Pradesh. The distinctive local terrain plays a significant role in this phenomenon. The area's relatively enclosed nature results in a gradual internal temperature change. Additionally, the transport capacity within the planetary boundary layer (PBL) is limited, leading to temperature inversion and frequent stagnation of local air, hindering the dispersion of air pollutants.

Methodology

The methodology begins with the delineation of the airshed, which involves identifying the spatial domain where air pollutants accumulate and are transported, based on both meteorological and topographical factors relevant to the study region. Once the airshed boundaries are established, a combined emission inventory for CO, NO_2 and $PM_{2.5}$ is prepared by integrating CAMS-GLOB-ANT and EDGAR HTAPv3, encompassing anthropogenic, emission sources within the defined spatial extent. This emission inventory serves as a key input for the WRF-Chem model, which is then configured and executed for the study period. The model is run for 1 day, 1 Nov 2022, with chemistry modules suitable for pollutant species, enabling quantitative assessment of the contribution of different emission sources to observed air pollutant concentrations.

Table 1: Datasets

Data	Type	Resolution	Source
NCEP GDAS/FNL	Meteorological Data	0.25° x 0.25°	https://gdex.ucar.edu/datasets/d083003/
NCEP GFS	Meteorological Data	0.25° x 0.25°	https://gdex.ucar.edu/datasets/d084001/
EDGAR-HTAPv3	Emission Inventory Data	0.1° x 0.1°	https://edgar.jrc.ec.europa.eu/dataset_htap_v3
CAMS-GLOB-ANT	Emission Inventory Data	0.1° x 0.1°	https://eccad.sedoo.fr/#/metadata/479
WACCM forecasts	Upper Boundary Conditions	0.9° x 1.25°	https://www2.acom.ucar.edu/acresp/forecasts-and-near-real-time-nrt-products
NICES land use/land cover	IRS-P6 AWiFS derived gridded LU/LC Data	30s(0.925km ~1km)	https://bhuvan-app3.nrsc.gov.in/data/download/index.php

Then the post-processing of the output files was done in python to find the contribution of each sector for the different pollutants. An overall methodology is given in Figure 1 and the datasets used are given in Table 1.

