

Study to survey ambient atmospheric SO₂ concentrations in different category of cities based on their vicinity to thermal power plants (TPPs)



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A report prepared by



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31 May 2024

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Executive Summary

To address environmental issues, the Ministry of Environment, Forest, and Climate Change (MoEF&CC) in India has mandated that TPPs install Flue Gas Desulfurization (FGD) units to control SO₂ emissions and improve air quality. These regulations, part of the “Environment (Protection) Amendment Rules 2015,” aim to reduce PM_{2.5}, SO_x, NO_x, and mercury emissions from TPPs.

In this context, the Central Electricity Authority (CEA), under the direction of the Ministry of Power (MoP), Government of India (GoI), signed an MOU with IIT Delhi to conduct a comprehensive survey of ambient air SO₂ concentrations across three categories of cities from February 2023 to February 2024: cities without coal-based TPPs (Category-1), cities with coal-based TPPs without FGDs (Category-2), and cities with coal-based TPPs with FGDs (Category-3). The survey, conducted by IIT Delhi in three phases, assessed SO₂ levels and the impact of TPPs on local air quality. Results indicated that all surveyed locations were within the National Ambient Air Quality Standards (NAAQS) of 80 µg/m³ based on 24 hours average measurements. Daily mean SO₂ concentrations ranged from 2.48 ± 0.49 µg/m³ to 9.26 ± 3.28 µg/m³ in Category-1 cities, 3.12 ± 0.81 µg/m³ to 6.48 ± 3.08 µg/m³ in Category-2 cities, and 4.24 ± 0.31 µg/m³ to 12.51 ± 2.82 µg/m³ in Category-3 cities. Even the maximum instantaneous ambient air SO₂ concentrations measured across the cities and phases of our survey never exceeded the daily mean permissible limit, confirming compliance with NAAQS.

Our study assessed the contribution of SO₂ emissions from coal-based thermal power plants to ambient SO₂ concentrations across different city categories. In Category-1 cities, the energy sector's contribution was relatively low, ranging from 11.44% to 16.53%, with New Delhi at 16.53% (1.36 µg/m³), Hyderabad at 11.57% (0.42 µg/m³), and Lucknow at 11.44% (0.66 µg/m³). In Category-2 cities, contributions were more significant, ranging from 27.99% (1.82 µg/m³) to 38.57% (1.99 µg/m³), with notable values in Kolkata, Nagpur, Kota, and Shahdol. Category-3 cities such as Ghaziabad, Khargone, and Gautam Buddha Nagar showed contributions between 17.37% (1.43 µg/m³) and 22.54% (2.17 µg/m³), exhibiting seasonal variations.

Our study reveals that the contribution of sulfate aerosols (SO₄) from SO₂ emissions of coal-based TPPs to ambient PM_{2.5} and PM₁₀ concentrations varies significantly across different city categories and seasons. Averaging across all cities and phases, contributions ranged from 0.96% (0.44 µg/m³) to 5.21% (3.30 µg/m³) for PM_{2.5} and from 0.57% (0.49 µg/m³) to 3.67% (3.60 µg/m³) for PM₁₀. The highest contributions were in Category-2 cities, averaging 3.83% (2.19 µg/m³) to PM_{2.5} and 2.87% (2.49 µg/m³) to PM₁₀. Category-3 cities showed intermediate contributions, averaging 2.45% (1.61 µg/m³) to PM_{2.5} and 1.97% (2.13 µg/m³) to PM₁₀, while Category-1 cities had the lowest, averaging 1.79% (0.93 µg/m³) to PM_{2.5} and 1.04% (1.07 µg/m³) to PM₁₀. Installing FGD systems with an 87.5% SO₂ removal efficiency in all coal-based TPPs across India

would reduce PM_{2.5} concentrations by up to 4.56% (2.89 µg/m³) and PM₁₀ concentrations by up to 3.21% (3.15 µg/m³) across all surveyed cities and seasons. These findings indicate that while TPP SO₂ emissions contribute to ambient PM levels, their impact is relatively minor. Implementing FGD systems in all TPPs would likely have an insignificant impact on lowering PM_{2.5} and PM₁₀ levels, resulting in only a marginal improvement (5%) in PM air quality. It should be noted that SO₂, a colourless gas, does not directly reduce visibility but contributes to haze formation after being converted into sulfate particles. Therefore, eliminating SO₂ emissions from TPPs is likely to result in a modest improvement in visibility and a reduction in haze formation.

Our study also explored the lifecycle of SO₂ in the atmosphere and the likelihood of acid rain in India. Once emitted, SO₂ undergoes oxidation, forming sulfuric acid or sulfate aerosols through gas-phase reactions with hydroxyl radicals and aqueous-phase reactions in cloud droplets with oxidants like hydrogen peroxide and ozone. However, in India, acid rain is mitigated by alkaline substances like ammonia (NH₃) from agricultural activities and carbonate minerals in dust, which neutralize sulfuric acid. Consequently, acid rain is not a significant issue in most parts of India except in the southern peninsular region where alkaline substances are less prevalent. However, the sea breeze naturally keeps ambient SO₂ levels lower in coastal areas of peninsular India. Additionally, the inherent alkalinity of seawater droplets, due to the presence of bicarbonate ions and carbonate ions, effectively neutralizes sulfuric acid in the atmosphere over coastal areas.

While FGD implementation will significantly reduce SO₂ emissions from TPPs, it is likely to have only a nominal impact on lowering ambient air PM_{2.5} and PM₁₀ levels, as SO₂ and sulfate aerosol concentrations in the surveyed cities are already low and within NAAQS. Further, there are no credible studies quantifying the overall life-cycle assessment (LCA) of costs and benefits of FGDs in the Indian context. Current FGD technologies will increase CO₂ emissions, water consumption, and secondary pollution due to the mining and transportation of limestone/gypsum. Each SO₂ molecule captured by FGDs releases a CO₂ molecule, and FGD operations also contribute to CO₂ emissions. Additionally, sulfate aerosols block solar radiation, partially offsetting CO₂-induced global warming. The impacts of reduced SO₂ and increased CO₂ emissions on India's regional climate, monsoon system, and extreme weather events are not well-studied. Our study estimates that installing FGD systems with 87.5% SO₂ removal efficiency in all coal-based TPPs across India would reduce annual SO₂ emissions by 4.88 MT per year, but this would result in an immediate increase of 14.4 MT per year in CO₂ emissions from mining, transportation, reagent operations, and increased auxiliary power consumption (APC). Additionally, considering the LCA of FGD implementation suggested by several previous studies, which accounts for both immediate and long-term environmental impacts, the reduction in SO₂ emissions could lead to an increase in annual equivalent CO₂ emissions by a few hundred MT of CO₂ per year and would consume an extra couple of hundred million liters of water annually. It is important to note that the exact additional CO₂ emissions beyond the immediate increases, as well as the additional water

consumption, can only be accurately determined through a comprehensive LCA of FGD implementation across all TPPs in India. It's worth noting that SO₂ and CO₂ have significantly different atmospheric lifetimes, which carries important implications for climate policy. SO₂ has a short atmospheric lifetime ranging from a few hours to about 15 days, while CO₂ persists for over 100 years. While SO₂ is a significant air pollutant and its emissions should be reduced, the trade-off between reducing SO₂ and increasing CO₂ emissions must be carefully considered. If reducing a relatively smaller amount of SO₂ emissions comes at the cost of a larger increase in CO₂ emissions, it raises serious concerns. This scenario necessitates a broader debate among stakeholders to ensure that efforts to improve air quality do not inadvertently strain water resources, exacerbate global warming, and impact the regional weather and climate of India.

India should heed the lessons from China's experience, as the idea that cleaning up air pollution can worsen atmospheric warming may seem counterintuitive but is a real and ongoing issue. Recently published research articles (Wang et al. 2024; Pearse, 2024) highlight how a dramatic reduction in Chinese air pollution, coinciding with the installation of FGD systems in coal-based TPPs, has been attributed to the recent extraordinary heating over the Northeast Pacific region, leading to more heat waves with global climate consequences.

Based on our survey conducted over two years ago, discussions with the CEA, and considering subsequent price escalations due to inflation, it is reasonable to assume that the current cost of FGD systems is approximately Rs. 1.20 Crore per MW. With a total installed capacity of 211,860 MW in coal-based TPPs across India as of May 31, 2023, the total cost of installing FGD systems would be approximately Rs. 254,232 Crore, excluding running and maintenance costs.

Finally, based on our findings that current ambient air SO₂ levels are within NAAQS and that eliminating SO₂ emissions from TPPs would only marginally improve PM air quality, the urgency of FGD installation must be reassessed. Our recommendations are as follows: Consider halting FGD installation in TPPs that have not yet begun and revisit this decision after taking the following steps. Conduct a follow-up study to comprehensively evaluate the LCA of implementing FGD technology in coal-based TPPs across India. This assessment should include various FGD technologies, operating and maintenance costs, and impacts on electricity prices. Initiating a broader stakeholder debate after this evaluation is crucial to weigh the investment in non-sustainable, CO₂-emitting sources against expanding renewable energy like solar and wind. Gradually phase out older and less efficient coal-based TPPs and transition to a sustainable energy future, ensuring the country's energy security. The installation of FGD systems and carbon capture technologies should not justify the continued use of CO₂-intensive sources. Instead, prioritize cleaner energy alternatives that offer long-term benefits and promote energy security, while developing strategies that address both air quality and climate goals.

CHAPTER-2: SURVEY OF AMBIENT ATMOSPHERIC SO₂ CONCENTRATIONS IN DIFFERENT CATEGORY OF CITIES: PHASE-I

2.1 Introduction

One of the basic information that must be considered while formulating any policy on SO₂ reduction for achieving clean air goals for cities is an assessment of current status of ambient air SO₂ concentrations in various cities across the country. It is only through such a survey, one can know the status of the air pollution levels with regards SO₂ in different category cities of the country and confirm if the air quality in these cities is meeting the National Ambient Air Quality Standards (NAAQS) for SO₂ set by the MoEF&CC, Govt. of India.

In this chapter, we discuss the results of a measurement-based baseline survey of ambient atmospheric SO₂ concentrations that has been conducted in different category of cities across India based on their vicinity to coal based thermal power plants (TPPs). Cities across the country are classified into three categories based on their vicinity to coal based thermal power plants (TPPs) and the status of FGD installation in these TPPs. These categories are:

Category-1: Cities with no coal based TPP.

Category-2: Cities with a coal based TPP in which FGD has not been installed and the TPP is located within 10km from the boundary of the city.

Category-3: Cities with a coal based TPP in which FGD has been installed and the TPP is located within a distance of 10km from the boundary of the city.

This measurement-based survey of ambient air SO₂ concentrations in different category cities has been conducted in three phases. First phase of the survey started on 12th February 2023 and continued up to 29th May 2023, while the second phase of the survey started on 15th July 2023 and ended on 14th August 2023. Third phase of the survey started on 8th November 2023 and ended on 21st February 2024.

2.1 Cities and Measurement Sites Selected for Phase-I of the Survey

In the first phase of this survey, measurements have been conducted in six different cities (two cities under each category) across India namely, New Delhi (Category-1), Hyderabad (Category-1), Kolkata (Category-2), Nagpur (Category-2), Ghaziabad (Category-3), and Gautam Buddha Nagar (Category-3). In order to capture the spatial variability in ambient air SO₂ concentrations within each city, survey was conducted at two different locations in all six cities for one month period each. Measurements were conducted at more than one location in each city so that the results of our survey are able capture the variation in ambient air SO₂ concentrations within the city in a better way and hence it can be considered as the representative of that city. Conducting

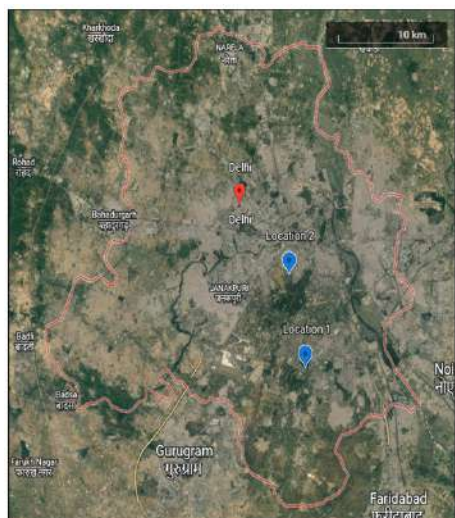
the survey at two different locations also helped us know if there exists a gradient in SO₂ concentrations with distance from the TPP for Category-2 and Category-3 cities. The present survey also allows us to confirm if the ambient air SO₂ concentrations in these cities are meeting the NAAQS set by the MoEF&CC. Additionally, we wanted to examine the effectiveness of the FGDs in limiting the ambient air SO₂ concentrations in Category-3 cities which are located in the vicinity of TPPs with FGD system installed in them.

It is worth mentioning here that all cities chosen for our baseline survey fall under the category of “non-attainment cities with million plus population” as per the Central Pollution Control Board (CPCB) classification. In all six cities, we carried out our survey by conducting measurements at two different locations for one month period at each measurement site. For cities which have TPPs in their vicinity, we have conducted this survey of ambient air SO₂ concentrations in such a way that one of the measurement site is close to the TPP (at a distance of about 1-10 km from the TPP) while the second measurement site is at a distance of about 40-60 km from the location of the TPP.

During the first phase of the survey, following measurement sites were identified in the selected six cities across India (two cities under each category).

Category-1 Cities

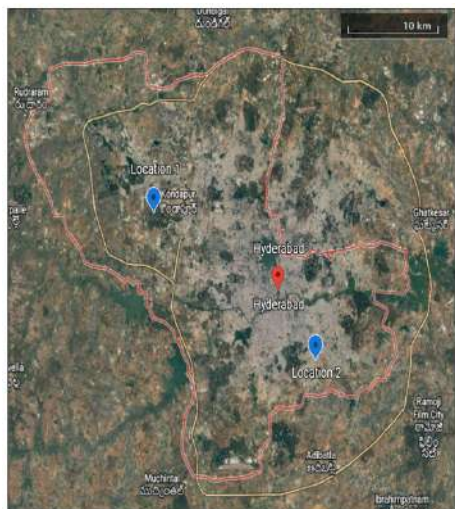
Delhi:



Location 1	Indian Institute of Technology Delhi Hauz Khas, New Delhi, Delhi – 110016, India.
Location 2	CSIR-National Physical Laboratory Dr. K.S. Krishnan Marg, New Delhi – 110012, India.

Figure 2.1: Satellite image (google earth) showing location of the measurement sites for Category-1 city Delhi considered during Phase-I of the survey

Hyderabad:

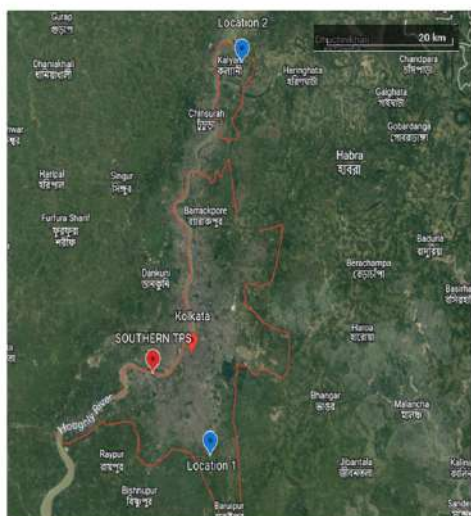


Location 1	University of Hyderabad, India Post Lingampally CR Rao Road, Hyderabad Central University Rd, Gachibowli, Hyderabad, Telangana 500046, India.
Location 2	TKR College of Engineering & Technology, Survey No.8/A, Medbowli, Meerpet, Hyderabad – 500097, India.

Figure 2.2: Satellite image (google earth) showing location of the measurement sites for Category-1 city Hyderabad considered during Phase-I of the survey

Category-2 Cities

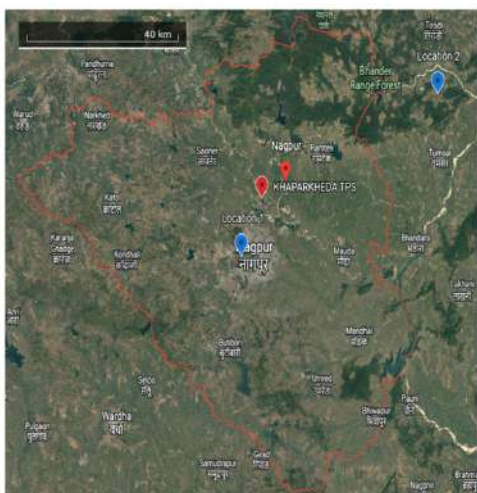
Kolkata:



SOUTHERN TPS	Garden Reach, Kolkata – 700024, WB, India. Operated by the CESC Limited.
Location 1	Ramakrishna Mission Vidyalaya, Narendrapur, Kolkata – 700103, WB, India.
Location 2	University of Kalyani, Block C, Nadia, Kalyani, West Bengal- 741245, India.

Figure 2.3: Satellite image (google earth) showing location of the measurement sites for Category-2 city Kolkata considered during Phase-I of the survey

Nagpur:

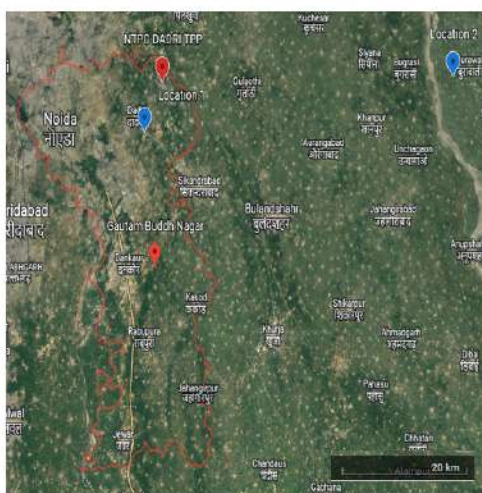


KHAPARKHEDA TPS	Khaperkheda Town, Nagpur district. Operated by the Maharashtra State Power Generation Company Limited.
Location 1	Rashtrasant Tukadoji Maharaj Nagpur University, Chhatrapati Shivaji Maharaj Administrative Premises, Ravindranath Tagore Marg, Nagpur – 440001, MH, India.
Location 2	Vivekanand Polytechnic, SitaSaongi Post – Sitasongi, Tal – Tumsar, District – Bhandara, Maharashtra – 441907, India.

Figure 2.4: Satellite image (google earth) showing location of the measurement sites for Category-2 city Nagpur considered during Phase-I of the survey

Category-3 Cities

Gautam Buddha Nagar:



NTPC DADRI TPP	Gautam Budh Nagar, Ghaziabad, UP – 201008, India. Operated by the NTPC.
Location 1	Shiv Nadar University, NH - 91, Tehsil Dadri, Gautam Buddha Nagar, UP - 201314, India.
Location 2	Government Polytechnic, Vill. Sutawali, Rehra Road, Amroha UP - 244255, India.

Figure 2.5: Satellite image (google earth) showing location of the measurement sites for Category-3 city Gautam Buddha Nagar (GBN) considered during Phase-I of the survey

Ghaziabad:

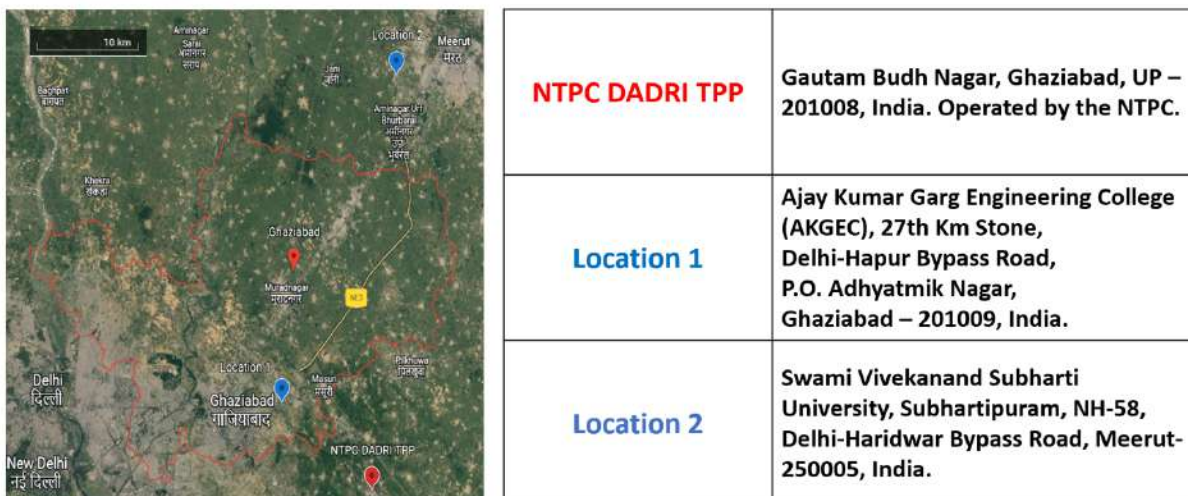


Figure 2.6: Satellite image (google earth) showing location of the measurement sites for Category-3 city Ghaziabad considered during Phase-I of the survey

2.3 Measurement Plan for Phase-I of the Survey

In the first phase of this survey, our aim was to make simultaneous measurements of ambient air SO₂ concentrations in all six cities (at least at one location in each city) so as to avoid any seasonal bias in the results of our survey from different cities that can be caused due to seasonal variations in general meteorological conditions prevailing across the country which influence the large scale transport and removal of SO₂ as well all air pollutants and hence the lifetime of SO₂ in the atmosphere. We made continuous measurements of ambient air SO₂ concentrations averaged after every 10-minute intervals (or more frequently) for at least 30 days during the survey period at each measurement site in all six cities. In every city, first the continuous measurements were made for one month period at the first measurement site and then the measurements were made for another month at the second measurement site in the same city. If we wish to compare the results of the survey from different cities, then it is important to make simultaneous measurements in all cities during the same month or season so that the result from each city qualifies as the representative values of ambient air SO₂ concentrations from that city corresponding to the chosen month or season. This avoids any kind of possible bias in the results of the survey due to seasonal variability in meteorological parameters which are known to influence the transport and removal of SO₂ from the atmosphere and hence its concentrations. That means, the results of our survey on ambient air SO₂ concentrations are based on at least 4320 air samples from each measurement location and a total of at least 8640 air samples for each city. In the first phase, ambient air SO₂ concentrations from six different cities have been surveyed. First phase of the survey started on 12th February 2023 and continued up to 29th May 2023.

2.4 Measurement Technique and Equipment used in the Survey

We used pulsed fluorescence technology based SO₂ gas analyzers having a pulsing source lamp in the ultraviolet (UV) wavelength of 214 nm to make continuous measurement of ambient air SO₂ concentrations in all selected measurement sites. All SO₂ gas analyzers used in this study were calibrated on-site on every 24 hours basis. Daily calibration and regular maintenance of the SO₂ gas analyzer systems is crucial for making reliable measurements using these sophisticated equipment. Two different types of calibration were performed to ensure the reliability of the measurement data (i) Span gas calibration involving measurement of a known standard concentration of gas kept in a cylinder and (ii) Zero air calibration involving measurement of a zero-air gas with no SO₂ kept in another cylinder. The entire measurement system involving a SO₂ gas analyzer, a calibrator analyzer both mounted in a rack, span gas cylinder, zero-air cylinder, a data acquisition system for saving the data and display in a monitor, power backup system was housed in a standalone portable air-conditioned hut in every measurement site. In all our survey sites, measurements of ambient air SO₂ concentrations has been made by keeping our equipment on the rooftop of a three-story building or inside a room on the 3rd floor of a building. Inlet height in all our measurement sites was fixed at about 20 meters above the ground level.



Figure 2.7: Left-side image is showing one of our standalone air-conditioned portable hut with SO₂ gas analyzer kept on the rooftop of a three-story building at one of the measurement site and the right-side image is of the same system kept inside a room in another measurement site.

Figure 2.7 shows the images of the Standalone air-conditioned portable hut with SO₂ gas analyzer and all necessary accessories for ambient air monitoring, data acquisition and storage, on-site calibration of SO₂ gas analyzers, power backup system used in our survey.

2.5 Results from Phase-I of the Survey

This section presents the results of measurements conducted in various category cities across the country during Phase I of our survey. Table 2.1 summarizes the daily mean, maximum instantaneous, and minimum instantaneous values of ambient air SO₂ concentrations measured

at two different locations in six cities, classified into three categories, during the pre-monsoon season. In the Category 1 city of New Delhi, the maximum instantaneous ambient air SO₂ concentration was 29.37 µg/m³, the minimum was 0.83 µg/m³, and the daily mean values ranged from 7.22 ± 2.73 µg/m³ to 9.26 ± 3.28 µg/m³. In Hyderabad, the maximum concentration was 7.86 µg/m³, the minimum was 1.01 µg/m³, and the daily mean values ranged from 2.48 ± 0.49 µg/m³ to 4.65 ± 0.55 µg/m³. In the Category 2 city of Kolkata, the maximum instantaneous concentration was 32.25 µg/m³, the minimum was 1.29 µg/m³, and the daily mean values ranged from 4.32 ± 1.51 µg/m³ to 6.48 ± 3.08 µg/m³. In Nagpur, the maximum ambient air SO₂ concentration was 20.54 µg/m³, the minimum was 1.13 µg/m³, and the daily mean values ranged from 3.55 ± 0.53 µg/m³ to 6.07 ± 2.83 µg/m³. In the Category 3 city of Ghaziabad, the maximum instantaneous concentration was 33.51 µg/m³, the minimum was 2.62 µg/m³, and the daily mean values ranged from 7.87 ± 1.89 µg/m³ to 8.51 ± 2.56 µg/m³. In Gautam Buddha Nagar, the maximum ambient air SO₂ concentration was 33.34 µg/m³, the minimum was 2.71 µg/m³, and the daily mean values ranged from 8.31 ± 2.03 µg/m³ to 9.86 ± 2.12 µg/m³.

Summarizing by city categories, Category 1 cities had maximum instantaneous ambient air SO₂ concentrations of up to 29.37 µg/m³ and minimum concentrations down to 0.83 µg/m³, with daily mean values ranging from 2.48 to 9.26 µg/m³. Category 2 cities had maximum concentrations of up to 32.25 µg/m³ and minimum concentrations down to 1.13 µg/m³, with daily mean values ranging from 3.55 to 6.48 µg/m³. Category 3 cities had maximum concentrations of up to 33.51 µg/m³ and minimum concentrations down to 2.62 µg/m³, with daily mean values ranging from 7.87 to 9.86 µg/m³. These results highlight the variability in ambient air SO₂ concentrations across different locations and city categories, with Category 2 and Category 3 cities both showing higher SO₂ levels. As the National Ambient Air Quality Standards (NAAQS) or the maximum permissible limit of ambient air SO₂ concentrations based on 24 hours average measurements for industrial, residential, rural, and other areas as notified by the MoEF&CC, Govt. of India is 80 µg/m³, results of our survey confirm that the ambient air SO₂ concentrations in all cities are meeting the existing standards during the period of our survey.

As evident from Table 2.1, the daily mean values of ambient air SO₂ concentrations measured at various locations in all six cities during Phase I of our survey are comparable to the SO₂ data from the CPCB/SPCB/PCC measurement sites in those cities (<https://cpcb.nic.in/air-pollution/>), thereby validating the robustness of our collected data.

Next, we discuss the findings of our survey from Category-1 cities with no coal based TPP with more details. These two cities are Delhi and Hyderabad. For the city of Delhi, our survey of ambient air SO₂ concentrations started in Location-1 on 12th February and continued up to 14th March 2023. While the survey in the second location of Delhi or Location-2 was conducted during the period 23rd March to 22nd April 2023.

	Name of City (Measurement Site, distance from TPP)	Data Analysis Duration	This Study SO ₂ Concentration (µg m ⁻³)			CPCB/SPCB measurements (µgm ⁻³)
			Maximum (Instantaneous)	Minimum (Instantaneous)	Daily Mean ± 1σ (NAAQS = 80 µg m ⁻³)	
Category-1	New Delhi Location-1	12-02-2023 to 14-03-2023	29.37	1.9	9.26 ± 3.28	10.65 ± 1.26
	New Delhi Location-2	23-03-2023 to 22-04-2023	23.28	0.83	7.22 ± 2.73	
	Hyderabad Location-1	23-03-2023 to 22-04-2023	7.86	2.72	4.65 ± 0.55	2.91 ± 0.82
	Hyderabad Location-2	29-04-2023 to 29-05-2023	4.81	1.01	2.48 ± 0.49	
Category-2	Kolkata Location-1 15 Km from SOUTHERN TPS	12-02-2023 to 14-03-2023 (One month)	32.25	1.29	6.48 ± 3.08	6.95 ± 3.19
	Kolkata Location-2 51 Km from SOUTHERN TPS	23-03-2023 to 22-04-2023 (One month)	21.41	1.37	4.32 ± 1.51	
	Nagpur Location-1 15 Km from KHAPARKHEDA TPS	23-03-2023 to 22-04-2023 (One month)	20.54	1.21	6.07 ± 2.83	6.31 ± 1.08
	Nagpur Location-2 57 Km from KHAPARKHEDA TPS	29-04-2023 to 29-05-2023 (One month)	9.46	1.13	3.55 ± 0.53	
Category-3	Ghaziabad Location-1 13 Km from DADRI TPP	23-03-2023 to 22-04-2023 (One month)	33.51	2.92	8.51 ± 2.56	6.25 ± 2.16
	Ghaziabad Location-2 42 Km from DADRI TPP	29-04-2023 to 29-05-2023 (One month)	18.66	2.62	7.87 ± 1.89	
	Gautam Buddha Nagar Location-1 10 Km from DADRI TPP	23-03-2023 to 22-04-2023 (One month)	33.34	4.60	9.86 ± 2.12	10.97 ± 1.69
	Gautam Buddha Nagar Location-2 53 Km from DADRI TPP	29-04-2023 to 29-05-2023 (One month)	17.54	2.71	8.31 ± 2.03	

Table 2.1: Daily mean, maximum, and minimum values of ambient air SO₂ concentration (µg/m³) measured at two different locations of six different cities classified under three different categories from across the country during Phase-I of our survey are listed here. SO₂ concentrations data from CPCB/SPCB measurements sites from each city are also mentioned.

Figure 2.8 shows the time series of daily mean ambient air SO₂ concentration (µg/m³) measured on different days of our survey at two different measurement sites in Delhi. Figure 2.9 shows the diurnal variation of ambient air SO₂ concentration (µg/m³) measured on different days of our survey at two different measurement sites in Delhi. Figures 2.8 and 2.9 illustrate significant diurnal variations as well as notable intra-day fluctuations in ambient air SO₂ concentrations at both of these measurement locations in Delhi. Table 2.1 lists the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentration (µg/m³) measured at two different locations of all six cities from across the country that were selected during Phase-I of our survey. Maximum instantaneous values of ambient air SO₂ concentrations measured at location-1 and location-2 of Delhi during phase-I of our survey are 29.37 µg/m³ and 23.28 µg/m³ respectively. While the minimum instantaneous values of ambient air SO₂ concentrations measured at location-1 and location-2 of Delhi during phase-I of our survey are 1.90 µg/m³ and 0.83 µg/m³ respectively. Monthly average daily mean values of ambient air SO₂ concentrations measured at location-1 and location-2 of Delhi during phase-I of our survey are 9.26±3.28 µg/m³ and 7.22±2.73 µg/m³ respectively. As the National Ambient Air Quality Standards (NAAQS) or the maximum permissible limit of ambient air SO₂ concentrations based on 24 hours average measurements for industrial, residential, rural, and other areas as notified by the MoEF&CC, Govt. of India is 80 µg/m³, results of our survey confirm that the ambient air SO₂ concentrations in Delhi are meeting the existing standards during the period of our survey.

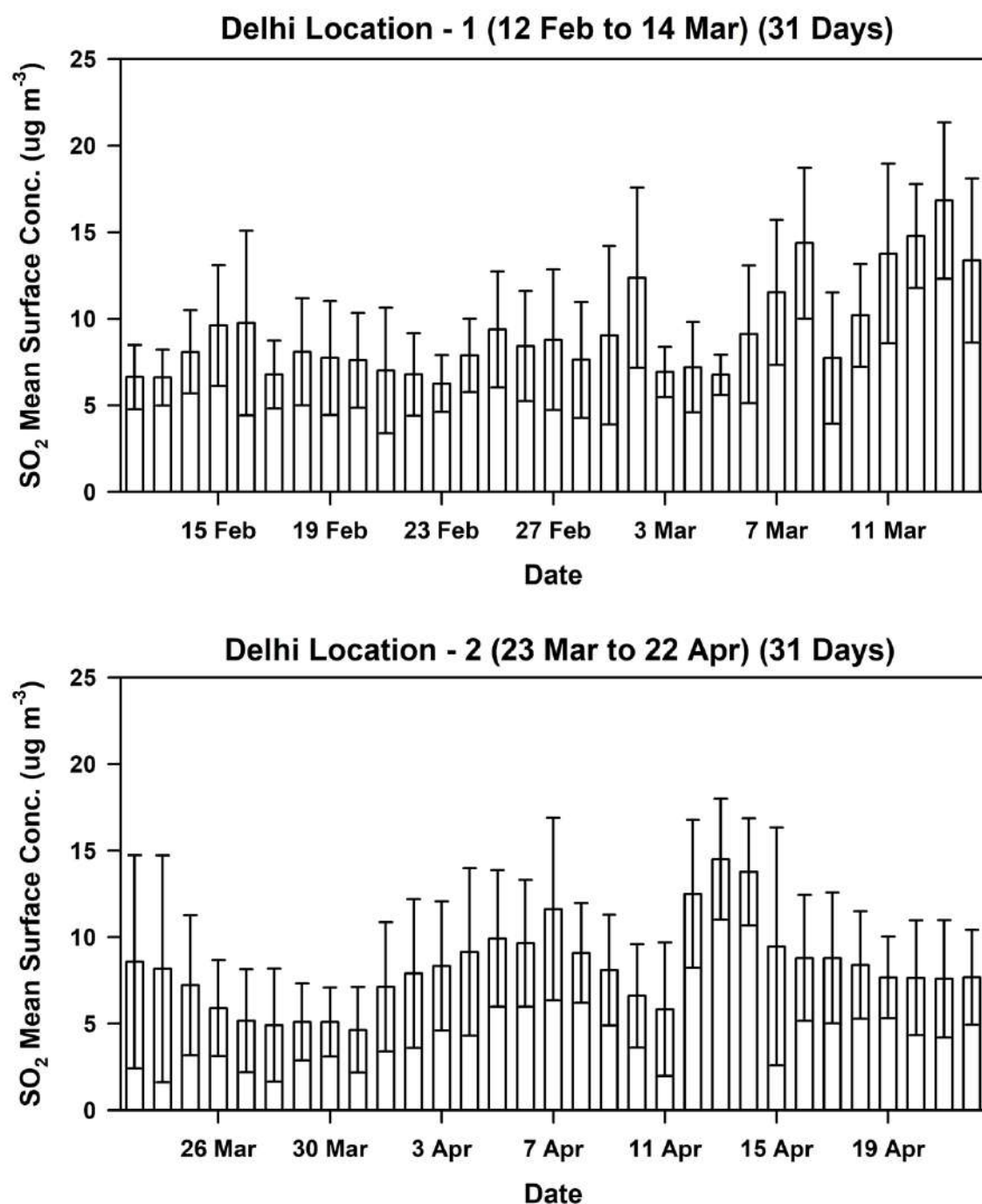


Figure 2.8: Time series of daily mean ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (12th February – 14th March 2023) as measured in Location-1 of Delhi (upper panel) and for the period 23rd March – 22nd April 2023 in Location-2 of Delhi (lower panel). Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

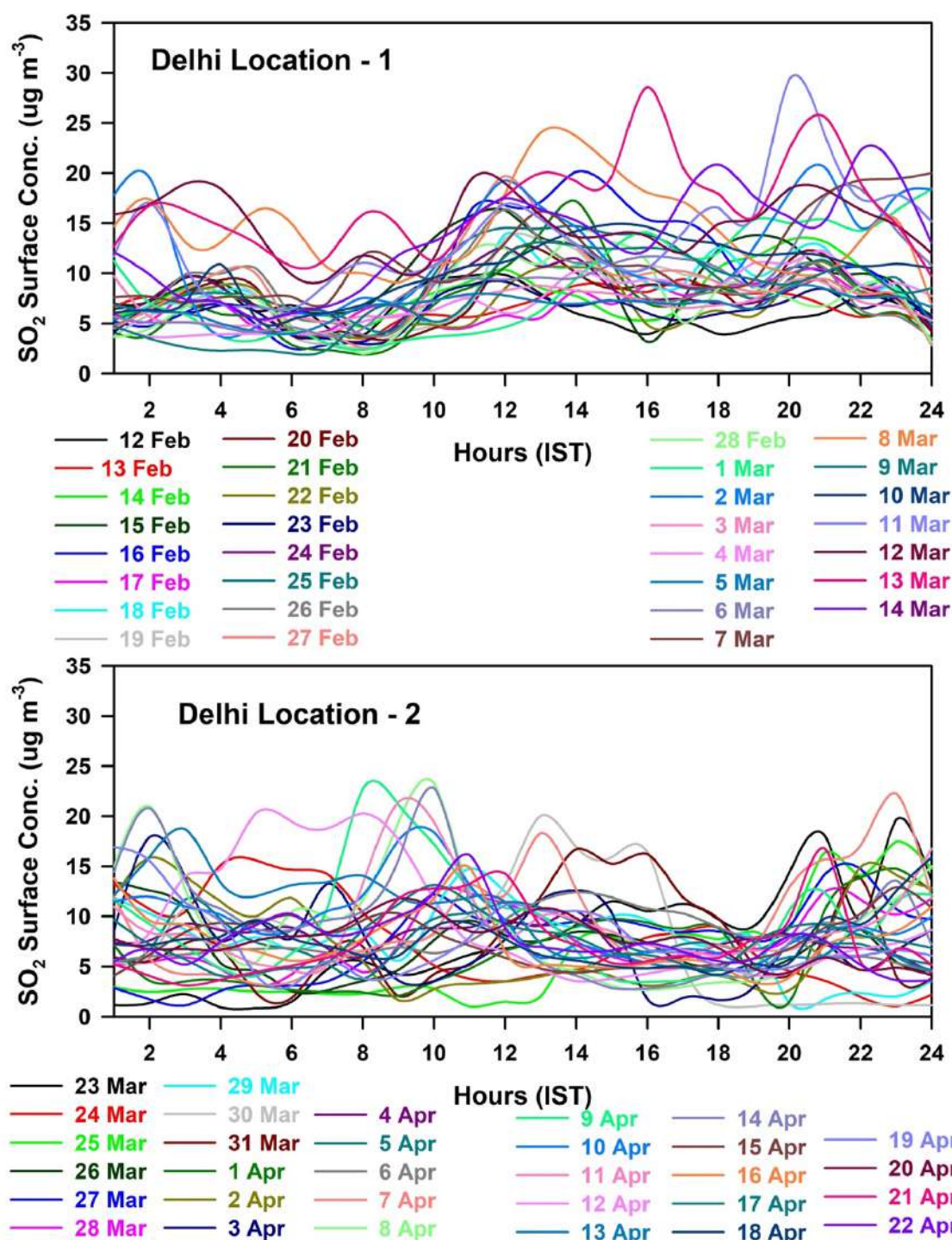


Figure 2.9: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (12th February – 14th March 2023) as measured in Location-1 of Delhi (upper panel) and for the period 23rd March – 22nd April 2023 in Location-2 of Delhi (lower panel).