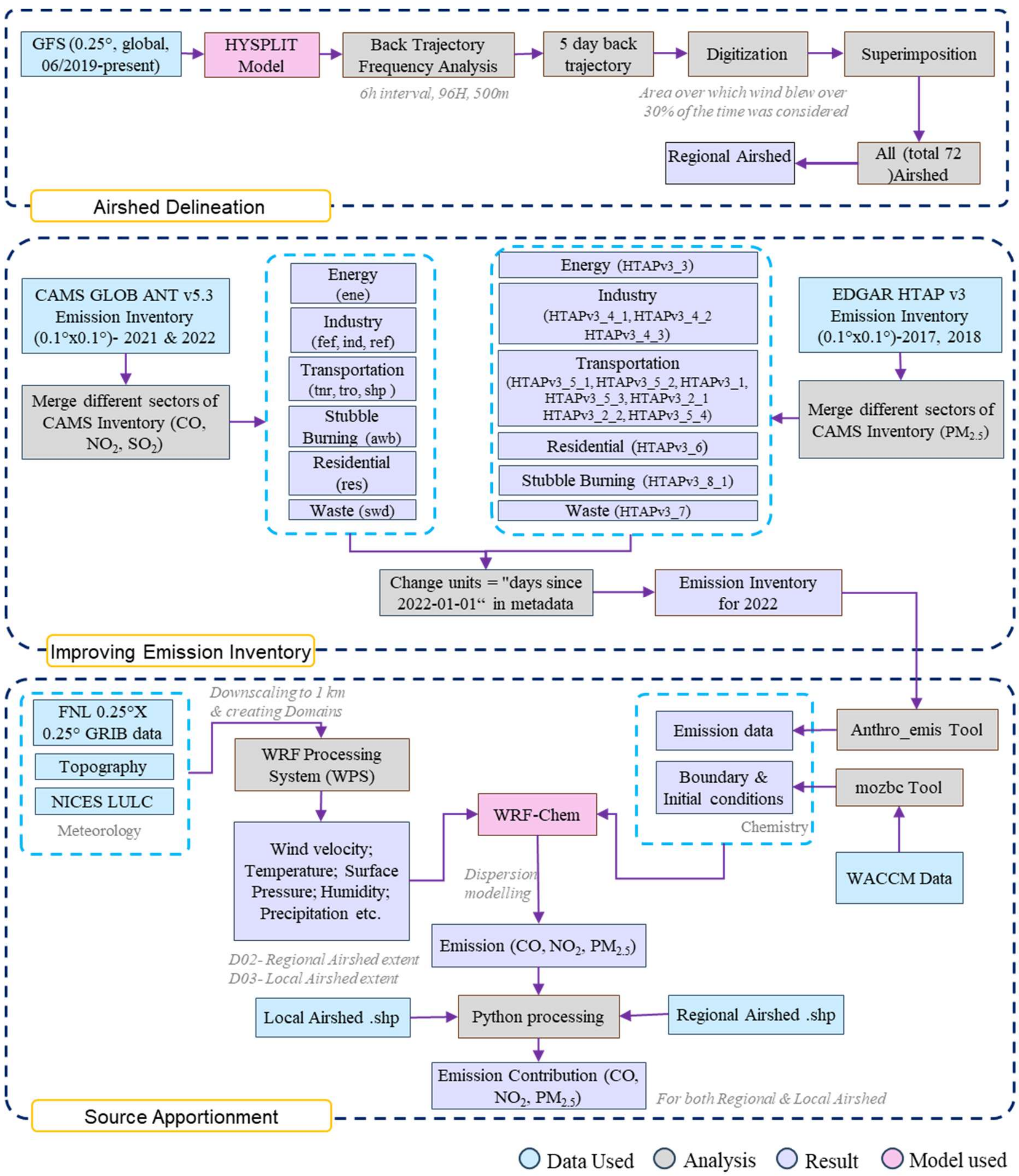

Figure 2: Methodology Chart

To delineate the airsheds back trajectory Frequency analysis was done using the web based HYSPLIT Trajectory model available on NOAA Air Resource Laboratory (https://www.ready.noaa.gov/hypub-bin/trajtype.pl?runtype=archive). Archive trajectories were calculated for single starting location which is taken as the Delhi's Urban Agglomeration (DUA) center having coordinates 28.5895°N, 77.2361°E and Trajectory Frequency option was selected. The Trajectory Frequency feature initiates a trajectory at a specific location and altitude every 6 hours. Subsequently, it calculates the total frequency of trajectories traversing a grid cell, normalizing the result either by the total number of trajectories or their endpoints. It's important to note that a trajectory can cross a grid cell once or multiple times, with the option to consider residence time (choices include 1, 2, or 3). For meteorological data, Global Forecasting System (GFS) 0.25° global data which is available from June 2019 to present is used. In Model Run Details, trajectory direction is selected to be backward, vertical motion is set to model vertical velocity, start time is set according to analysis with starting hour to be 00, total run time is taken as 96 hour, Number of days to calculate trajectory frequencies is 1, starting interval selected was 6 hrs, frequency grid resolution selected to be 0.25° and the height at which back trajectories will be calculated over the selected point location was taken 500 meters above ground level. This is done for the year 2022 starting from 1 Dec 2021 to 30 Nov 2022, a total of 72 outputs were generated for 5 days back trajectories. PC Version of HYSPLIT model cannot make frequency maps with customized legends therefore the online version was used but in this version there is no option to download the output as a GeoTIFF file. So, the output is downloaded as a PDF. Trajectory frequency has 4 results according to the residence time. Output with 0 residence time is taken which is defined as follows:

Equation 1: Trajectory Frequency

$$Traj.freq\ 0 = \frac{100 * \text{ number of trajectories passing though each grid square}}{\begin{array}{c}\text{Number of trajectories - No residence time in grid cell}\\ \text{(each trajectory is counted only once per grid cell)}\end{array}}$$

PDF is exported to high resolution JPEG file which is then georeferenced in ArcGIS all the georeferenced output are shown in Appendix A. Georeferenced image is then exported as TIFF file and manual digitization was done on each file to delineate the airshed where 30% of the time wind was present. All the 72 shapefiles were superimposed according to the seasons and then merged to get annual airshed of Delhi for 2022 which is defined as the Regional Airshed in Study. The local airshed is 70km x 65km which covers the Delhi Urban Agglomeration area and some part of NCR (National Capital Region). The size of the airshed was determined by initially defining the administrative boundary of the primary city and then extending it to encompass satellite cities, as well as any nearby high-density diffuse and point sources. These airshed extents were used to create the domains for WRF-Chem model.

The Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) is a mesoscale numerical weather prediction model with chemical transport capabilities. Integrating advanced parameterizations for atmospheric chemistry, aerosols, and gas-phase species, WRF-Chem allows for the study of interactions between emissions, transport, chemical transformation, and feedback on weather and climate.

To find the emissions at regional and local airshed for Delhi, we need emission data. To generate the emission data for model a tool named anthro_emiss was used. The input data for this tool was CAMS-GLOB-ANT inventory and EDGAR HTAPv3 inventories were used. For NO_2 and CO, CAMS inventory data from Dec 2021 to Nov 2022 was used. Due to the limitation of data availability of $PM_{2.5}$ in CAMS inventory, EDGAR HTAP inventory data of $PM_{2.5}$ from Dec 2017 to Nov 2018 was used.

An inventory by combining both CAMS and HTAP inventory was made with 6 anthropogenic emission sectors considered (Agriculture, Energy, Industry, Residential, Transportation, Waste). Python was used to merge the Emission inventories and create new sectors, metadata was also changed for both the emission inventories, unit for HTAP_v3 inventory was changed to unit= "days since 2022-01-01" so that HTAP's 2018 inventory and CAMS's 2022 inventory can be used together.

Table 2: Static Geographical Data

Name	Data
HGT_M	topo_gmted2010_30s
LANDUSEF	usgs_30s (modified)
SOILTEMP	soiltemp_1deg
SOILCTOP	bnu_soil_30s
SOILCBOT	bnu_soil_30s
ALBEDO12M	albedo_modis
GREENFRAC	greenfrac_fpar_modis
LAI12M	modis_lai
SNOALB	maxsnowalb_modis

Running the WRF-Chem model involves several sequential steps, beginning with the preprocessing of meteorological data and the preparation of gridded emissions datasets according to the domain extent specified in the namelist file, Figure 3 shows the domain configuration. Subset of 6-hourly NCEP GDAS/FNL (Final) gridded meteorological data of 0.25x0.25-degree resolution used as input meteorological data for WPS. The static geographical data used is given in Table 2.

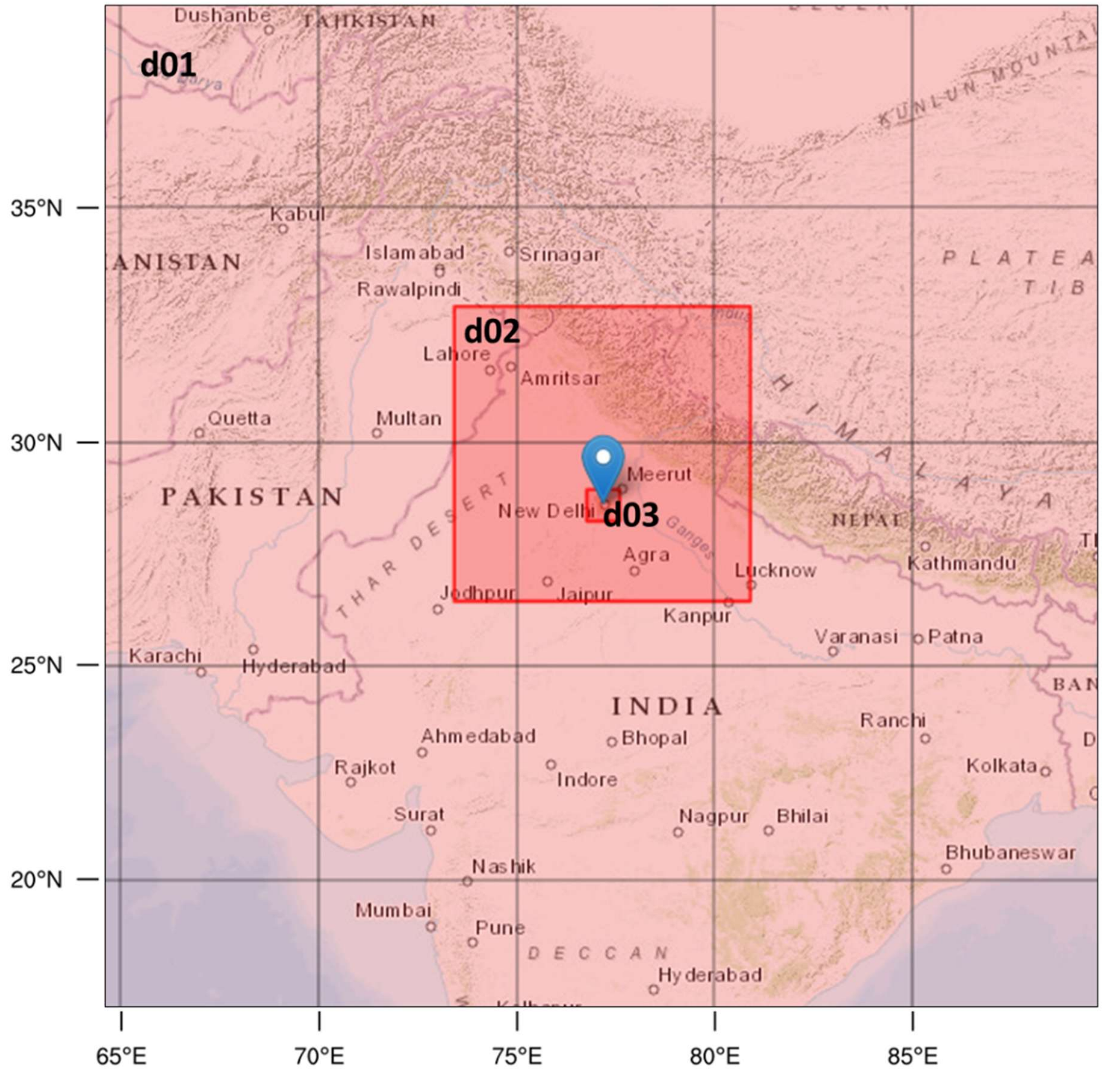

Figure 3: Domain configuration

The 25-category (including no data class) US Geological Survey (USGS) LU/LC dataset is deficient in its characterization of the urban/ suburban landscape for Indian region. Land use data of usgs_30s is modified by replacing the data files for India provided by NICES

(National Information system for Climate and Environment Studies) available on Bhuvan Portal for more accurate LU/LC. Initial and boundary conditions were generated using the mozbc tool, the input data for this tool was WACCM forecast data. The main executable (wrf.exe) is run to perform the simulation, producing output files with meteorological and chemical variables throughout the defined spatial domain and simulation period. Finally, post-processing and visualization tools are used to analyze the results.

Results and Discussion

a. Airshed Delineation

Airshed is delineated by 5-day back trajectory frequency analysis for year 2022 using the HYSPLIT model and GFS input Data, detailed methodology for delineating airshed is provided in Methodology. The annual airshed delineated is the superimposed area of 72 airsheds which goes up to Pakistan and covers cities like Lahore and Gujranwala shown in Figure 4. Most of the areas of Punjab, Haryana and some areas of Uttar Pradesh come under Delhi's Regional Airshed. The delineated airshed is in the same region which World Bank's new report has shown as West/central Indo-Gangetic planes airshed (World Bank, 2023). The local airshed, spanning 70 km by 65 km, includes the Delhi Urban Agglomeration and parts of the National Capital Region (NCR). Its extent was defined by first outlining the administrative boundary of the core city, then expanding it to incorporate surrounding satellite towns and nearby high-density point and diffuse emission sources.