Diurnal variations in ambient air SO₂ concentrations are influenced by a combination of factors, including fluctuations in SO₂ emissions from different sources, variations in atmospheric boundary (or mixed) layer height throughout the day, changes in wind patterns or air circulation,

and other meteorological conditions. Additionally, elevated levels of SO_2 aloft (above the boundary layer in the free troposphere), resulting from regional-scale air pollution, can also impact ambient air SO_2 concentrations. This occurs through the downward mixing of constituents from the elevated layer with the surface layer during the boundary layer's evolution after sunrise in the morning hours. In general, potential sources of SO_2 over any location include emissions from energy sector, transportation sector (burning of fossil fuel), industries (such as petroleum refineries, cement manufacturing, paper pulp manufacturing, iron and steel, and metal smelting, processing facilities, brick kilns, etc.), residential sector (involving burning of fossil fuel or biomass for various purposes including usage of diesel/petrol generators), agricultural waste burning, solid waste treatment etc. SO_2 is also used in bleaching materials, as a fumigant, preserving dry fruits to prevent discoloration. In the residential sector SO_2 gas can be emitted from tobacco smoke, improperly or inadequately vented solid/gas fuel appliances (such as biomass or fossil fuel-based cooking stoves, furnaces, heaters), as well as kerosene or wood or coal stoves or burning of these things for any other household purposes. It is also worth mentioning here that in nature, volcanic eruptions also release SO_2 into the air. The presence of multiple peaks in the diurnal patterns of ambient air SO_2 concentrations at various times of the day, including evening and nighttime, on different days throughout our measurement period at both sites in Delhi suggests a strong influence of local sources within approximately 60 km of the measurement site. This inference is supported by numerous previous studies using dispersion models and chemical transport models. These studies have shown that the influence of a single fixed-point SO_2 emission source, such as a thermal power plant with a capacity of up to 2000 MW, under moderate wind speed conditions of up to 5 m/s (or 18 km/h), on ambient air SO_2 concentrations beyond about 120 km from the source is generally minimal (*Fioletov et al.* 2015). Beyond this distance, the emissions from the fixed-point source become part of the regional background concentration, typically decreasing by about two orders of magnitude compared to the highest concentrations observed near the source.

Figure 2.10 shows the monthly mean pattern of diurnal variation of ambient air concentration of SO_2 observed at both measurement sites in Delhi during Phase-I of our survey. One of the unique features noticeable in the monthly mean diurnal pattern from both measurement sites is the gradual increase in ambient air concentrations during daytime after sunrise till 10AM or up to local noon. Thereafter the monthly mean diurnal patterns of SO_2 generally show a decreasing trend up to about 7 PM in the evening (although we noticed random spikes in SO_2 at different times and lasting for couple of hours on different days). We also noted a second peak in ambient air SO_2 concentrations in both measurement locations at around 9-10 PM in the late evening. While SO_2 concentrations in location-1 generally decreased gradually after this late evening peak to reach minimum values just before the sunrise but, in location-2, the monthly values remained high during late night up to 2-3 AM, probably due to some local activities contributing to spikes in SO_2 concentrations during such late-night hours on several days of our survey period.

Nevertheless, higher values of ambient air SO₂ concentrations were generally observed during the daytime and relatively lower values were noted during nighttime during our survey period.

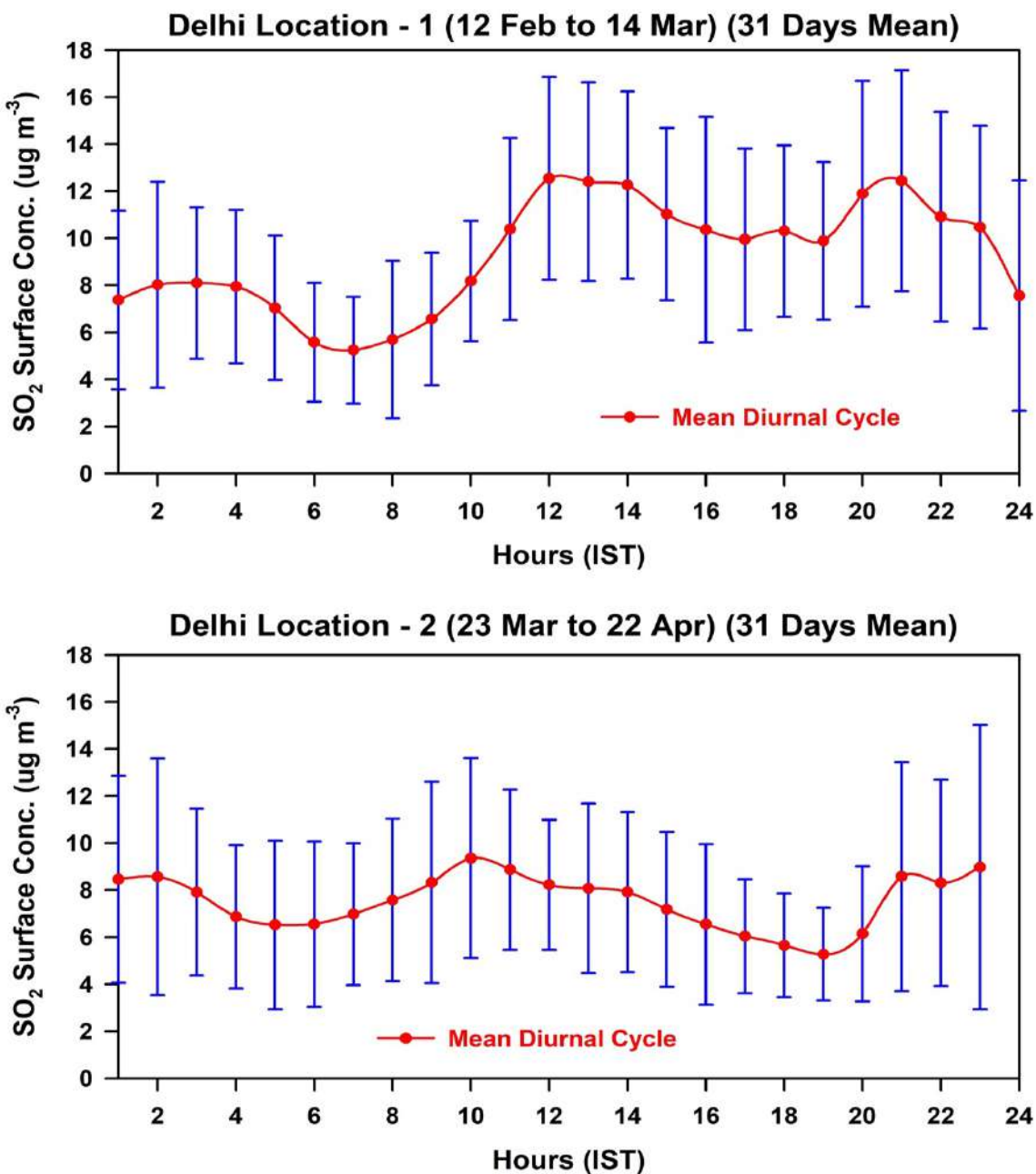


Figure 2.10: Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) for Location-1 (upper panel) and Location-2 (lower panel) of Delhi. Vertical lines in this figure represents the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

If the SO₂ concentrations at any location were influenced solely by sources with constant emission rates or those with minimal diurnal variations in emission rates (such as TPPs), then the

diurnal pattern of ambient air SO₂ concentrations would largely be governed by the vertical movement of the atmospheric boundary layer. This would result in higher SO₂ concentrations at night due to the shallow boundary layer and lower concentrations during the day due to the increased boundary layer height, better ventilation, and the presence of higher OH radical levels in the atmosphere, which oxidize SO₂ to form sulfate aerosols.

During our survey period, we observed that the diurnal variations of ambient air SO₂ concentrations in Delhi increased after sunrise, gradually reaching their peak either during or shortly after peak traffic hours. This morning rise in SO₂ concentrations, despite the increasing boundary layer height during the same period, indicates a significant contribution from local sources during the forenoon. Additionally, the higher SO₂ concentrations during the daytime, particularly the increasing trend in the forenoon, could also be attributed to the downward mixing of SO₂-rich air from an elevated layer into the surface layer as the boundary layer height evolves after sunrise. This elevated layer of SO₂-rich air likely results from regional-scale pollution or haze caused by emissions from various sectors such as industrial, energy, transportation, agriculture, and residential activities over densely populated and industrial areas like the Indo-Gangetic belt.

Gradual decrease in SO₂ concentrations after the daytime maxima is likely due to increased boundary layer height, higher ventilation during afternoon hours, and presence of higher OH radical in the atmosphere during this time which efficiently oxidizes SO₂ to sulfate aerosols. It is worth mentioning here that the heterogeneous aqueous-phase oxidation of SO₂ plays a more significant role than its gas-phase oxidation with OH. Although there are several pathways for the aqueous-phase oxidation of SO₂, the two most crucial involve its reactions with dissolved O₃ and H₂O₂. In fact, for SO₂, the reaction with H₂O₂ is its most significant oxidation pathway. This heterogeneous oxidation of SO₂ occurs through its dissolution in water from clouds and fog, followed by reactions with other dissolved species, and can take place both day and night. The oxidation via the dissolved H₂O₂ pathway is greatly enhanced when ammonia (NH₃), the main alkaline gas in the atmosphere, dissolves in the reacting droplets and neutralizes the acidity. As the decreasing trend continues into the afternoon, ambient air SO₂ concentrations in Delhi typically reach a minimum by around 7 PM. Afterward, SO₂ concentrations begin to rise rapidly, peaking again between 9-10 PM. This rapid increase over 1-2 hours is likely due to the quick collapse of the boundary layer after sunset, which traps the prevailing SO₂ in a smaller volume of air close to the surface, combined with continued emissions from transportation, residential, and industrial sectors within the city and nearby areas during the late evening hours.

As mentioned earlier, while SO₂ concentrations at location-1 generally decreased after the late evening peak, reaching their lowest values just before sunrise, at location-2, the ambient air SO₂ concentrations often remained high until 2-3 AM, likely due to local activities emitting SO₂ during

these late-night hours, as observed on several days during our survey period. Nevertheless, the highest ambient air SO₂ concentrations were typically observed during the daytime, with relatively lower values recorded at night throughout our survey period.

Next, we discuss the findings from our survey in Hyderabad, the second Category-1 city selected for Phase-I. Our survey of ambient air SO₂ concentrations in Hyderabad began at Location-1 on March 23 and continued until April 22, 2023. The survey at the second measurement location, Location-2, started on April 29 and continued until May 29, 2023. Figure 2.11 shows the time series of daily mean ambient air SO₂ concentrations ($\mu\text{g}/\text{m}^3$) measured on various days at the two different measurement sites in Hyderabad. It is clear from Figures 2.8 and 2.11 that ambient air SO₂ concentrations in Hyderabad are much lower compared to Delhi. Additionally, Figure 2.11 indicates that day-to-day variations in ambient air SO₂ concentrations in Hyderabad, particularly at Location-1, are also lower than those observed in Delhi.

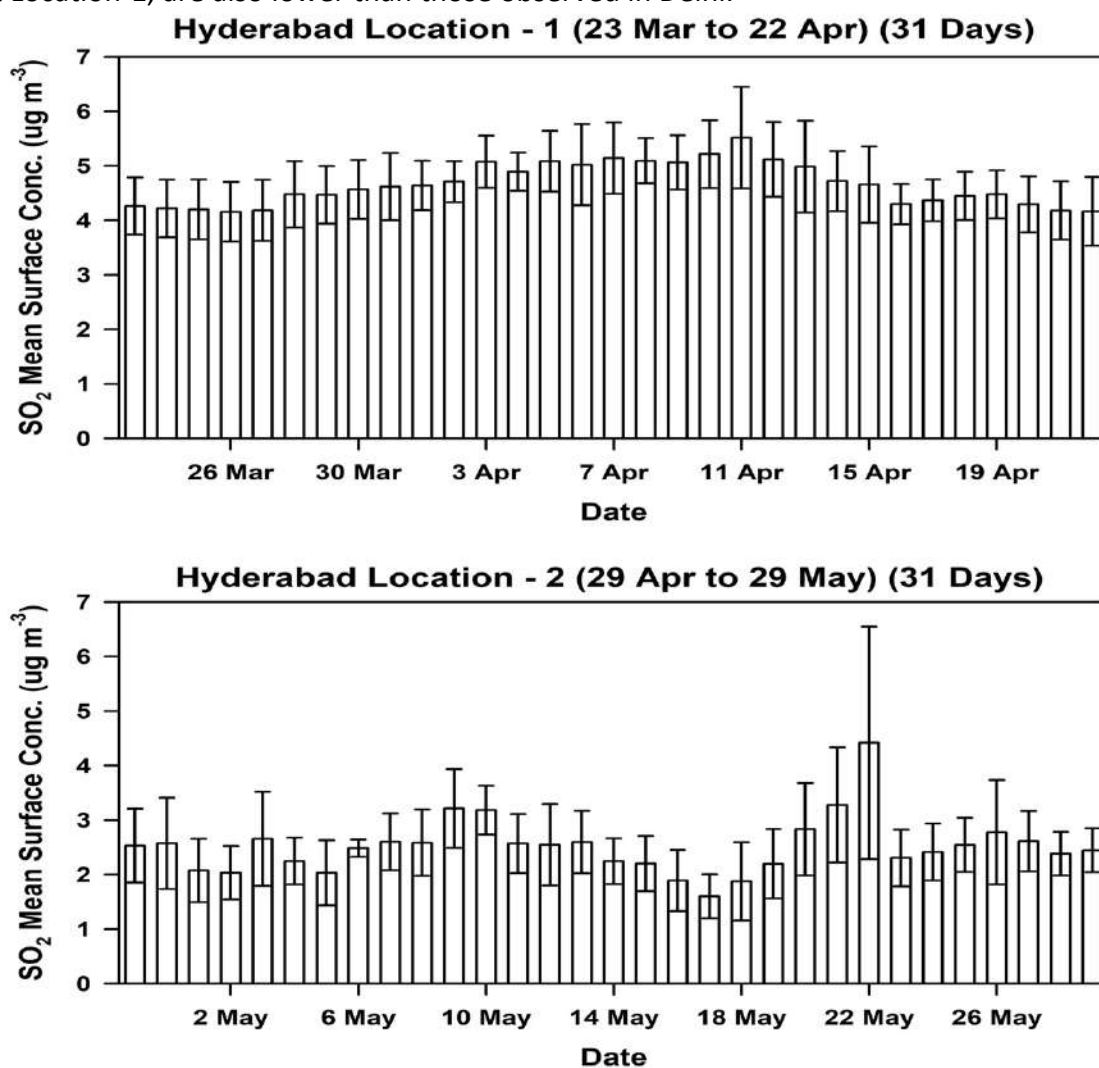


Figure 2.11: Time series of daily mean ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Hyderabad (upper panel) and for the period 29th April – 29th May 2023 in Location-2 of Hyderabad (lower panel). Vertical lines

on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

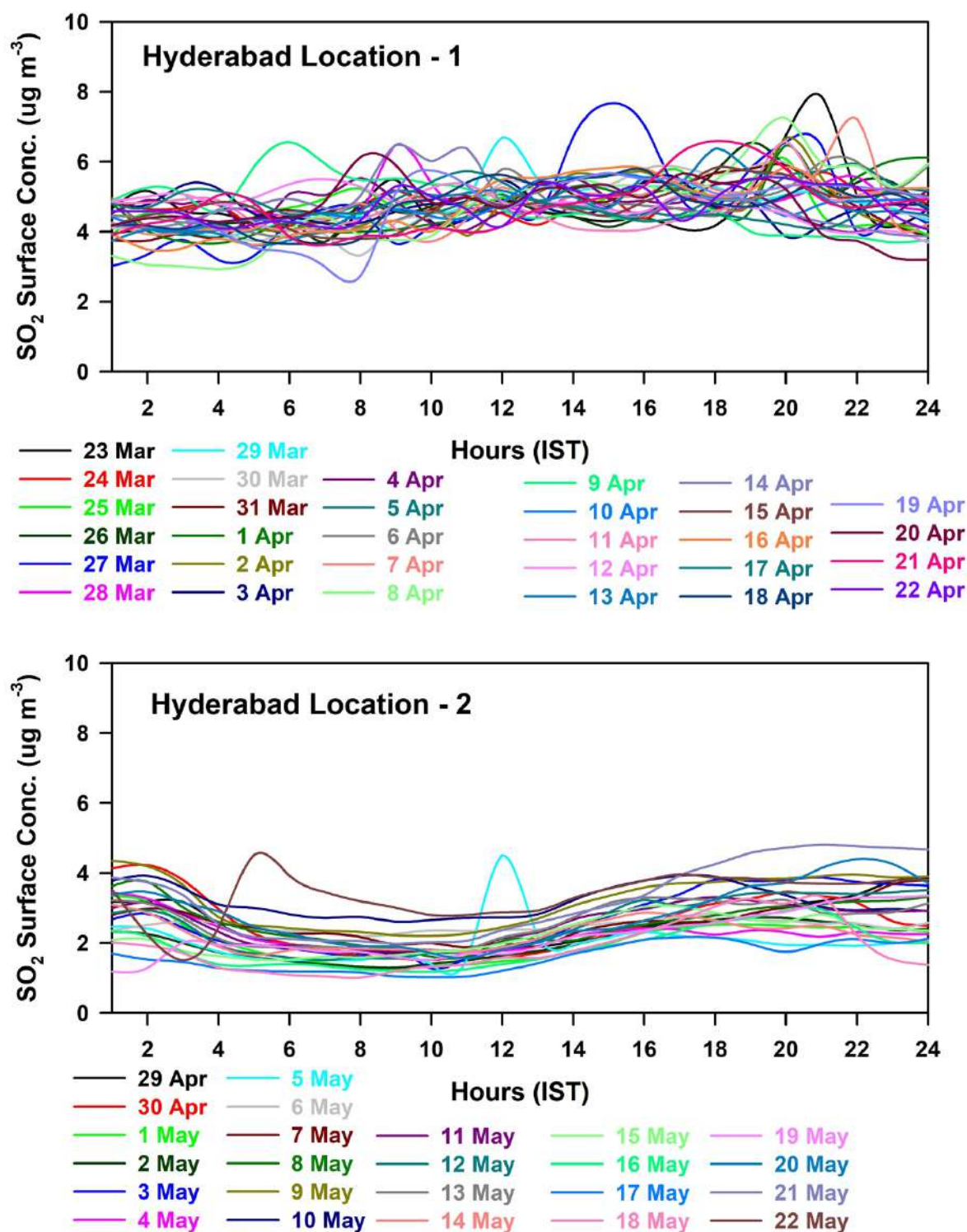


Figure 2.12: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Hyderabad (upper panel) and for the period 29th April – 29th May 2023 in Location-2 of Hyderabad (lower panel).

Figure 2.12 shows the diurnal variation of ambient air SO₂ concentrations (µg/m³) measured on different days at two different sites in Hyderabad. Figures 2.11 and 2.12 indicate that both diurnal variations and intra-day variability in ambient air SO₂ concentrations are minimal at both measurement locations in Hyderabad. As stated in Table-1, the maximum instantaneous SO₂ concentrations recorded at Location-1 and Location-2 during Phase-I of our survey are 7.86 µg/m³ and 4.81 µg/m³, respectively. The minimum values are 2.72 µg/m³ and 1.01 µg/m³, respectively. The monthly average daily mean SO₂ concentrations are 4.65 ± 0.55 µg/m³ at Location-1 and 2.48 ± 0.49 µg/m³ at Location-2. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations over a 24-hour average for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that ambient air SO₂ concentrations in Hyderabad are well within these standards during the survey period.