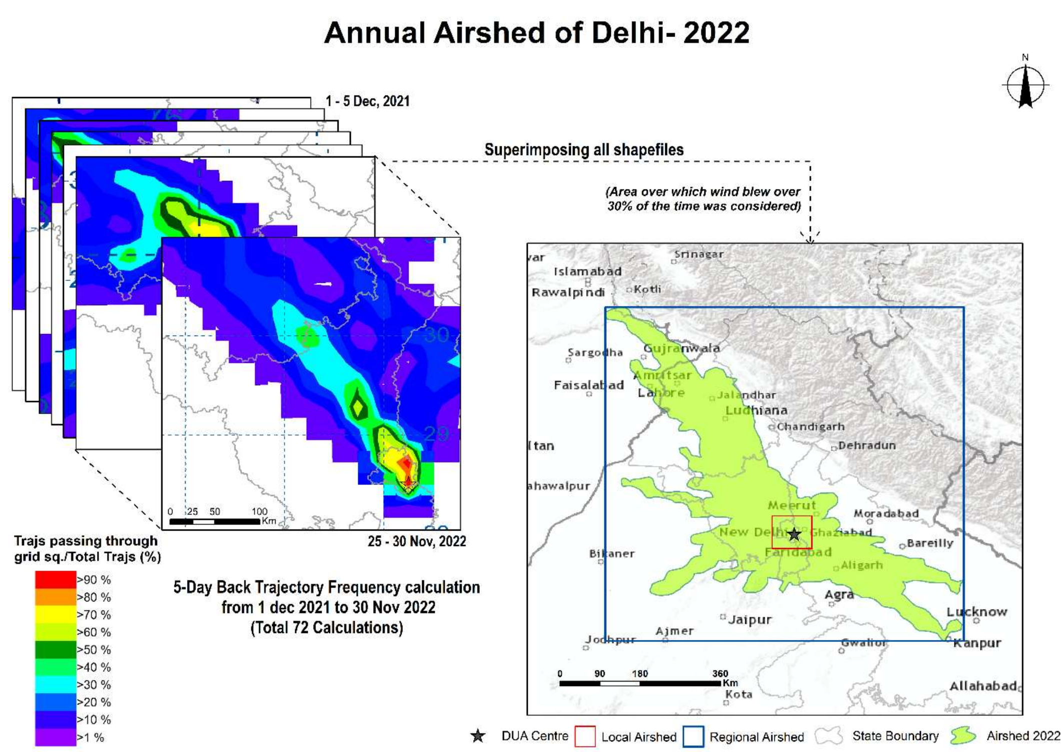

Figure 4: Regional and Local Airshed

a. Source Apportionment

Figure 5 shows 24 hours mean concentration for 1 Nov 2022 at 1000hPa for different pollutants in regional airshed when emissions from all the 6 sectors (Agriculture, Energy, Industry, Residential, Transportation, Waste) were considered in simulation. The maximum concentration of CO is 3.27 ppmv and spatial mean for Regional airshed is 0.94 ppmv. For Nitrogen dioxide the maximum concentration is 0.29 ppmv and spatial mean is 0.022 ppmv. For $PM_{2.5}$ maximum concentration is 91.004 µg/kg-dryair and spatial mean is 16.86 µg/kg-dryair.

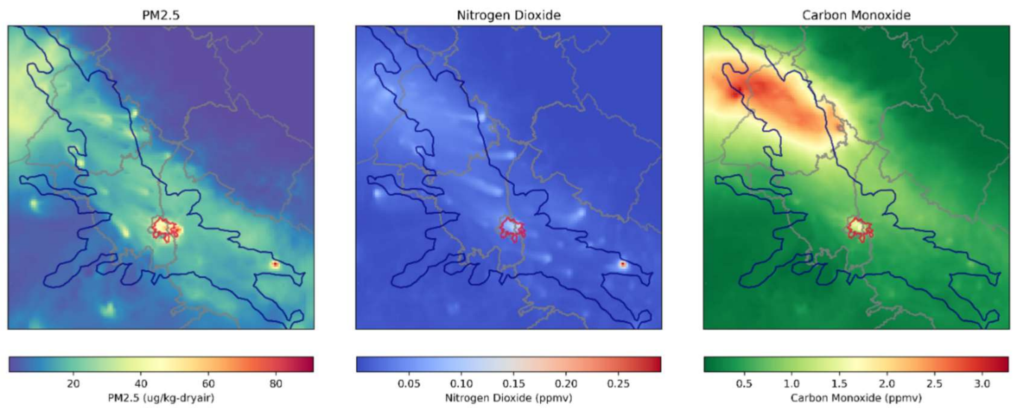

Figure 5: 24H mean concentration from all 6 sectors for d02 (Regional Airshed)

Figure 6 shows 24 hours mean concentration for 1 Nov 2022 at 1000hPa for different pollutants when emissions from all the 6 sectors in local airshed. the maximum value of 3.274 ppmv for CO, 0.290 ppmv for NO_2 and 91.00 µg/kg-dry air for $PM_{2.5}$. Spatial mean for value is 0.605 ppmv for CO, 0.012 ppmv for NO_2 and 10.539 µg/kg-dry air for $PM_{2.5}$

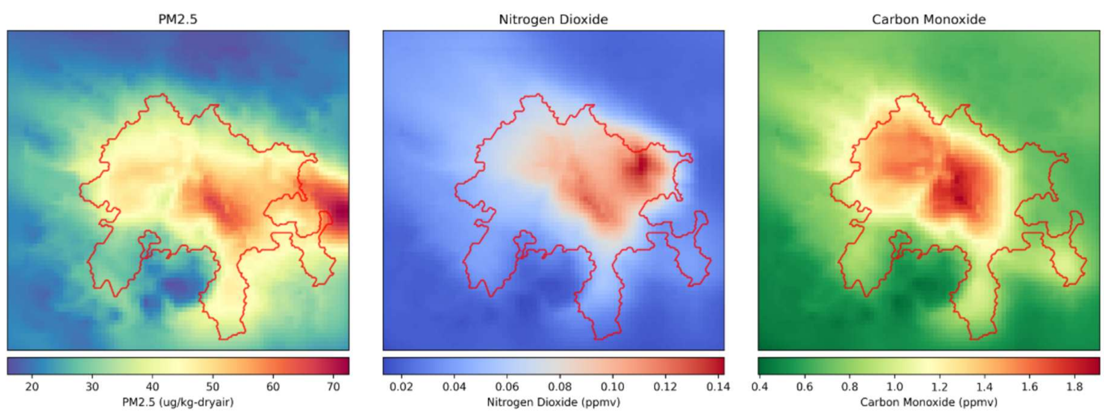

Figure 6: 24H mean concentration from all 6 sectors for d03 (Local Airshed)

(i) Carbon Monoxide:

Spatial distribution of carbon monoxide emission in different sectors for regional and local airshed is shown in Figure 7 and Figure 8. Figure 9 shows the contribution percentage of all the sectors for CO in regional airshed and Local Airshed.

In the Figure 7 The agriculture map indicates varying CO levels across agricultural areas of Pakistan, Punjab and Haryana the flow of high concentration CO can be clearly seen in the Indo-Gangetic Planes (IGP). Emissions likely result from activities such as crop burning, fertilizer use, and machinery. In the map of Energy, CO emissions are prominent in industrial zones and urban centers. Power plants, factories, and transportation contribute significantly. For Industrial sector, industrial areas exhibit high CO concentrations. Factories, manufacturing processes, and heavy machinery are key contributors. Delhi being the capital of Country have many type of industries in and around that's why high concentration of CO can be seen in Delhi Urban agglomeration. Very high values of CO can be seen for Residential areas, Punjab is showing the highest concentration for CO. Combustion of fossil fuels for heating and cooking are the main contributors in Punjab region. The transportation map shows high CO values in Urban centers and major roadways have elevated CO emissions.Vehicles (cars, trucks, buses) are the primary source. In waste sector not much contribution is seen negligible emissions are traced. Waste disposal sites exhibit localized CO emissions. Landfills and waste treatment facilities release CO.

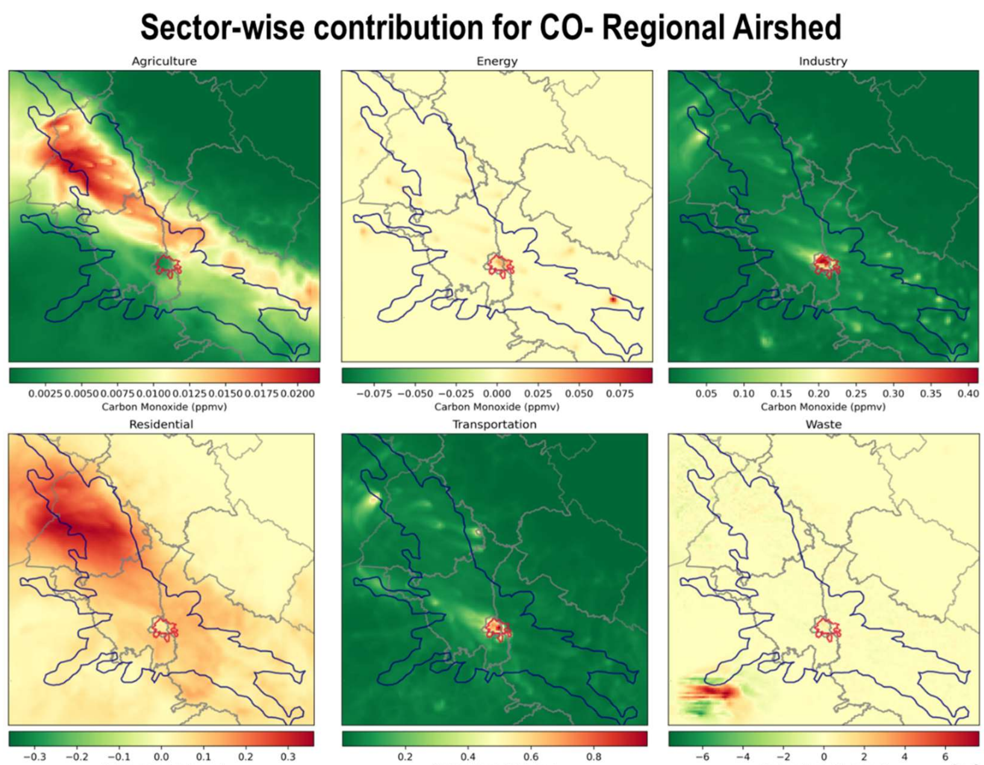

Figure 7: Spatial distribution of CO emission for different sectors in d02 (Regional Airshed)

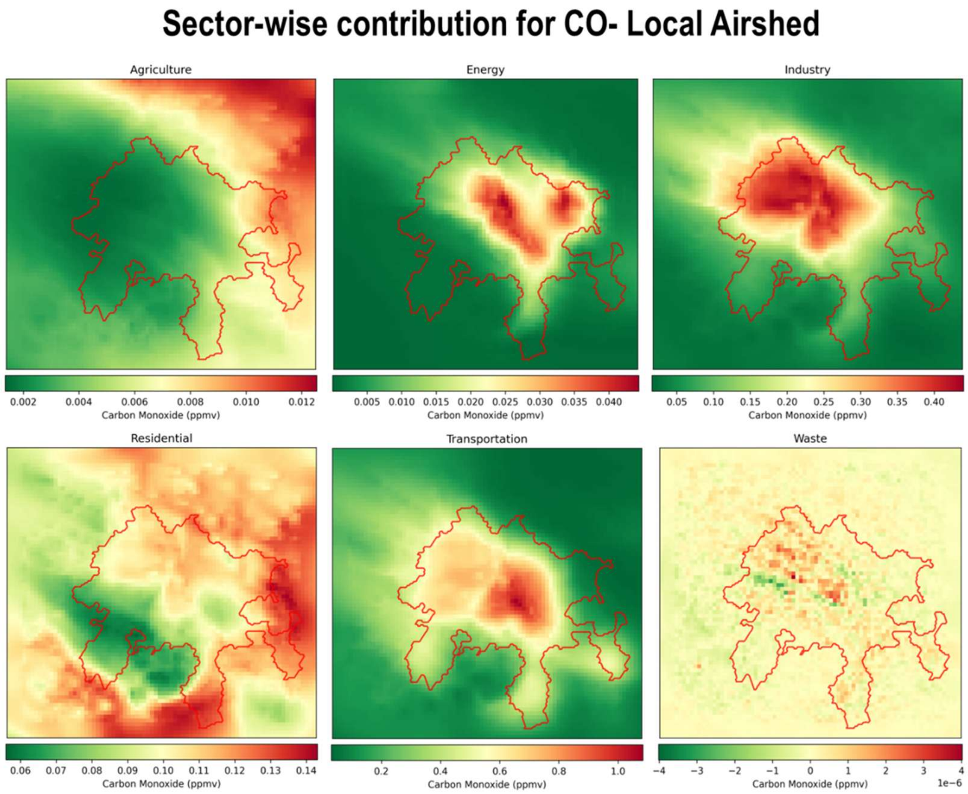

Figure 8: Spatial distribution of CO emission for different sectors in d03 (Local Airshed)

From Figure 9, Highest contributor for CO in Regional airshed is the residential sector with a contribution of 55.9% for 1 day (1 Nov 2022). Second largest contributor of CO is Transportation sector followed by Industry with 27% contribution. Effect of stubble burning in November can be clearly seen and there is a significant contribution of CO from agriculture sector which cannot be seen for other trace gases. Whereas in local airshed Maximum contribution for carbon monoxide is by transportation which contributes 54.2% and second contributing sector is Industry sector with 22.6% whereas Residential sector is the third largest contributing sector, contributing a total of 21.0%.