Diurnal variations in ambient air SO₂ concentrations are influenced by several factors, including fluctuations in SO₂ emissions from various sources, changes in atmospheric boundary (or mixed) layer height, variations in wind patterns or air circulation, and other meteorological conditions. The relatively smooth variations with fewer spikes in the diurnal patterns of ambient air SO₂ concentrations throughout our measurement period at both Hyderabad sites suggest a weaker influence of local sources compared to Delhi. However, the occasional random spikes in SO₂ concentrations at different times and locations within Hyderabad (sometimes observed at one site but not the other) indicate that these spikes are caused by emissions from various nearby local sources.

Figure 2.13 shows the monthly mean pattern of diurnal variation in ambient air SO₂ concentration at both measurement sites in Hyderabad during Phase-I of our survey. It is evident from Figure 2.13 that the diurnal variations in ambient air SO₂ concentration in Hyderabad are minimal and significantly less pronounced compared to those observed in Delhi. At Location-1 in Hyderabad, the monthly mean pattern of diurnal variation in SO₂ concentration remains almost flat throughout the day, with slightly higher values in the evening, peaking around 8 PM. This evening peak is likely due to increased local emissions from the transport and residential sectors around this time, as well as the collapse of the boundary layer after sunset. At Location-2, the monthly mean pattern shows maximum SO₂ concentrations in the evening after sunset, remaining high until about 2 AM, with minimum values noted in the forenoon hours. The slow but steady increase in ambient air SO₂ concentrations during the afternoon, despite the higher boundary layer height, is likely due to the gradual buildup of SO₂ levels within the city from various daytime activities and the transport of regional SO₂ plumes from upwind sources.

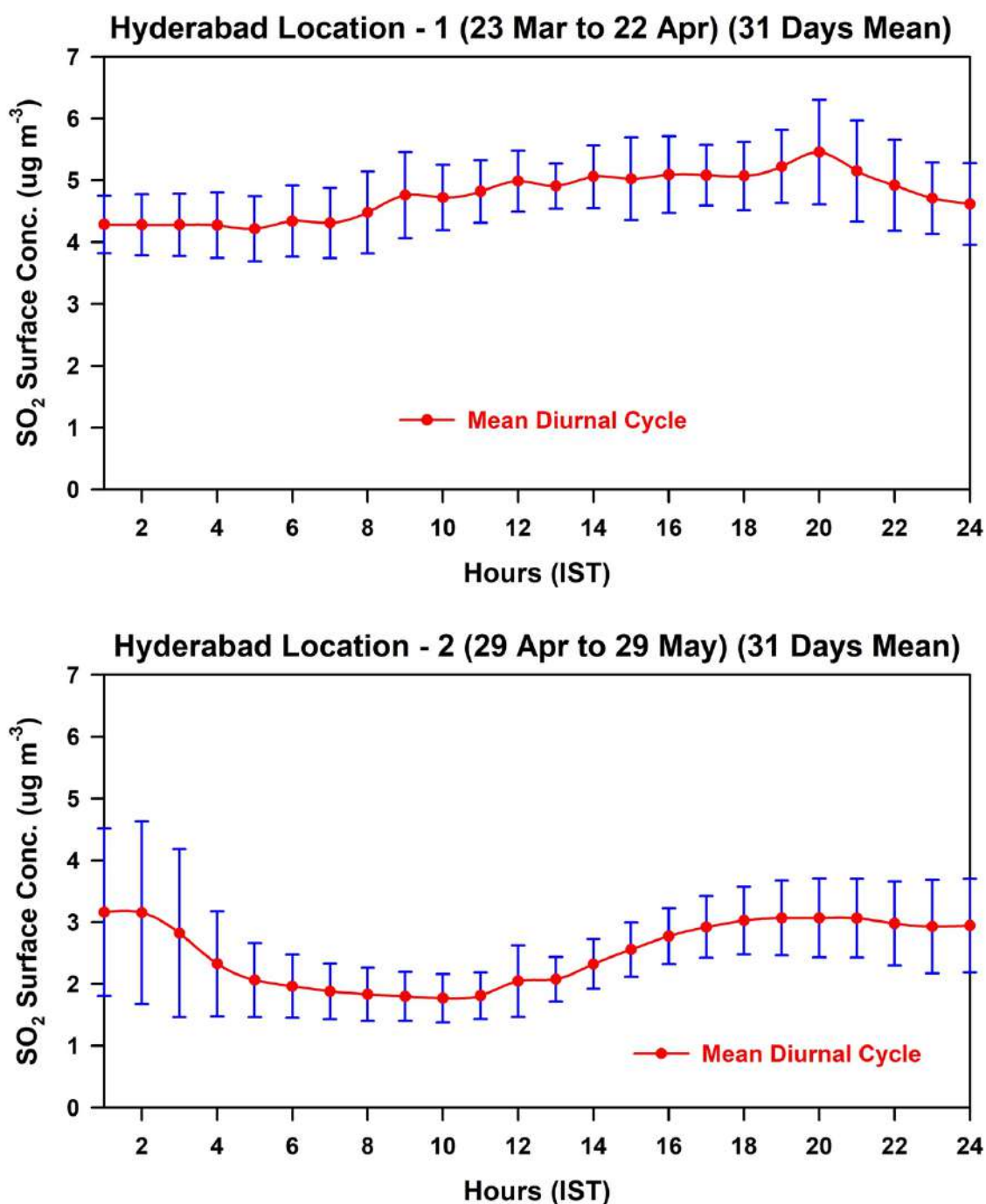


Figure 2.13: Monthly mean pattern of diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for Location-1 (upper panel) and Location-2 (lower panel) of Hyderabad. Vertical lines in this figure represents the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Next, we discuss the findings from our survey in Category-2 cities, which have a coal-based TPP without an installed FGD, located within 10 km of the city boundary. The Category-2 cities selected in Phase-I of our survey are Kolkata and Nagpur.

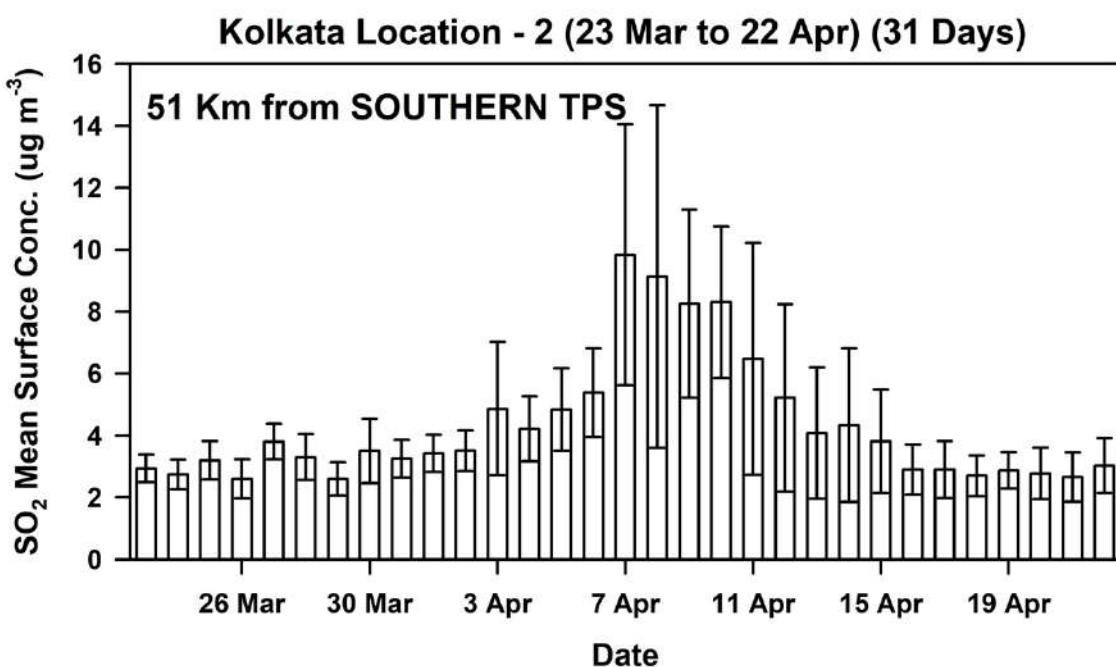
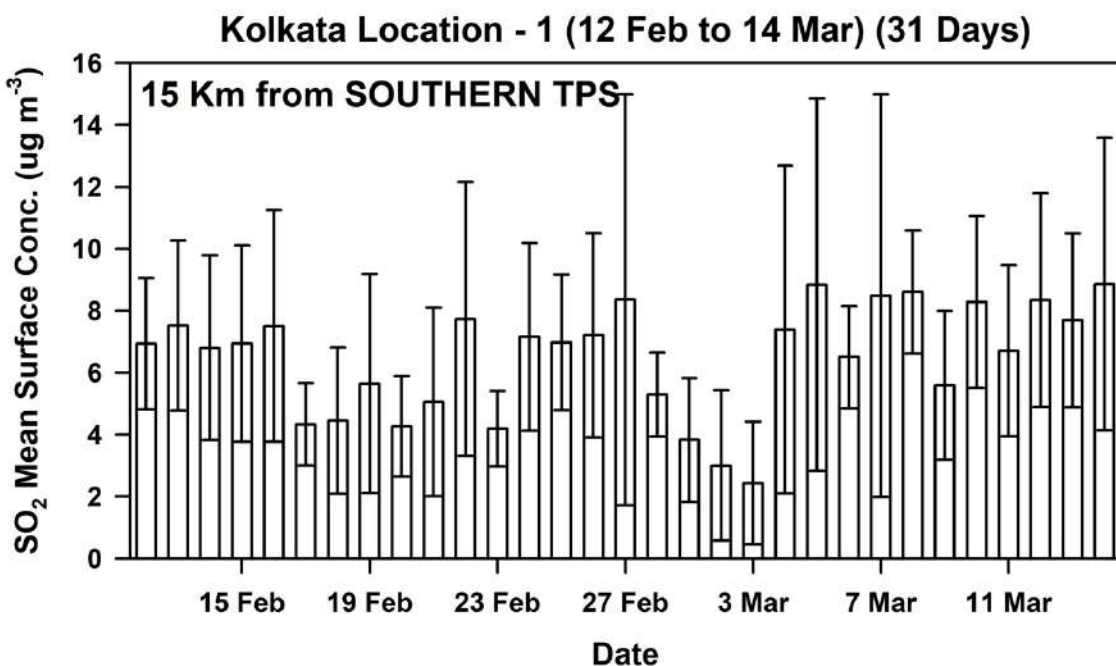


Figure 2.14: Time series of daily mean ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (12th February – 14th March 2023) as measured in Location-1 of Kolkata (upper panel) and for the period 23rd March – 22nd April 2023 in Location-2 of Kolkata (lower panel). Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

For the city of Kolkata, our survey of ambient air SO₂ concentrations began at Location-1 on February 12 and continued until March 14, 2023. The survey at the second measurement site, Location-2, started on March 23 and continued until April 22, 2023.

Figure 2.14 depicts the time series of daily mean ambient air SO₂ concentrations (µg/m³) measured on various days of our survey at the two different measurement sites in Kolkata. It is evident from the results presented in Figure 2.14 that there are significant day-to-day variations in ambient air SO₂ concentrations in the city of Kolkata, particularly at Location 1.

Figure 2.15 illustrates the diurnal variation of ambient air SO₂ concentrations (µg/m³) measured on different days of our survey at the two different measurement sites in Kolkata. It is apparent from Figures 2.14 and 2.15 that there are substantial diurnal variations as well as significant intra-day variations in ambient air SO₂ concentrations at both of these measurement locations in Kolkata.

Table 2.1 lists the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentrations (µg/m³) measured at the two different locations in all six cities across the country selected during Phase-I of our survey. The maximum instantaneous values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Kolkata during Phase-I of our survey are 32.25 µg/m³ and 21.41 µg/m³, respectively. The minimum instantaneous values measured at Location-1 and Location-2 of Kolkata during Phase-I of our survey are 1.29 µg/m³ and 1.37 µg/m³, respectively. The monthly average daily mean values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Kolkata during Phase-I of our survey are 6.48 ± 3.08 µg/m³ and 4.32 ± 1.51 µg/m³, respectively. As per the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that ambient air SO₂ concentrations in Kolkata are within these standards during the survey period.

Diurnal variations in ambient air SO₂ concentrations over both measurement locations of Kolkata are characterized by relatively lower values during the nighttime and higher values during daytime. However, multiple spikes in ambient air SO₂ concentrations are noted at different times of the day (including evening and nighttime) on different days throughout the survey period in location-1 of Kolkata, thereby indicating a strong influence of local sources within a distance of approximately 60 km from the measurement site, such as transportation sector, residential activities, and industrial emissions in creating these spikes. The role of TPPs in creating these short spikes in ambient air SO₂ concentrations can be ruled out because TPP units typically operate continuously and are not switched on and off intermittently. Unlike location-1, spikes in ambient air SO₂ concentrations are noted only during daytime in location-2 of Kolkata, thereby suggesting that the sources responsible for creating these spikes in SO₂ concentrations over location-2 are active only during daytime. Incoherency associated with the occurrences of these random spikes in diurnal pattern of ambient air SO₂ concentration on different days over both the measurement locations of Kolkata (for example often a spike in SO₂ concentration is noted in only one of the measurement locations but no such spike is noted around the same time on the

same day in the other measurement location and vice-versa) indicate that these spikes are mostly caused by emissions from different local sources nearby each measurement site with a much shorter distance of influence (less than 50 km).

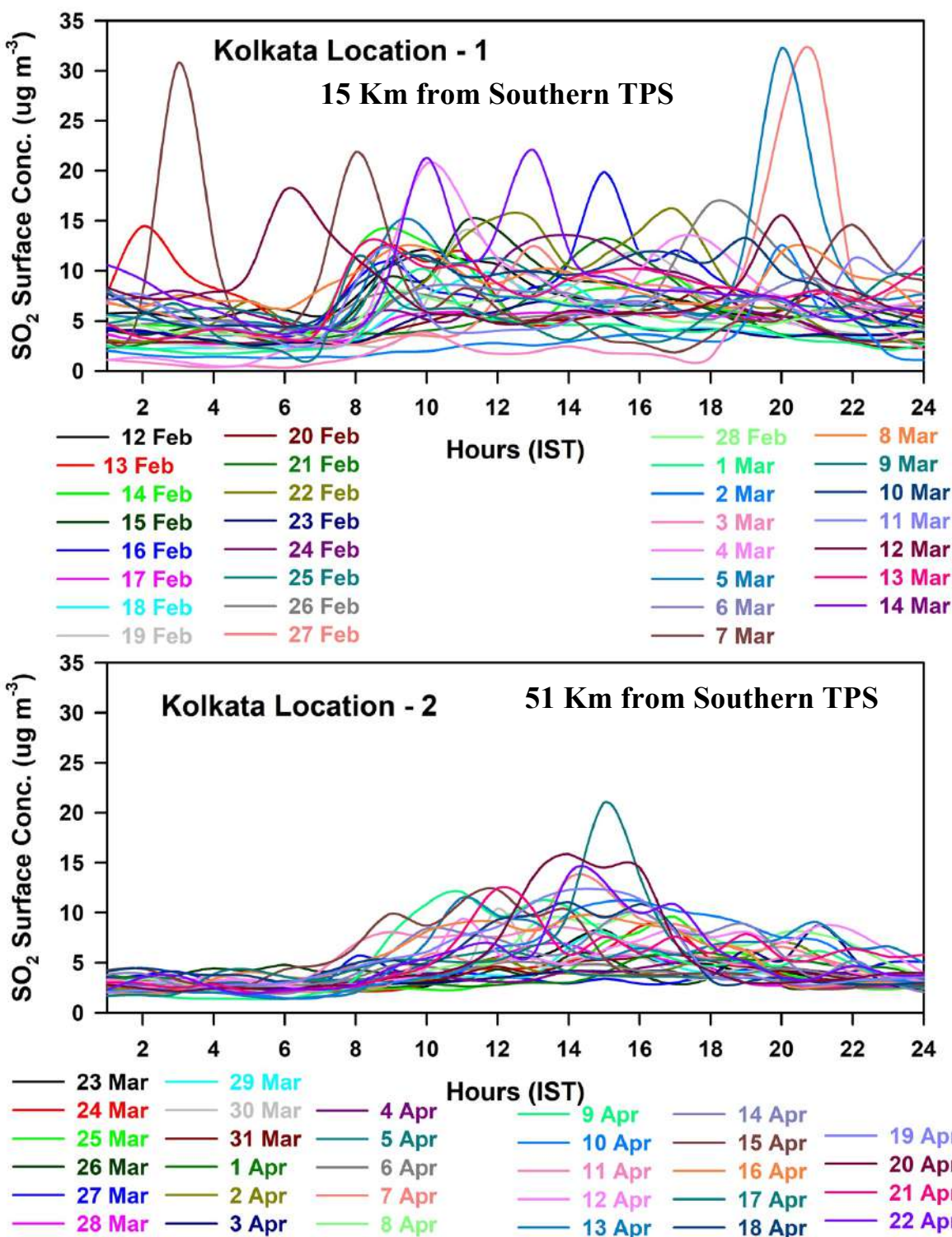


Figure 2.15: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (12th February – 14th March 2023) as measured in Location-1 of Kolkata (upper panel) and for the period 23rd March – 22nd April 2023 in Location-2 of Kolkata (lower panel).

Figure 2.16 shows the monthly mean pattern of diurnal variation of ambient air SO₂ concentration observed at both measurement sites in Kolkata during Phase-I of our survey. As mentioned earlier, diurnal variations in ambient air SO₂ concentrations over both measurement locations of Kolkata are characterized by relatively lower values during the nighttime and higher values during daytime. However, there are also some clearly noticeable differences in the diurnal patterns of ambient air SO₂ concentrations over the two different measurement locations of Kolkata. For example, the ambient air SO₂ concentrations over location-1 of Kolkata increases rather rapidly almost immediately after sunrise to reach a maxima by around 10AM and thereafter either remains steady almost throughout the day or shows a very gentle decreasing trend up to around 6PM in the evening before increasing again to reach another maxima at around 8PM in the evening. On the contrary, ambient air SO₂ concentrations over location-2 of Kolkata increases slowly but steadily after sunrise to reach a maxima in the afternoon hours by around 3PM, in spite of the increases in the boundary layer height during the same period of time. It is likely that the rapid increases in SO₂ concentrations noted over location-1 of Kolkata are caused by emissions from various sectors (especially transportation, industrial, and residential sectors) within the city which becomes more active immediately after sunrise in the morning hours. As the location-2 of Kolkata is in a more suburban locality rather than within the metropolitan city of Kolkata, we notice a slow but steady increase in SO₂ concentrations in this site after sunrise due to slow buildup of SO₂ levels caused by emissions from local sources as well as contributed by transport of regional SO₂ plumes from upwind sources to this measurement site. The evening peak in SO₂ concentrations noted in location-1 of Kolkata is likely due to peak in local emissions from transport and residential sector around this time or slightly before it as well as a collapse of the boundary layer height after sunset. SO₂ concentrations in location-1 generally decreased gradually after this late evening peak to reach minimum values just before the sunrise. Thus, higher values of ambient air SO₂ concentrations were generally observed during the daytime and lower values were noted during nighttime over both measurement sites of Kolkata during our survey period. Lower values of ambient air SO₂ concentrations during nighttime in spite of lower boundary layer height during this time is likely due to decrease in activities contributing to emissions of SO₂ from various local sources such as transportation, industrial, and residential sectors.