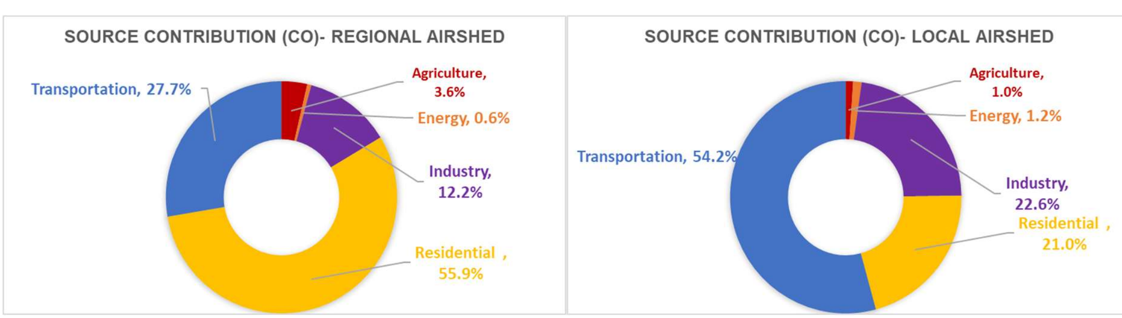

Figure 9: Source Contribution for CO

(ii) Nitrogen Dioxide:

Similar trends like CO can be seen for NO_2 in the agriculture sector in Figure 10. Stubble burning emissions can be seen in the Punjab and Haryana regions. Concentrated NO_2 emissions around specific points suggest fossil fuel combustion at power plants or industrial facilities for energy and industry sector. There is not much contribution of NO_2 from the residential sector, widespread, low-level NO_2 concentrations across regions are attributed to home heating and cooking activities. and Transportation sector is showing distinct patterns along roads or highways highlight vehicular emissions as the primary source. Figure 11 shows the spatial distribution in the local airshed.

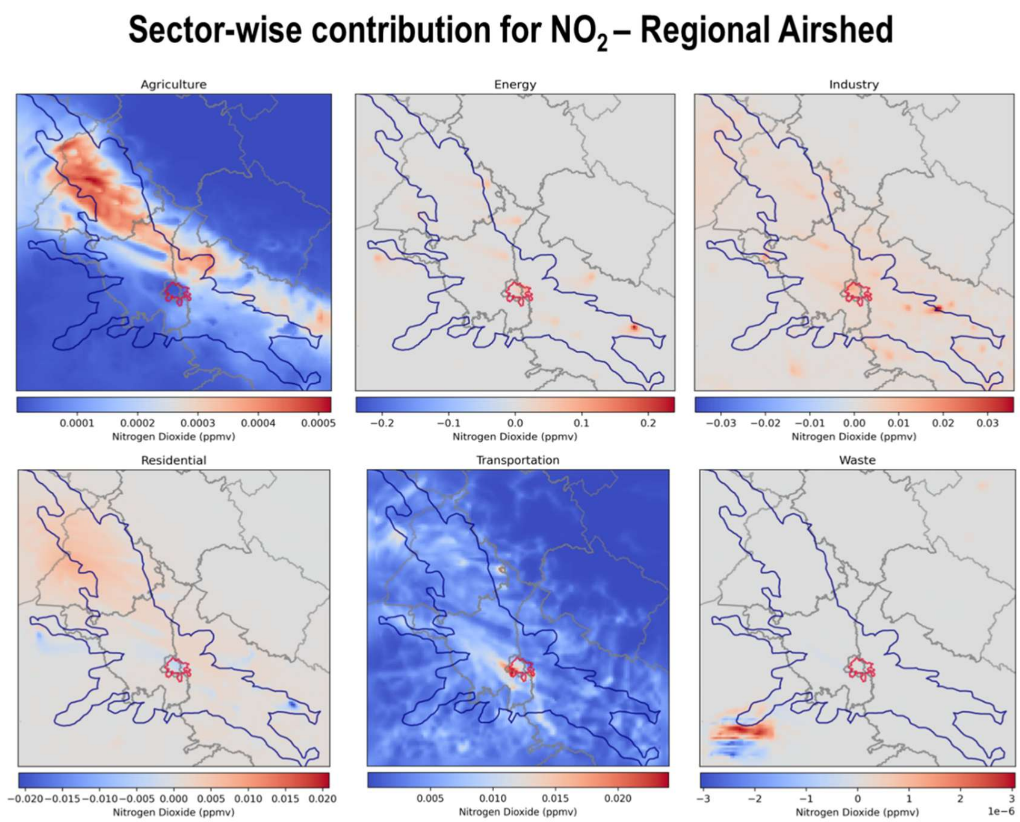

Figure 10: Spatial distribution of NO_2 emission for different sectors in d02 (Regional Airshed)

In Figure 12 for regional airshed the highest contribution at 39.04%, it's clear that vehicular emissions are a major source of NO_2. Close behind, the energy sector accounts for 27.15% of emissions, likely from fossil fuel combustion. Industry sectors contribute 21.28% indicating NO_2 emissions from industrial processes. Agriculture is a smaller contributor at 1.43%, but still significant in the context of NO_2 emissions from fertilizers and farming practices.

For local airshed energy sector is the major contributor followed by the transportation sector with 39.67% and 35.47%.