Next, we discuss the findings from the second Category-2 city selected for Phase-I, which is Nagpur. Our survey of ambient air SO₂ concentrations began at the first measurement site, Location-1, in Nagpur on March 23 and continued until April 22, 2023. The survey at the second measurement site, Location-2, started on April 29 and continued until May 29, 2023.

Figure 2.17 illustrates the time series of daily mean ambient air SO₂ concentrations (µg/m³) measured on various days of our survey at the two different measurement sites in Nagpur. It is apparent from the results presented in Figure 2.17 that the day-to-day variations in ambient air SO₂ concentrations at Location-1 are much larger than those noted at Location-2 in Nagpur. This

suggests that the ambient air SO₂ concentrations at Location-1 in Nagpur are influenced by a greater number of sources with significant day-to-day variations compared to those at Location-2.

Figure 2.18 depicts the diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) measured on different days of our survey at both measurement sites in Nagpur. It is evident from Figures 2.17 and 2.18 that there are substantial diurnal variations as well as significant intra-day variations in ambient air SO₂ concentrations at Location-1 compared to Location-2 in Nagpur.

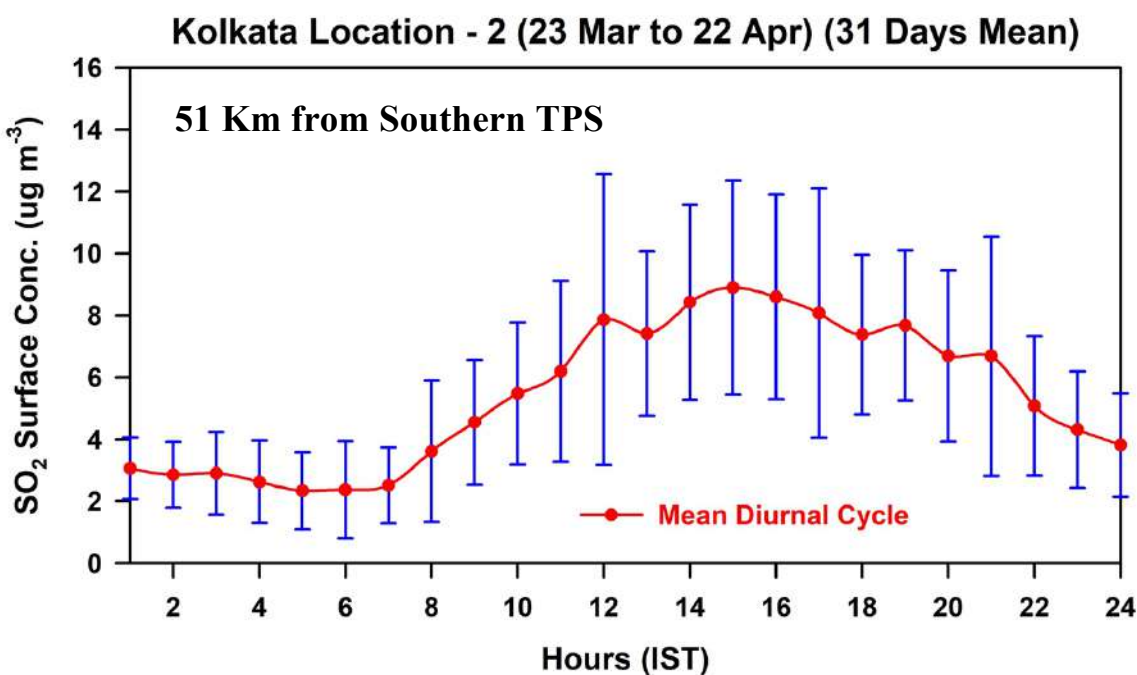
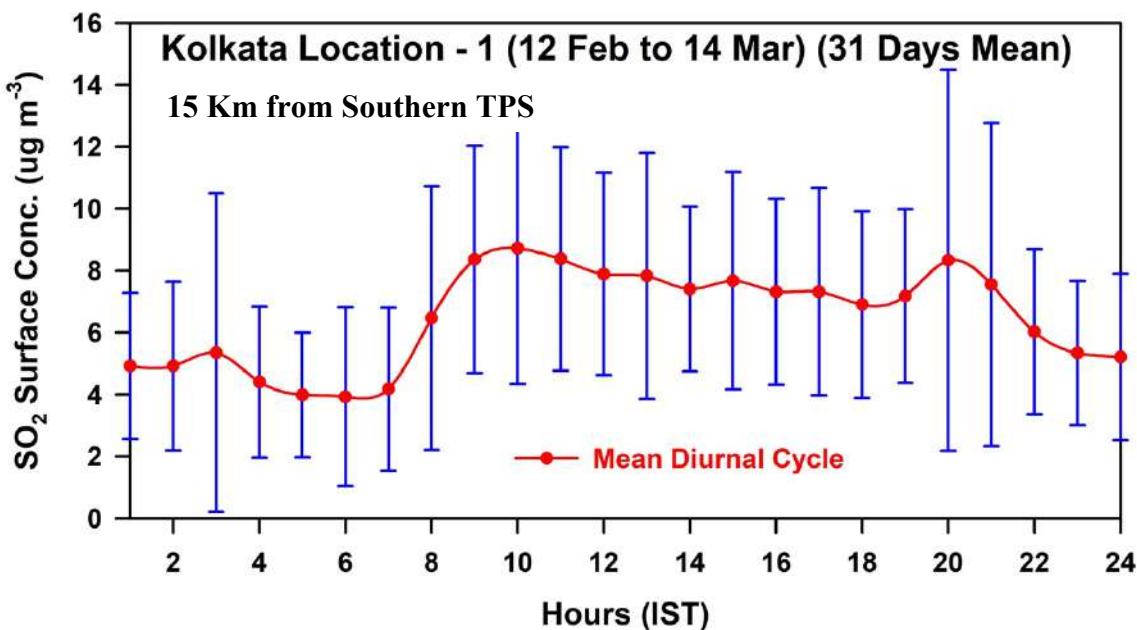


Figure 2.16: Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) for Location-1 (upper panel) and Location-2 (lower panel) of Kolkata. Vertical lines in this figure represents the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

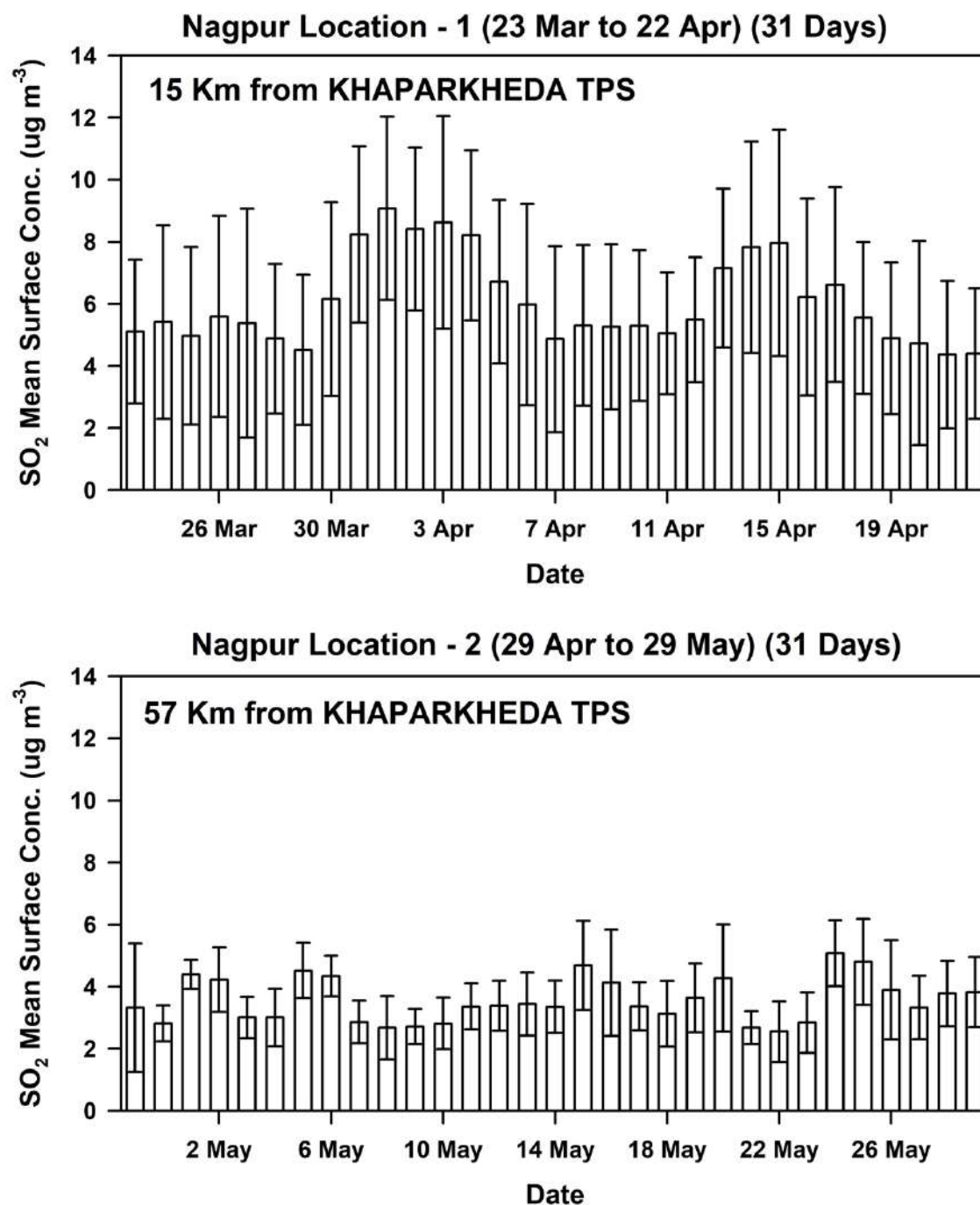


Figure 2.17: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Nagpur (upper panel) and for the period 29th April – 29th May 2023 in Location-2 of Nagpur (lower panel). Vertical lines on

each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

Table 2.1 presents the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) measured at two different locations in all six cities across the country selected during Phase-I of our survey. The maximum instantaneous values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Nagpur during Phase-I of our survey are $20.54 \mu\text{g}/\text{m}^3$ and $9.46 \mu\text{g}/\text{m}^3$, respectively. The minimum instantaneous values measured at Location-1 and Location-2 of Nagpur during Phase-I of our survey are $1.21 \mu\text{g}/\text{m}^3$ and $1.13 \mu\text{g}/\text{m}^3$, respectively. The monthly average daily mean values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Nagpur during Phase-I of our survey are $6.07 \pm 2.83 \mu\text{g}/\text{m}^3$ and $3.55 \pm 0.53 \mu\text{g}/\text{m}^3$, respectively. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is $80 \mu\text{g}/\text{m}^3$. Our survey results confirm that ambient air SO₂ concentrations in Nagpur meet these existing standards during the survey period.

Interestingly, our survey results reveal significant differences in the diurnal variations of ambient air SO₂ concentrations between the two measurement locations in Nagpur. In Location-1, SO₂ concentrations typically peak during the daytime, especially in the forenoon hours, and decrease during the nighttime. However, there are considerable day-to-day variations in this pattern. Multiple spikes in SO₂ concentrations occur at various times of the day, including evening and nighttime, throughout the survey period in Location-1. This suggests a strong influence of local sources within the city contributing to these spikes, which typically last for a maximum of 1-2 hours each time. On the contrary, ambient air SO₂ concentrations in Location-2 of Nagpur show little diurnal variability and minimal day-to-day variations throughout our survey period. While spikes in SO₂ concentrations are also observed in Location-2 on some days, they are much smaller in magnitude compared to those in Location-1. Additionally, the randomness associated with the occurrence of these spikes in the diurnal pattern of ambient air SO₂ concentration at both measurement locations in Nagpur indicates that they are primarily caused by emissions from various nearby local sources, with a shorter distance of influence (less than 60 km).

Figure 2.19 illustrates the monthly mean pattern of diurnal variation in ambient air SO₂ concentration observed at both measurement sites in Nagpur during Phase-I of our survey. As mentioned earlier, the monthly mean pattern of diurnal variations in ambient air SO₂ concentrations over Location-1 of Nagpur is characterized by relatively lower values during the nighttime and higher values during the daytime, especially in the forenoon hours. The ambient air SO₂ concentrations over Location-1 of Nagpur increase rather rapidly almost immediately after sunrise, reaching a maximum around 9 AM. Subsequently, they either remain steady for the

next couple of hours or show a very gentle decreasing trend until around 6 PM in the evening before increasing again to reach another maximum around midnight.

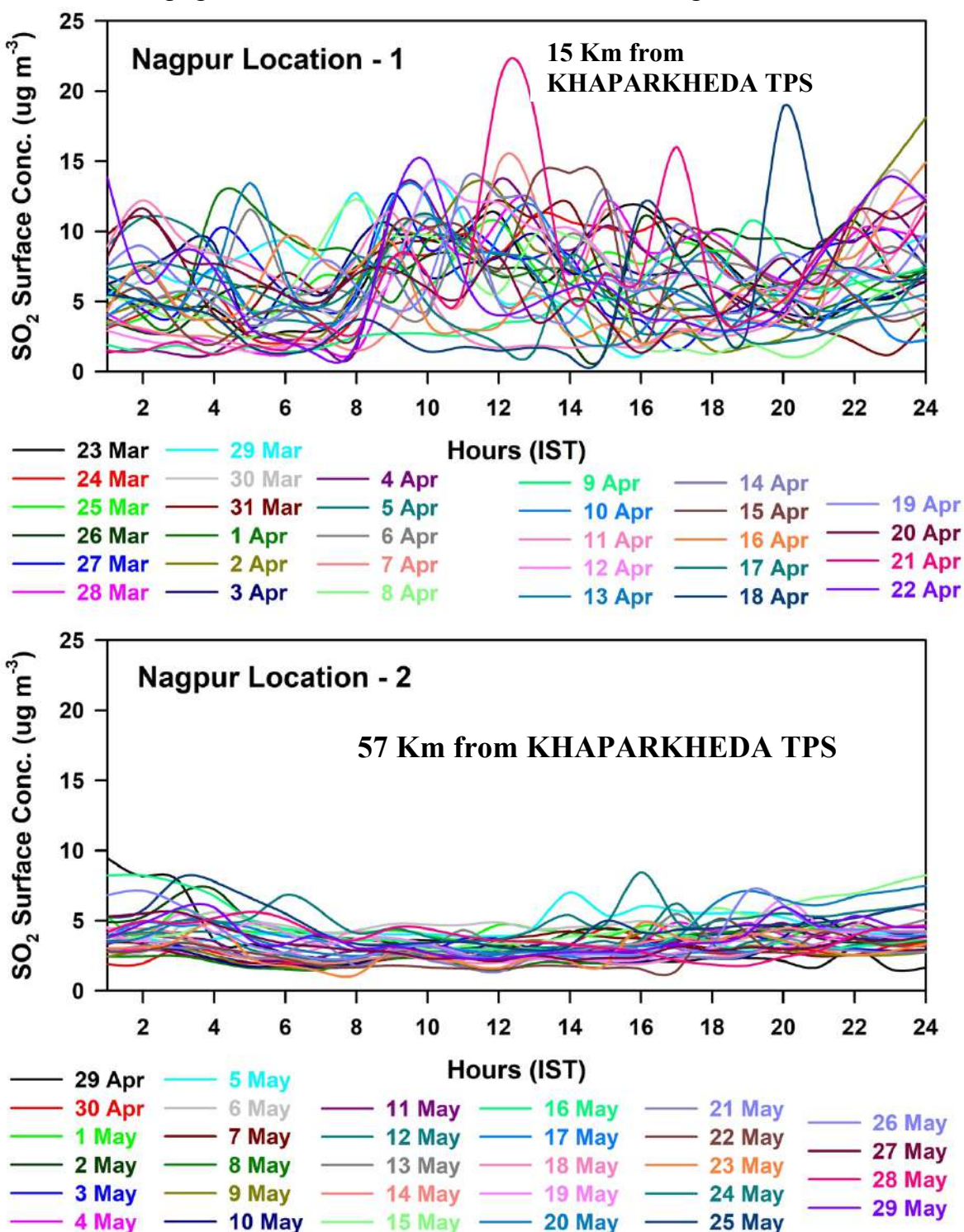


Figure 2.18: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Nagpur (upper panel) and for the period 29th April – 29th May 2023 in Location-2 of Nagpur (lower panel).

Conversely, ambient air SO₂ concentrations in Location-2 of Nagpur do not show such pronounced diurnal variability. In fact, we observed relatively higher values in ambient air SO₂ concentration during nighttime compared to daytime values in Location-2 of Nagpur.

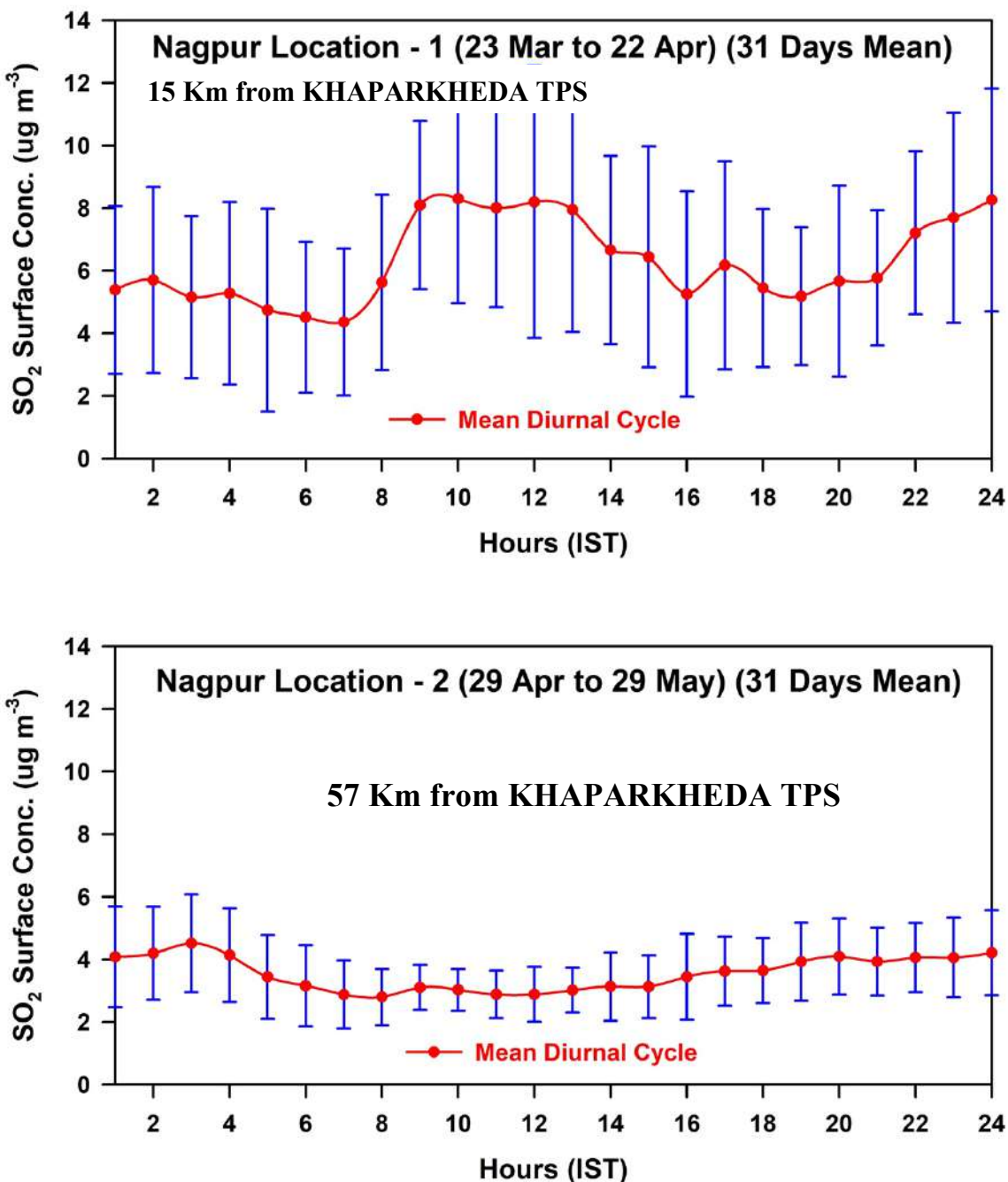
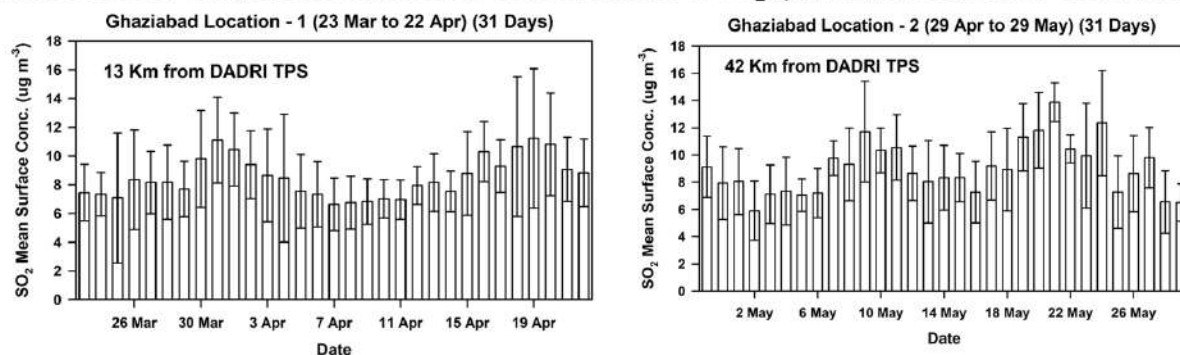


Figure 2.19: Monthly mean pattern of diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for Location-1 (upper panel) and Location-2 (lower panel) of Nagpur. Vertical lines in this figure represents the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

The monthly mean pattern of diurnal variation in ambient air concentration of SO₂ at location-2 of Nagpur indicates peak values in the evening hours after sunset, which typically remain elevated until about 2 AM, with minimum values observed in the forenoon hours around 10 AM. Despite the higher boundary layer height during the daytime at this second measurement location in Nagpur, there is a gradual but consistent increase in ambient air SO₂ concentrations during the afternoon. This increase is likely attributed to the slow accumulation of SO₂ levels resulting from emissions from various sectors predominantly active during the daytime, as well as the transport of regional SO₂ plumes from upwind sources to this measurement location throughout the day. Thus, the findings of our survey suggest that ambient air SO₂ concentrations in Location-2 of Nagpur are primarily influenced by the transport of regional SO₂ plumes to the measurement site, which is modulated by relatively weaker local sources throughout the day.

Next, we delve into the findings of our survey concerning Category-3 cities featuring a coal-based Thermal Power Plant (TPP) equipped with Flue Gas Desulfurization (FGD), situated within 10 kilometers from the city boundary. Category-3 cities selected during Phase-I of our survey comprise Gautam Buddha Nagar and Ghaziabad, both located in the state of Uttar Pradesh.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in Ghaziabad



National Ambient Air Quality Standards (NAAQS)

[NAAQS Notification dated 18th November, 2009]

S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (notified by Central Government)	
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual	50	20	1. Improved West and Gaeke 2. Ultraviolet Fluorescence
		24 Hours	80	80	

Figure 2.20: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Ghaziabad (upper left panel) and for the period 29th April – 29th May 2023 in Location-2 of Ghaziabad (upper right panel). Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

Our survey of ambient air SO₂ concentrations at the first measurement site, Location-1, in Ghaziabad commenced on March 23 and extended until April 22, 2023. Subsequently, the survey at the second measurement site, Location-2, in Ghaziabad began on April 29 and continued until May 29, 2023. Figure 2.20 displays the time series of daily mean ambient air SO₂ concentration (µg/m³) measured on various days of our survey at these two distinct measurement sites in Ghaziabad.

The results depicted in Figure 2.20 illustrate substantial day-to-day variations in ambient air SO₂ concentrations at both Location-1 and Location-2 of Ghaziabad. This suggests that the ambient air SO₂ concentrations at these locations are influenced by numerous sources of SO₂ exhibiting significant day-to-day variations. Table 2.1 presents the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentration measured at both measurement sites in all six cities across the country selected during Phase-I of our survey. The maximum instantaneous values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Ghaziabad during Phase-I of our survey are 33.51 µg/m³ and 18.66 µg/m³, respectively. The minimum instantaneous values measured at Location-1 and Location-2 of Ghaziabad during Phase-I of our survey are 2.92 µg/m³ and 2.62 µg/m³, respectively. The monthly average daily mean values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Ghaziabad during Phase-I of our survey are 8.51 ± 2.56 µg/m³ and 7.87 ± 1.89 µg/m³, respectively. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that ambient air SO₂ concentrations in Ghaziabad meet these existing standards during the survey period.

Additionally, Figure 2.21 illustrates the diurnal variation of ambient air SO₂ concentration measured on different days of our survey at both measurement sites in Ghaziabad. It is apparent from Figure 2.21 that substantial diurnal variations, along with significant intra-day variations, exist in ambient air SO₂ concentrations at both Location-1 and Location-2 of Ghaziabad. Interestingly, our survey results reveal both commonalities and significant differences in the diurnal variations of ambient air SO₂ concentrations between the two measurement locations in Ghaziabad. At both sites, SO₂ concentrations generally tend to be higher during nighttime. However, Location 1 exhibits multiple spikes in SO₂ concentrations during the forenoon hours throughout the survey period, suggesting a strong influence of local sources within the city contributing to these short-lived spikes, typically lasting 1-2 hours. Conversely, Location 2 shows a more consistent diurnal pattern, with higher SO₂ values at night and lower values during the daytime, particularly in the forenoon hours, indicating less influence from immediate local sources. While occasional spikes are also observed at Location 2, they are smaller in magnitude compared to those at Location 1. The randomness of these spikes suggests they are primarily

caused by emissions from nearby local sources with a shorter range of influence than the approximately 40 km distance between the two sites. This variability highlights the complex interplay of local emission sources in shaping ambient air quality in Ghaziabad, underscoring the need for more detailed investigations to identify and mitigate these sources.

Figure 2.21 illustrates the monthly mean pattern of diurnal variation in ambient air SO₂ concentration observed at both measurement sites in Ghaziabad during Phase-I of our survey. At Location 1, the SO₂ concentrations exhibit a bimodal pattern with peaks around 8 AM and 10 PM and a midday trough, indicating potential influences from local emissions and atmospheric dispersion conditions. Located just 13 km from NTPC Dadri TPP, Location 1 shows relatively stable SO₂ concentrations throughout the day, with slight peaks in the morning and late afternoon, fluctuating between approximately 6 to 12 µg/m³. In contrast, Location 2, situated 42 km from NTPC Dadri TPP, displays a pronounced decrease in SO₂ concentrations from midnight to noon, reaching a low in the early afternoon, and then gradually increasing back to initial levels by midnight. This pattern may be influenced by regional transport and diurnal atmospheric boundary layer dynamics, with concentrations varying more significantly, ranging from about 4 to 12 µg/m³. Both locations exhibit a noticeable diurnal cycle and higher variability during certain hours of the day, especially at Location 1, possibly due to fluctuating emission rates and meteorological conditions. However, the differences between the two locations are stark: SO₂ levels at Location 1 remain relatively higher and more stable compared to Location 2, which experiences a significant daytime dip. This difference could be attributed to the proximity to various emission sources, including NTPC Dadri TPP, resulting in more stable and elevated SO₂ levels at Location 1. Meanwhile, the greater distance of Location 2 from Ghaziabad city and the TPP allows for dispersion and dilution effects, leading to lower daytime concentrations. Thus, while both locations show variability in SO₂ levels, Location 1 has higher concentrations, likely due to its proximity to NTPC Dadri TPP and other emission sources in Ghaziabad. The diurnal variations at both sites are influenced by various emission sources and atmospheric processes, with the primary difference being the magnitude and timing of the diurnal peaks, reflecting the distance from emission sources and local environmental factors.

Next, we discuss the findings of our survey from the second Category-3 city namely Gautam Buddha Nagar from Uttar Pradesh, having a coal-based Thermal Power Plant (TPP) equipped with Flue Gas Desulfurization (FGD), situated within 10 kilometres from the city boundary.

Our measurements at the first measurement site, Location-1 of Gautam Buddha Nagar, began on March 23 and continued until April 22, 2023. Subsequently, the survey at the second measurement site, Location-2, commenced on April 29 and extended until May 29, 2023.

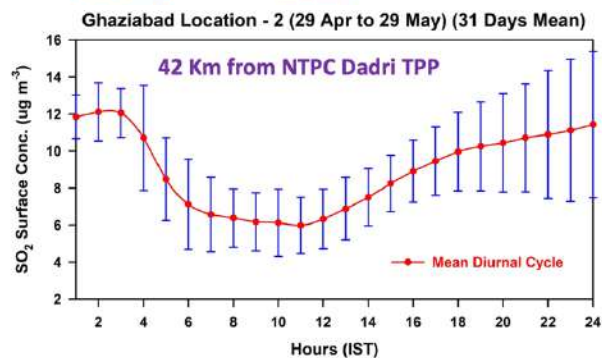
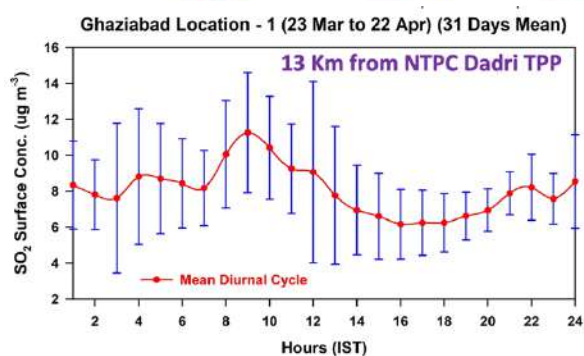
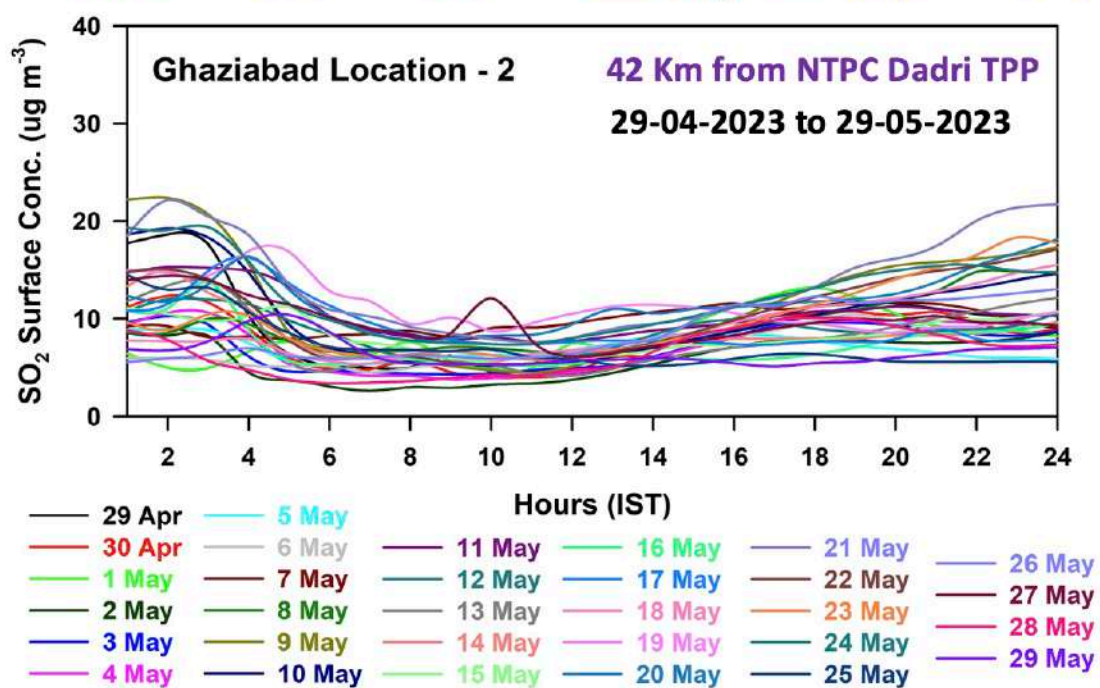
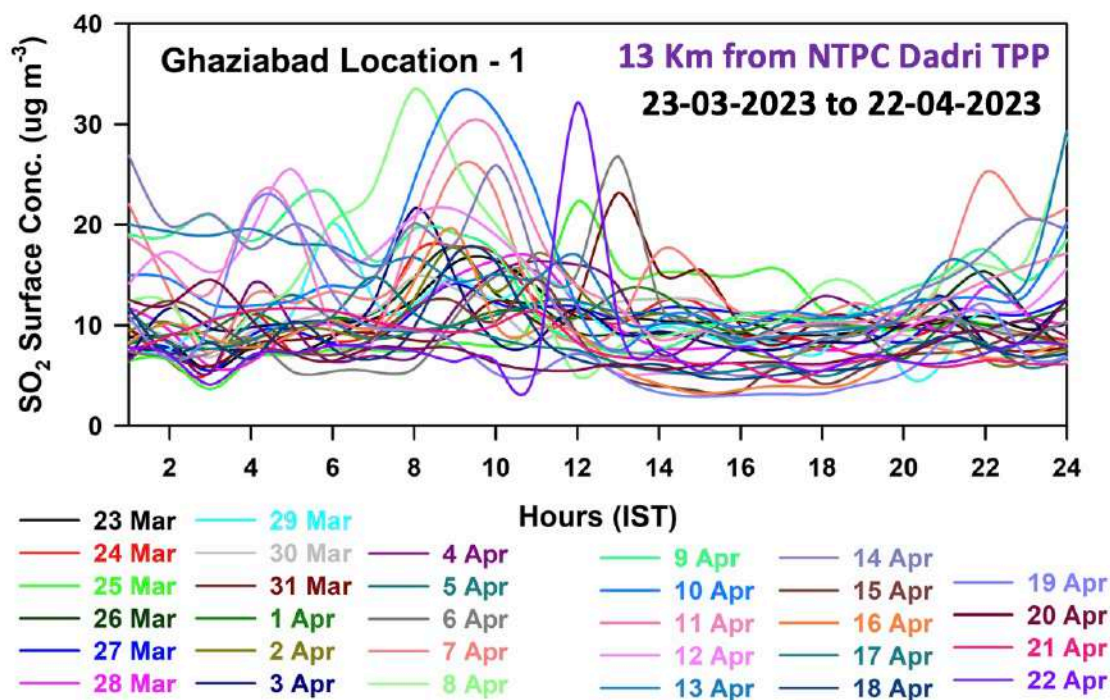


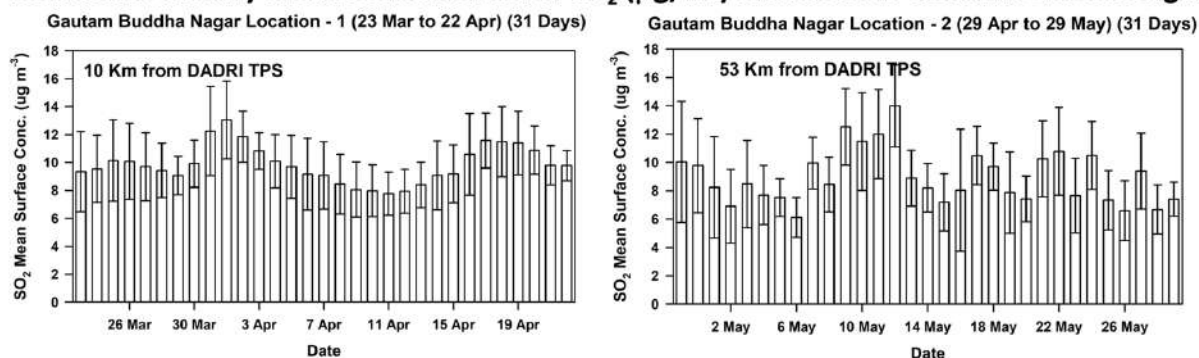
Figure 2.21: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Ghaziabad (top panel) and for the period 29 April – 29 May 2023 in Location-2 of Ghaziabad (middle panel). Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) derived from measurements made at both locations of Ghaziabad are also shown. Vertical lines in lower panels represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Figure 2.22 depicts the time series of daily mean ambient air SO₂ concentration measured on various days of our survey at these two distinct measurement sites in Gautam Buddha Nagar. The results depicted in Figure 2.22 illustrate substantial day-to-day variations in ambient air SO₂ concentrations at both Location-1 and Location-2 of Gautam Buddha Nagar. This suggests that the ambient air SO₂ concentrations at both these locations are influenced by numerous sources of SO₂ exhibiting significant day-to-day variations. Table 2.1 presents the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentration measured at both measurement sites in all six cities across the country selected during Phase-I of our survey. The maximum instantaneous values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Gautam Buddha Nagar during Phase-I of our survey are 33.34 µg/m³ and 17.54 µg/m³, respectively. The minimum instantaneous values measured at Location-1 and Location-2 of Ghaziabad during Phase-I of our survey are 4.60 µg/m³ and 2.71 µg/m³, respectively. The monthly average daily mean values of ambient air SO₂ concentrations measured at Location-1 and Location-2 of Gautam Buddha Nagar during Phase-I of our survey are 9.86 ± 2.12 µg/m³ and 8.31 ± 2.03 µg/m³, respectively. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that ambient air SO₂ concentrations in Gautam Buddha Nagar meet these existing standards during the survey period.

Figure 2.23 illustrates the diurnal variation of ambient air SO₂ concentration measured on different days of our survey at both measurement sites in Gautam Buddha Nagar. The figure shows substantial diurnal variations and significant intra-day variations in SO₂ concentrations at both Location 1 and Location 2. Similar to our findings in Ghaziabad, the survey reveals both similarities and significant differences in diurnal variations of SO₂ concentrations between the two locations. At both sites, SO₂ concentrations generally tend to be higher during nighttime. However, Location 1 exhibits multiple spikes in SO₂ concentrations during the forenoon hours throughout the survey period, indicating a strong influence of local sources within the city contributing to these short-lived spikes, typically lasting 1-2 hours. In contrast, Location 2 shows a more consistent diurnal pattern, with higher SO₂ values at night and lower values during the daytime, particularly in the forenoon hours, suggesting less influence from immediate local

sources. While occasional spikes are also observed at Location 2, they are smaller in magnitude compared to those at Location 1. The randomness of these spikes suggests they are primarily caused by emissions from nearby local sources with a shorter range of influence than the approximately 50 km distance between the two sites. This variability highlights the complex interplay of local emission sources in shaping ambient air quality in Gautam Buddha Nagar.