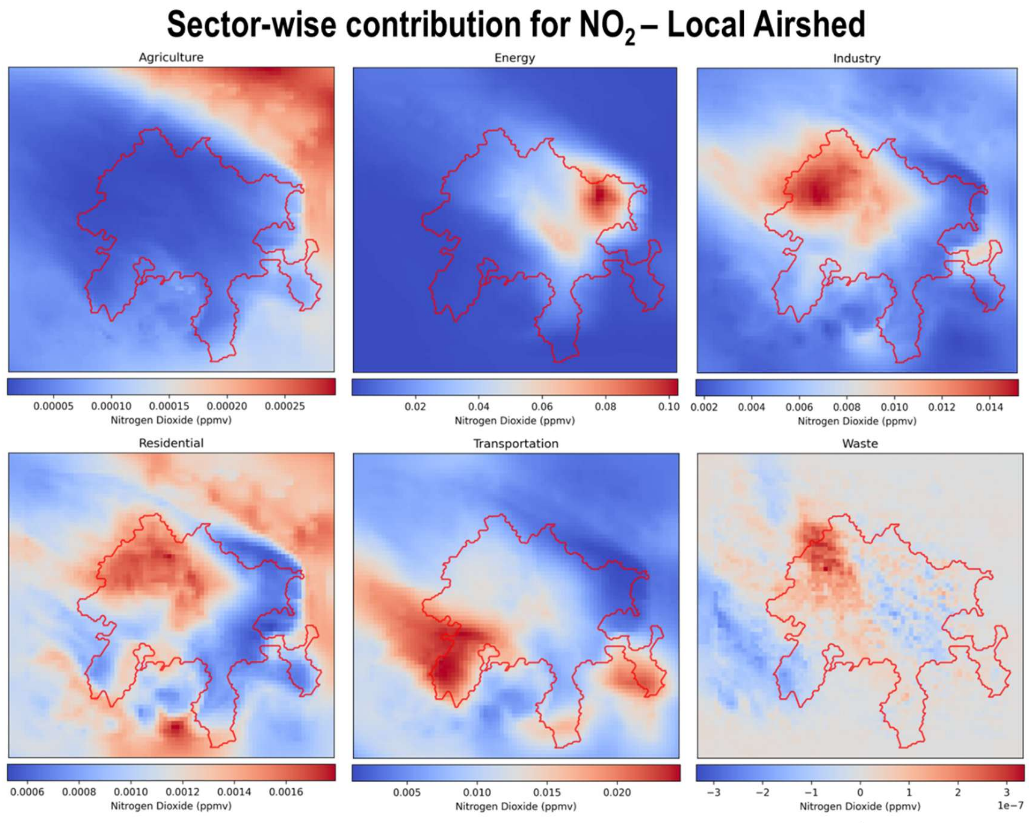

Figure 11: Spatial distribution of NO_2 emission for different sectors in d03 (Local Airshed)

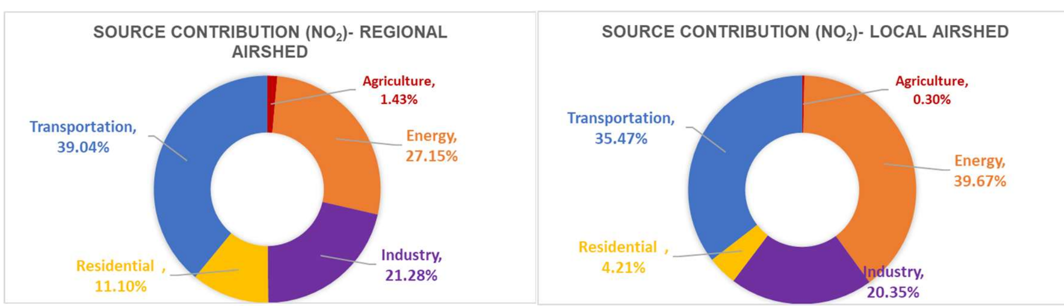

Figure 12: Source Contribution for NO_2

(ii) Particulate Matter 2.5:

Agriculture sector is also contributing towards the high concentration values of particulate matter in the regional airshed. For $PM_{2.5}$ it shows the maximum contribution of all the pollutants considered in the study. High values of $PM_{2.5}$ can be seen in Pakistan and Delhi Urban Agglomeration; some average values can be seen in Uttar Pradesh. Very high concentration can be seen in DUA for transportation sector, and some high values can be seen in Punjab and Haryana.

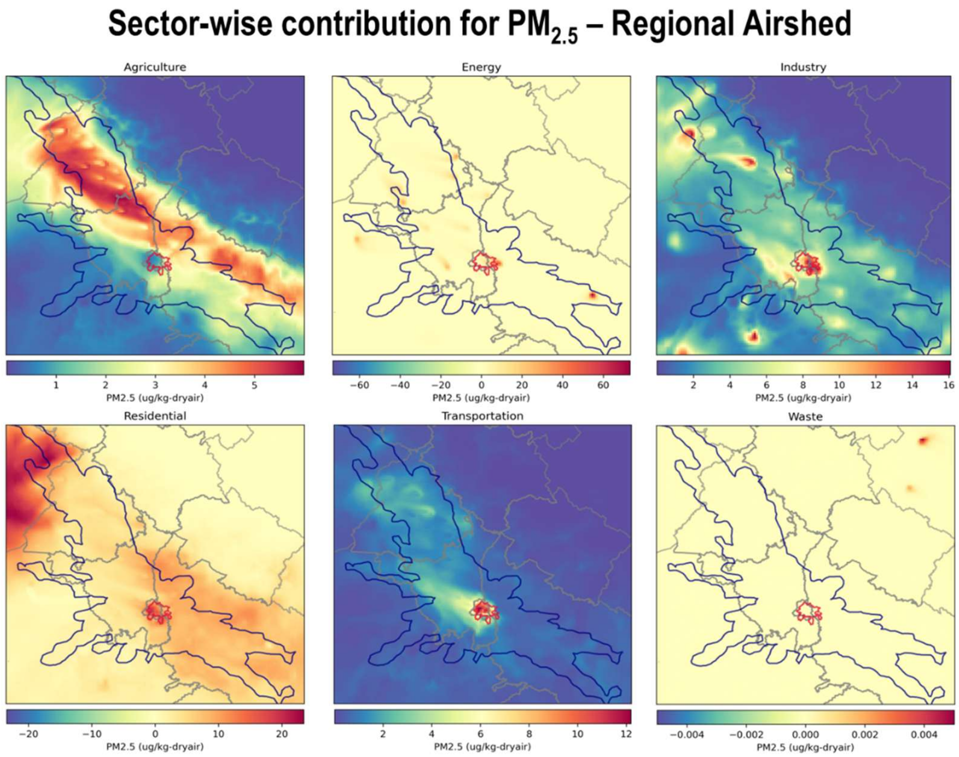

Figure 13: Spatial distribution of $PM_{2.5}$ emission for different sectors in d02 (Regional Airshed)