Time series of daily mean concentration of SO₂ (µg/m³) measured in Gautam Buddha Nagar



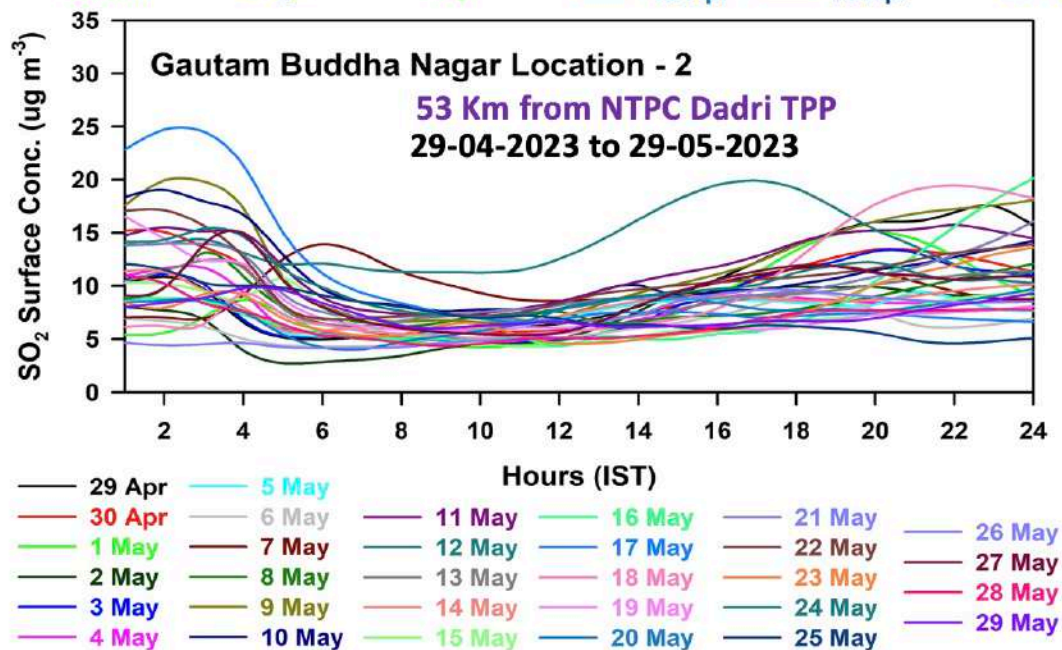
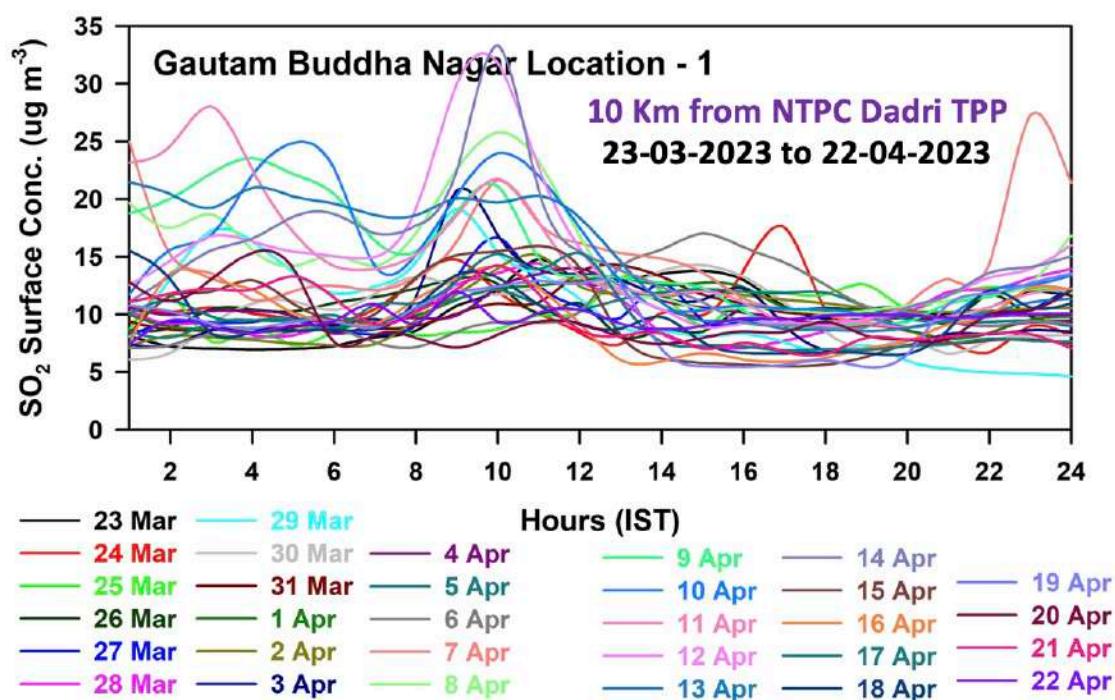
National Ambient Air Quality Standards (NAAQS)

[NAAQS Notification dated 18th November, 2009]

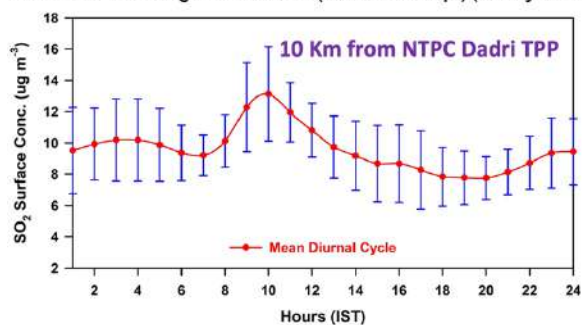
S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (notified by Central Government)	
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual	50	20	1. Improved West and Gaeke 2. Ultraviolet Fluorescence
		24 Hours	80	80	

Figure 2.22: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Gautam Buddha Nagar (upper left panel) and for the period 29th April – 29th May 2023 in Location-2 of Gautam Buddha Nagar (upper right panel). Vertical lines on each bar represents the ±1σ standard deviation variation around the daily mean values for each day.

Figure 2.23 also illustrates the monthly mean pattern of diurnal variation in ambient air SO₂ concentration observed at both measurement sites in Gautam Buddha Nagar during Phase-I of our survey. At Location 1, the SO₂ concentrations exhibit a bimodal pattern with peaks around 10 AM and 12 AM, and an evening trough around 7 PM, indicating potential influences from local emissions, boundary layer dynamics, and atmospheric dispersion conditions. Located just 10 km from NTPC Dadri TPP, Location 1 shows relatively stable SO₂ concentrations throughout the day, with slight peaks in the morning and late-night hours, fluctuating between approximately 6 to 12 µg/m³. In contrast, Location 2, situated 53 km from NTPC Dadri TPP, displays a pronounced decrease in SO₂ concentrations from 3 AM to around noon, reaching a low just before noon, and then gradually increasing back to higher levels by midnight. This pattern may be influenced by regional transport and diurnal atmospheric boundary layer dynamics, with mean concentrations varying more significantly, ranging from about 4 to 12 µg/m³.



Gautam Buddha Nagar Location - 1 (23 Mar to 22 Apr) (31 Days Mean)



Gautam Buddha Nagar Location - 2 (29 Apr to 29 May) (31 Days Mean)

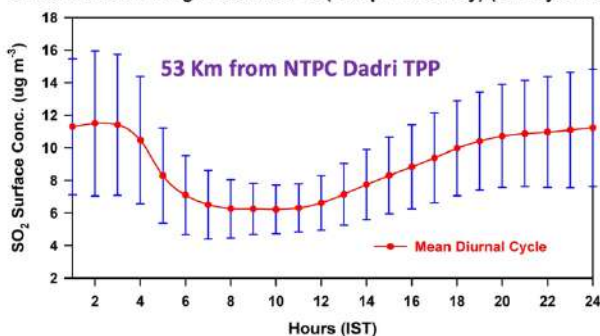


Figure 2.23: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (23rd March – 22nd April 2023) as measured in Location-1 of Gautam Buddha Nagar (upper panel) and for the period 29 April – 29 May 2023 in Location-2 of Gautam Buddha Nagar (middle panel). Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) derived from measurements made at both locations of Gautam Buddha Nagar are also shown. Vertical lines in lower panels represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Both locations exhibit a noticeable diurnal cycle and higher variability during certain hours of the day, especially at Location 1, possibly due to varying emission and meteorological conditions. However, the differences between the two locations are stark: SO₂ levels at Location 1 remain relatively higher and more stable compared to Location 2, which experiences a significant daytime dip. This difference could be attributed to the proximity to various emission sources, including NTPC Dadri TPP, resulting in more stable and elevated SO₂ levels at Location 1. Meanwhile, the greater distance of Location 2 from the Gautam Buddha Nagar city and the TPP allows for dispersion and dilution effects, leading to lower daytime concentrations. Thus, while both locations show variability in SO₂ levels, Location 1 has higher concentrations, likely due to its proximity to NTPC Dadri TPP and other emission sources in Gautam Buddha Nagar and the nearby city of Ghaziabad. The diurnal variations at both sites are influenced by various emission sources and atmospheric processes, with the primary difference being the magnitude and timing of the diurnal peaks, reflecting the distance from emission sources and local environmental factors.

CHAPTER-3: CONTRIBUTION OF SO₂ EMISSIONS FROM COAL-BASED TPPS TOWARDS AMBIENT ATMOSPHERIC SO₂, SULFATE AEROSOLS, PM_{2.5}, AND PM₁₀ MASS CONCENTRATIONS IN DIFFERENT CATEGORY CITIES DURING PHASE I OF SURVEY

To understand the contribution of SO₂ emissions from the power sector, specifically coal-based thermal power plants (TPPs), on ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in various cities selected for this survey, we conducted a series of meticulously planned simulations using the WRF-Chem chemical transport model. These simulations aimed to delineate the contributions of various sources, particularly TPP emissions, to ambient air SO₂ and sulfate aerosols as components of PM_{2.5} and PM₁₀ mass concentrations across the surveyed cities. Additionally, we aimed to determine the contributions of major aerosol types, including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust, to the ambient air concentrations of PM_{2.5} and PM₁₀ in these cities. Specifically, we sought to quantify the impact of SO₂ emissions from TPPs on the ambient air concentrations of PM_{2.5} and PM₁₀ in the cities included in this survey.

Model setup and Simulation Details

The Weather Research and Forecasting model coupled with a chemistry module (WRF-Chem) is a regional system designed for both operational weather forecasting and atmospheric chemistry research (Skamarock, 2008; Powers et al., 2017). In this study, WRF-Chem version 4.2.2 was utilized to conduct nine sets of atmospheric chemistry simulations over Delhi spanning from March 23rd to April 22nd, 2023. The model domains were centered at Delhi (77.12° E and 28.38° N), each covering approximately 2,250,000 square kilometres at a horizontal resolution of 10 km, with 150x150 grid cells in the outer domain and a horizontal resolution of 3 km, with 136x136 grid cells in the inner domain, following a nested WRF-Chem modeling setup. The model included 44 vertical levels on a hybrid-sigma coordinate system, extending from the surface to about 10 hPa as the model top pressure.

The NCEP GDAS Final Analysis data, available at 6-hour intervals and with a resolution of 0.25°x0.25°, provided the meteorological initial and lateral boundary conditions for the model simulations covering the period from March 23rd to April 22nd, 2023. Anthropogenic emissions were based on the EDGAR-v6.1 (2023) dataset. ERA5 Temperature, Water Vapor, and Wind data were used for both the WRF-Chem simulations and the Four-Dimensional Data Assimilation (FDDA) approach. Initial and lateral chemical boundary conditions for the WRF-Chem model simulations were obtained from previously available results from the Community Atmospheric Model With Chemistry (CAM-Chem) simulations.

CAM-Chem is the atmospheric component of the NCAR Community Earth System Model (CESM) and is used for global tropospheric and stratospheric atmospheric composition simulations, employing the MOZART chemical mechanism with various complexity choices for tropospheric and stratospheric chemistry. The WRF-Chem simulation setup incorporated the Model of Emissions of Gases and Aerosols from Nature (MEGAN) for online calculation of biogenic emissions and utilized Visible and Infrared Imaging Radiometer Suite (VIIRS) data for fire-related emissions within the simulation domain. The physical and chemical parameterization schemes selected for the WRF-Chem simulations discussed in this chapter are summarized in Table 3.1.

Table 3.1: WRF-Chem Physics and Chemistry schemes used in this study

Category	Schemes
Microphysics Schemes	Lin et al. scheme
Shortwave Radiation Scheme	Rapid Radiative Transfer Model new version (RRTMG) Scheme
Longwave Radiation Scheme	Rapid Radiative Transfer Model new version (RRTMG) Scheme
Surface Layer	Revised MM5 Monin-Obukhov Scheme
Land Surface	Noah Land Surface Model
Planetary Boundary Layer	Yonsei University (YSU) PBL scheme
Cumulus Parameterization	Grell 3D ensemble scheme
Emission	EDGAR-v5 (Primary pollutants and VOCs) (2015) MEGAN Biogenic (Online), FINN Biomass Burning (2019)
Gas-phase chemical mechanism & Aerosol module Scheme	MOZART & MOSAIC (4 Bin) + VBS (Volatility Basis Set) for organic aerosol evolution
Analysis Nudging	UVTQ Nudging in every 6 hours for Temperature, Water Vapor and Winds. Nudging Coeff. 0.001 s^{-1} and no nudging in the PBL
Photolysis Scheme	Fast-J photolysis scheme

In this study, our aim was to understand the contribution of SO₂ emissions from the power sector, specifically coal-based thermal power plants (TPPs), on ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in various cities selected for this survey. Emissions were categorized into several sectors, including Fossil fuel combustion for Energy (thermal power plants), Residential and Commercial (Fossil Fuel and biomass burning for cooking and other domestic use (power backup using diesel/petrol generators, heating in winter) and business (hotels, restaurants, street vendors, crematories, generators) use, other non-energy usage of fuels), Industry (combustion and production processes, losses from solvent use in production and end-use, Oil refineries and Transformation industry, Combustion for manufacturing, Non-metallic minerals production, Chemical processes, Iron and steel production, Non-ferrous metals production, Food and Paper, Non energy use of fuels), Land Transportation (both road and off-road vehicles), Agriculture (involving livestock and crop production, Agricultural manure/fertilizer management, soil management, usage of agricultural machineries, transportation associated with agriculture, agriculture waste burning (other than stubble burning)), Waste management

(covering solid waste, including landfill emissions and open trash burning, as well as residential and industrial wastewater), and Forest Fire and Grass Fire (representing natural burning of forest and grassland).

To assess the sectoral contribution to ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in Delhi, we employed an emission suppression method. This involved conducting a series of systematically designed simulations using the WRF-Chem model, where emissions from a specific sector were disabled in each simulation. Further details of the simulation setup are provided in Table 3.2.

Table 3.2: List of numerical experiments performed using WRF-Chem model for quantifying the sectoral emission contribution to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀

Experiment Design using WRF-Chem model for Source Apportionment of SO₂ in different category cities

To estimate the **contribution of individual emission sectors** on the air pollution levels (SO₂) for various cities, following experiments were designed

S. No.	Emission Sector	Simulation Name
1	All emission Sectors active	CNTL
2	Industrial Sector emissions switched off (0%)	NoIND
3	Power Sector emissions switched off (0%)	NoENE
4	Transport Sector switched off (0%)	NoTRA
5	Residential Sector switched off (0%)	NoRES
6	Agriculture Sector switched off (0%)	NoAGR
7	Waste Burning Sector switched off (0%)	NoTRB
8	Biogenic Emission Sector switched off (0%)	NoBio
9	Biomass Burning Emission switched off (0%)	NoBB

/03/24

Table 3.3: Emission Details: EDGAR-v6.1 (2023) Emission Sectors and Their Emission Activities
EDGAR-v6.1 (2018): Emission Sectors and Emission Activities

Sectors	Emission Sources Crippa et al. (2022)
Energy	Power industry (Thermal Power Plants)
Industry	Oil refineries and Transformation industry, Combustion for manufacturing, Non-metallic minerals production, Construction activities, Chemical processes, Iron and steel production, Non-ferrous metals production, Food and Paper, Non-energy use of fossil fuels
Transportation	Aviation cruise, Aviation landing & takeoff, Aviation climbing & descent, Road transportation no resuspension, Road transportation resuspension, Railways, pipelines, off-road transport, Shipping
Residential	Fossil Fuel and biomass burning for cooking and other domestic use (power backup using diesel/petrol generators, heating in winter) and business (hotels, restaurants, street vendors, crematories, generators) use, other non-energy usage of fuels
Agriculture	Agricultural manure/fertilizer management, soil management, usage of agricultural machineries, transportation associated with agriculture, agriculture waste burning (other than stubble burning)
Waste	Solid waste incineration, covering solid waste, including landfill emissions and open trash burning, as well as residential and industrial wastewater

In this study, we utilized MEGAN biogenic emissions, a modeling system designed to calculate emission rates of chemical compounds from terrestrial ecosystems to the atmosphere under varying environmental conditions. While emissions from biomass burning, considered natural sources, are not accounted for in the MEGAN model, it simulates net emission rates, factoring in losses of primary emissions within the canopy. The model employs canopy-scale emission factors, derived from above-canopy flux measurements or extrapolated from leaf and branch level data using a built-in canopy environment model.

MEGAN calculates the net primary emission of 19 compound classes, further decomposed into 147 individual species such as Isoprene, Monoterpene, sesquiterpenes, carbon monoxide, methanol, alkanes, alkenes, aldehydes, acids, ketones, and other oxygenated VOCs. The MEGAN model, in conjunction with the Modern Era Retrospective Analysis for Research and Applications (MERRA) meteorological fields, generated a global emission dataset of biogenic volatile organic compounds (BVOC) available on a monthly basis.

Additionally, the Fire INventory from NCAR (FINN) provides a daily, high-resolution fire emissions product for atmospheric chemistry models. Open biomass burning constitutes a significant portion of total global emissions of greenhouse gases, reactive trace gases, and particulate matter. Although sporadic and highly variable, open biomass burning emissions can impact local, regional, and global air quality, as well as climate forcings. FINN utilizes satellite observations of active fires and land cover, along with emission factors and estimated fuel loadings, to offer daily,

highly resolved (1kmX1km) estimates of open burning emissions for use in regional and global chemical transport models. Since 2012, fire detections from both MODIS and VIIRS satellite instruments have been incorporated into FINN for emission calculations.