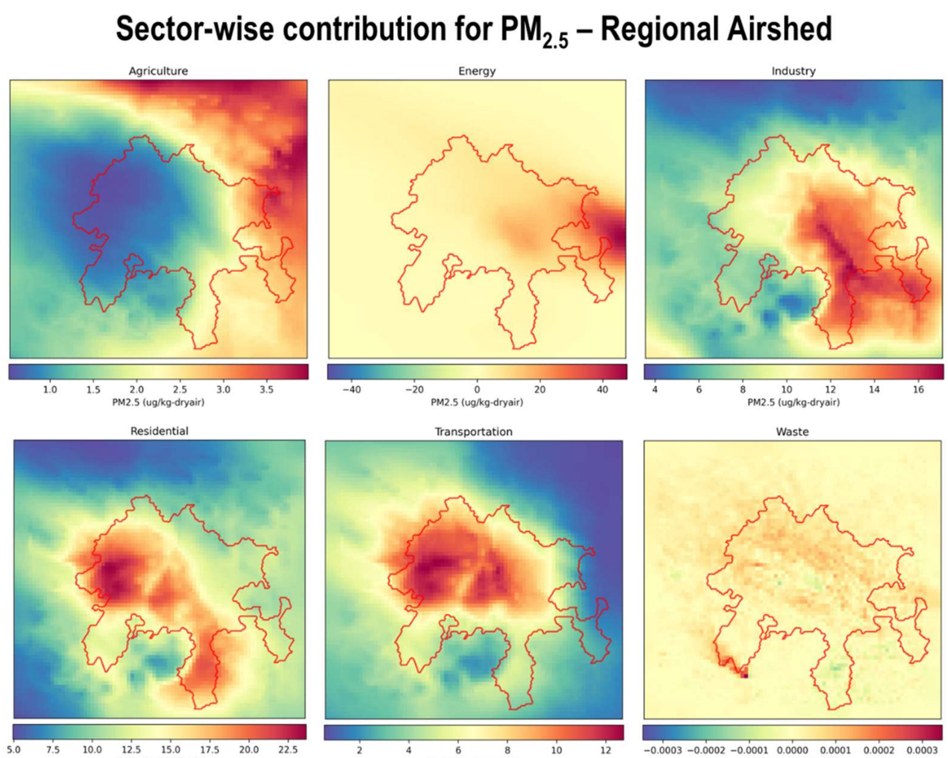

Figure 14: Spatial distribution of $PM_{2.5}$ emission for different sectors in d03 (Local Airshed)

Residential sector is the largest contributor at 41% in regional airshed, indicating significant emissions from household activities like cooking and heating. Industry accounts for 24.51% of $PM_{2.5}$ emissions, suggesting industrial processes are a major source. Agriculture contributes 18.01%, from practices such as burning crop residue. Transportation is at 8.64%, vehicle emissions are a notable source of these fine particulates. Energy sector contributes 7.85%, the energy sector's impact comes from power generation and other energy-related activities.

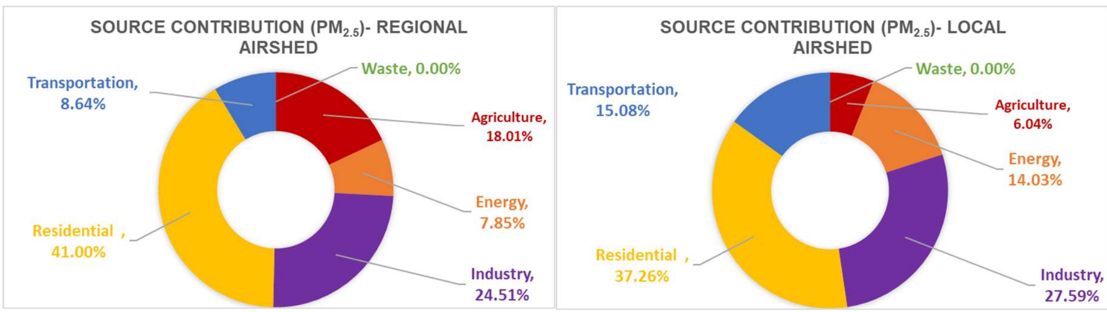

Figure 15: Source Contribution for $PM_{2.5}$

In the local airshed also the residential sector is the largest contributor at 37.26% followed by the industry sector, 27.59%.

Conclusion and Recommendation

This study highlights the critical influence of regional pollutant transport and diverse emission sectors on Delhi's air quality, demonstrating that a substantial portion of pollution originates beyond the city's administrative boundaries. The airshed-based approach combined with WRF-Chem and back trajectory analysis provides a comprehensive framework to quantify source contributions spatially and seasonally. Residential and transportation sectors emerge as dominant contributors within the local airshed, while agriculture-related stubble burning substantially impacts the regional airshed, especially during the pre-winter period. These findings emphasize the importance of adopting multi-scale air quality management strategies that extend beyond city limits to effectively mitigate pollution. To address the complex and transboundary nature of air pollution in Delhi, coordinated regional efforts are necessary. Policymakers should prioritize interventions targeting the most significant sectors identified, such as enhancing cleaner fuel adoption in residential areas and stricter vehicular emission controls. Seasonal measures to reduce agricultural residue burning through incentivized alternatives and enforcement can substantially improve air quality during critical periods. Additionally, investments in continuous air quality monitoring, public awareness campaigns, and cross-state collaboration will enhance pollution control outcomes. Integrating airshed-based modeling insights into policy can facilitate data-driven decisions for sustainable urban and regional air quality management.

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