Chemical Transport Modeling for Delhi

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

**Category 1 City:
New Delhi**



23-03-2023 to 22-04-2023
Wind speed and wind direction as per IMD data

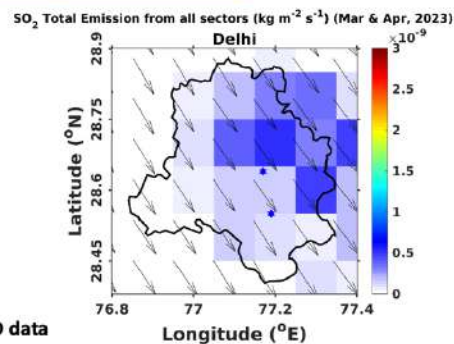
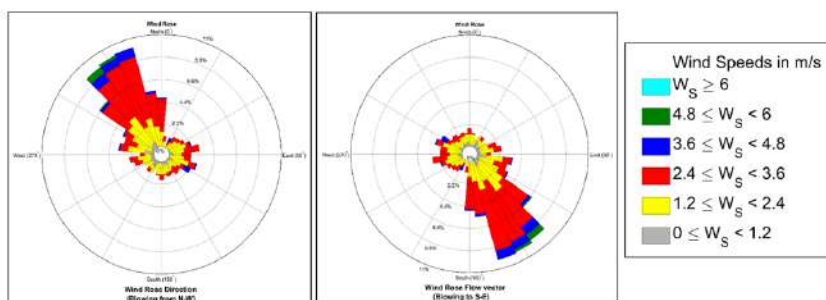


Figure 3.1: Simulation domain, gridded SO_2 emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Delhi during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO_2

**Category 1 City:
New Delhi**

Phase I
Pre-monsoon Season

Delhi SO_2 ($17.26 \pm 6.20 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

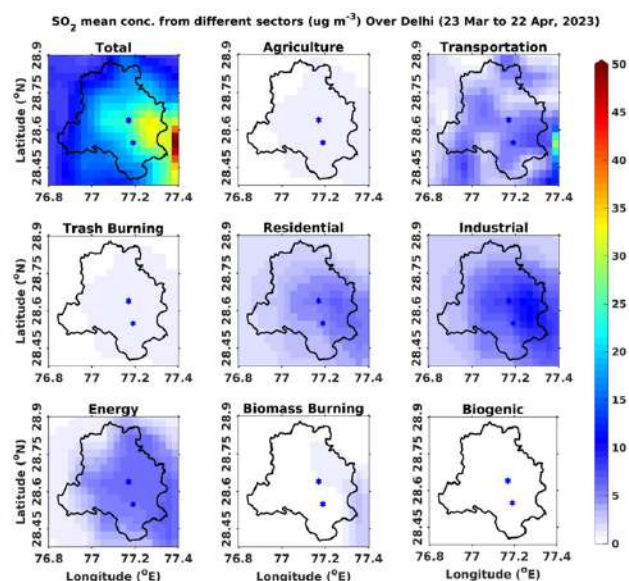
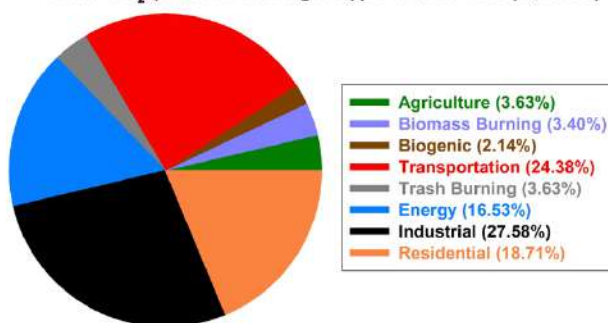


Figure 3.2: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Delhi during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

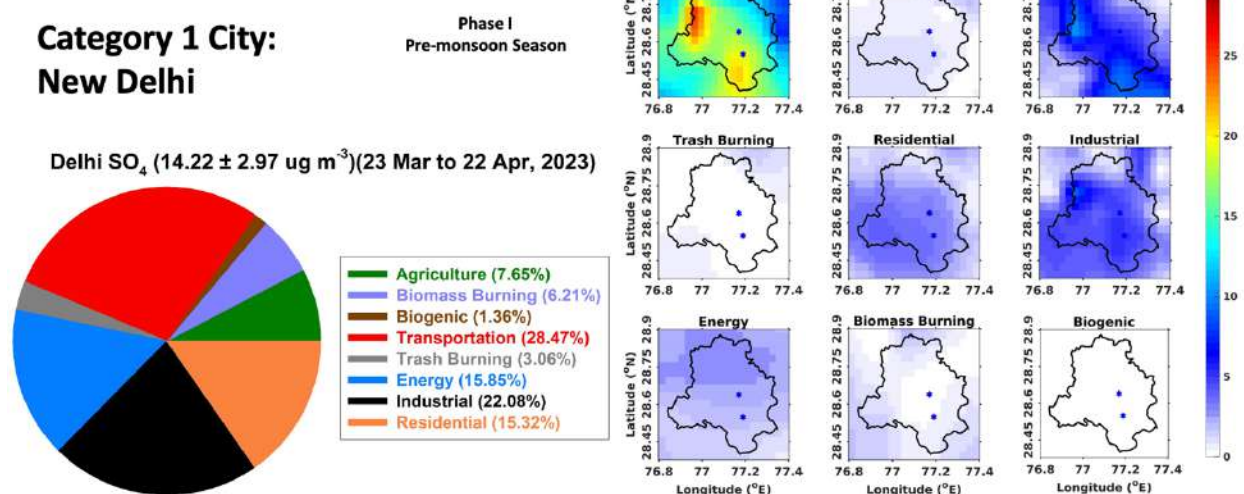


Figure 3.3: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

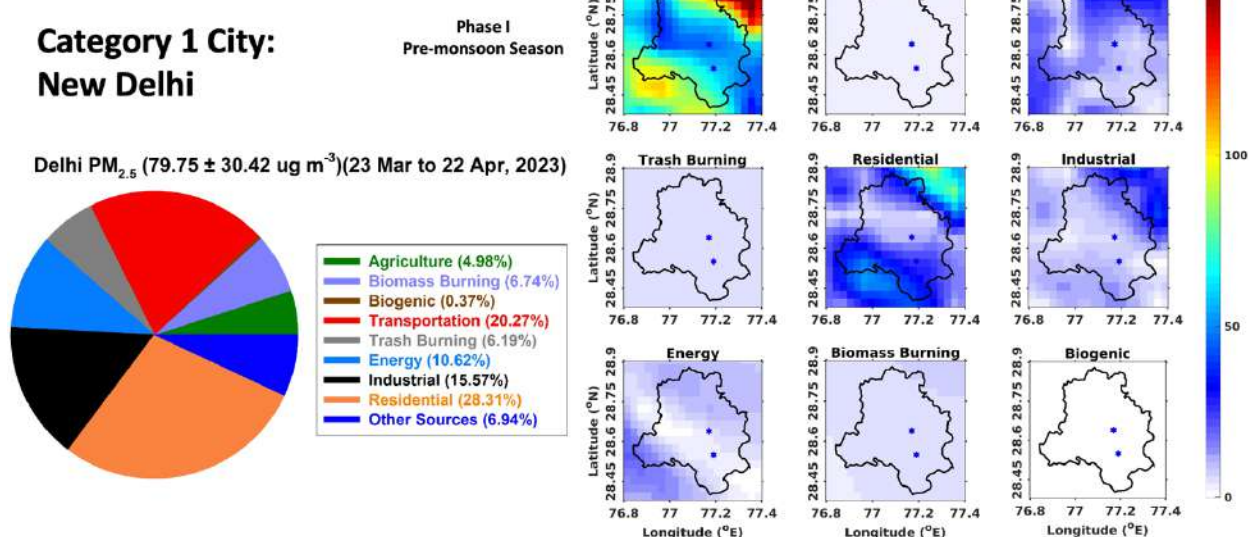


Figure 3.4: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category 1 City:
New Delhi

Phase I
Pre-monsoon Season

Delhi PM₁₀ ($137.56 \pm 15.58 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

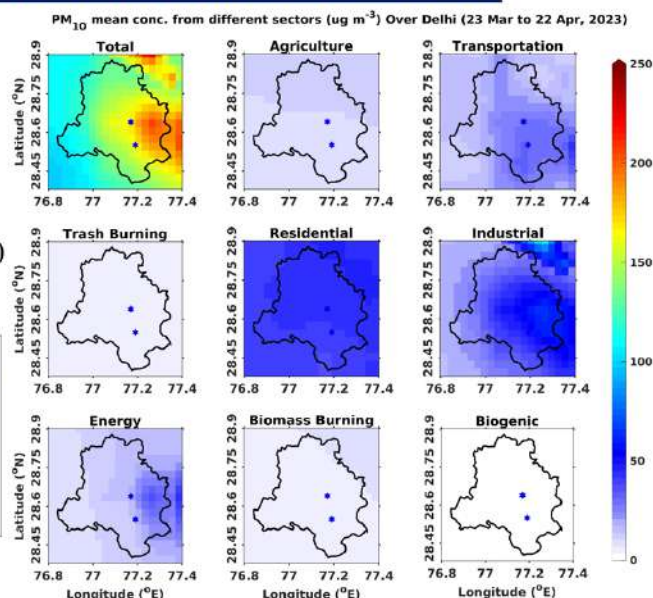
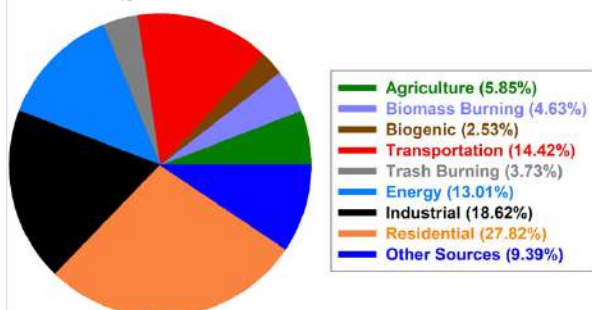


Figure 3.5: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023. Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Delhi during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category 1 City:
New Delhi

Phase I
Pre-monsoon Season

Delhi PM_{2.5} ($79.75 \pm 30.42 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

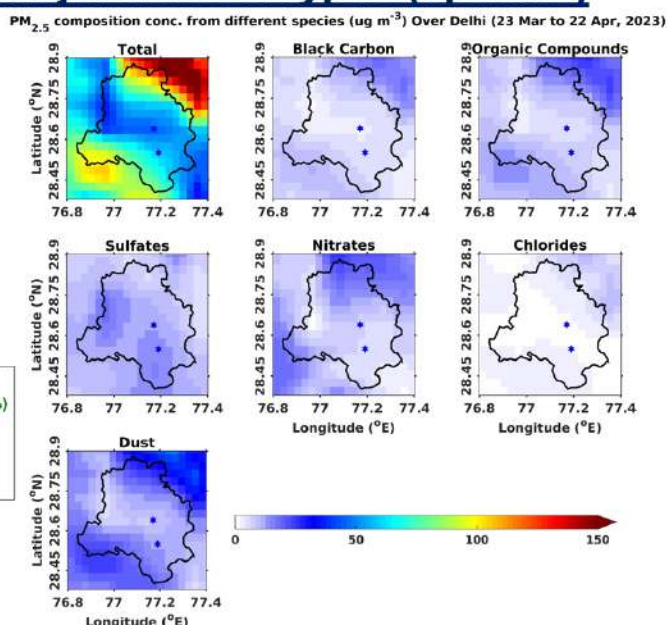
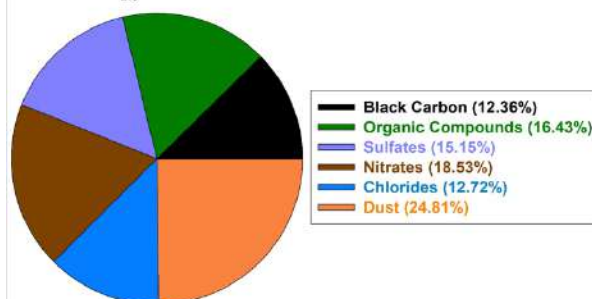


Figure 3.6: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category 1 City:
New Delhi

Phase I
Pre-monsoon Season

Delhi PM₁₀ ($137.56 \pm 15.58 \text{ ug m}^{-3}$) (23 Mar to 22 Apr, 2023)

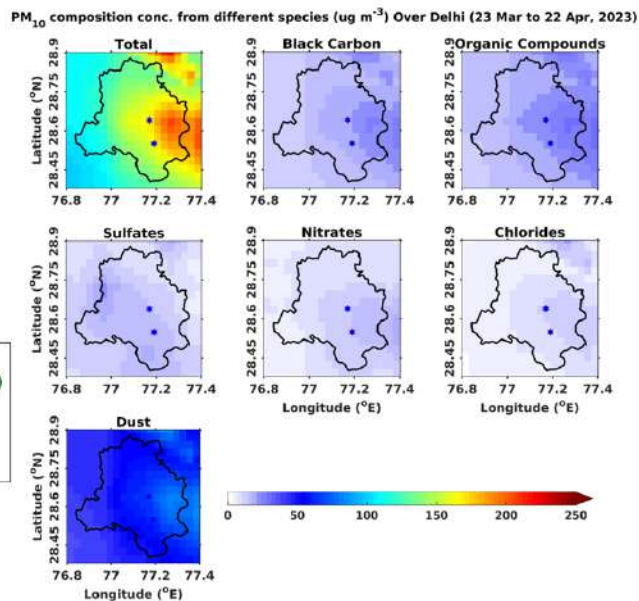
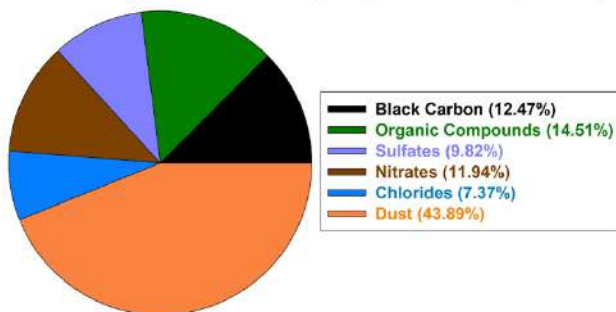


Figure 3.7: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category 1 City:
New Delhi

23rd March to 22 April 2023

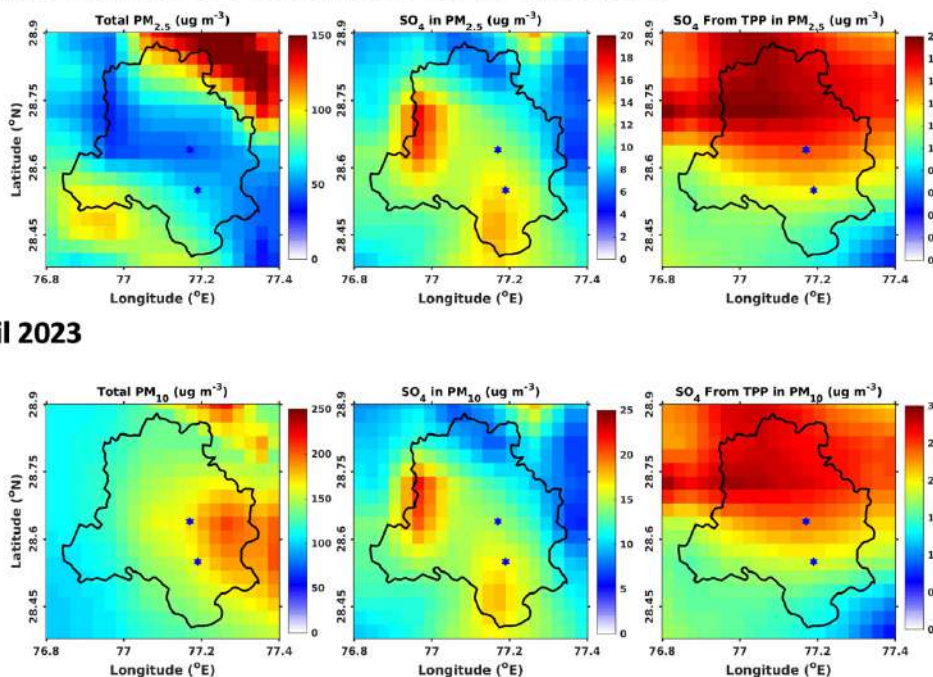


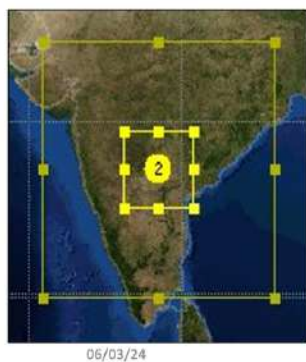
Figure 3.8: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in New Delhi during the simulation period from 23rd March to 22nd April 2023.

Next, we conducted another series of systematically designed WRF-Chem model simulations to determine the contribution of different sources to SO₂ and sulfate aerosols in Hyderabad, the second Category-1 city considered during Phase I of our survey. Additionally, we aimed to understand the contribution of the power sector to the ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in Hyderabad during our survey. We used WRF-Chem version 4.2.2 to perform a set of nine atmospheric chemistry simulations over Hyderabad from March 23 to April 22, 2023. The model domains are centered at Hyderabad (78.28° E and 17.21° N). Each simulation domain covers approximately 2,250,000 square kilometres at a horizontal resolution of 10 km × 10 km, with 150 × 150 grid cells in the outer domain and a resolution of 3 km × 3 km, with 136 × 136 grid cells in the inner domain, following a nested WRF-Chem modeling setup. The model includes 44 vertical levels (on a hybrid-sigma coordinate system) from the surface to about 10 hPa as the top pressure level. We used NCEP GDAS Final Analysis data (available at 6-hour intervals) with a resolution of 0.25° × 0.25° to provide meteorological initial and lateral boundary conditions for the simulation period. To estimate the sectoral emission contributions to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Hyderabad, we used an emission suppression method. This involved a series of systematically designed WRF-Chem simulations where emissions from a particular sector were turned off in each simulation. The details of the simulation setup are described in Table 3.2.

Chemical Transport Modeling for Hyderabad

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

**Category 1 City:
Hyderabad**



23-03-2023 to 22-04-2023
Wind speed and wind direction as per IMD data

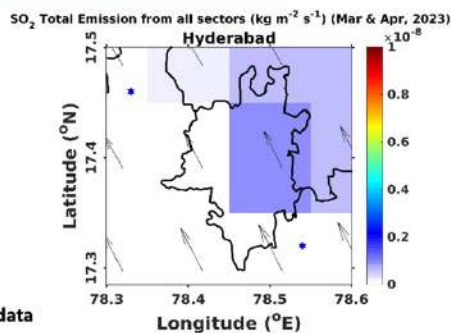
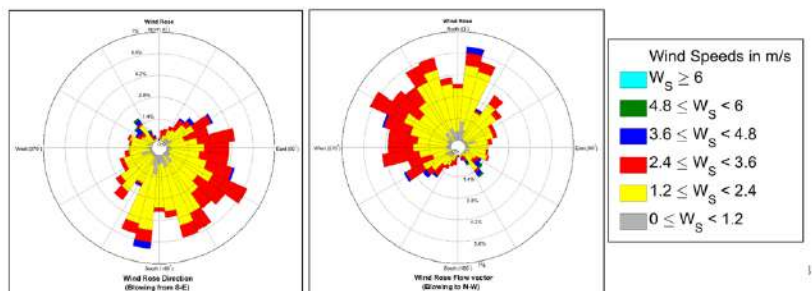


Figure 3.9: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category 1 City:
Hyderabad

Hyderabad SO₂ ($12.81 \pm 2.57 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

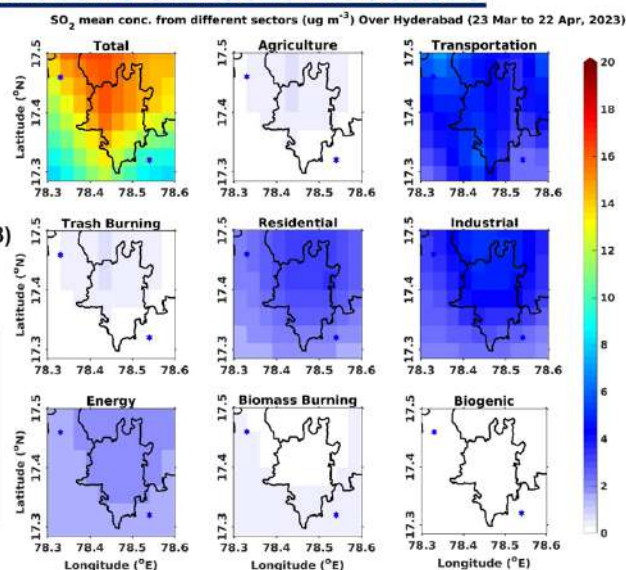
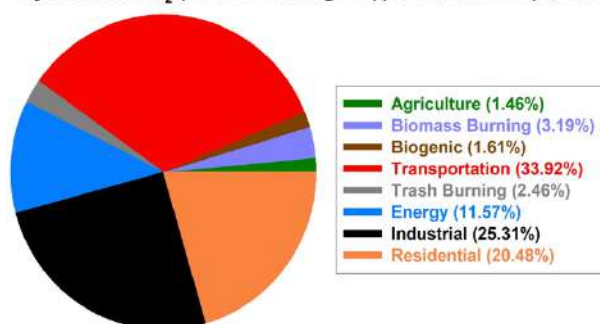


Figure 3.10: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category 1 City:
Hyderabad

Hyderabad SO₄ ($7.37 \pm 1.16 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

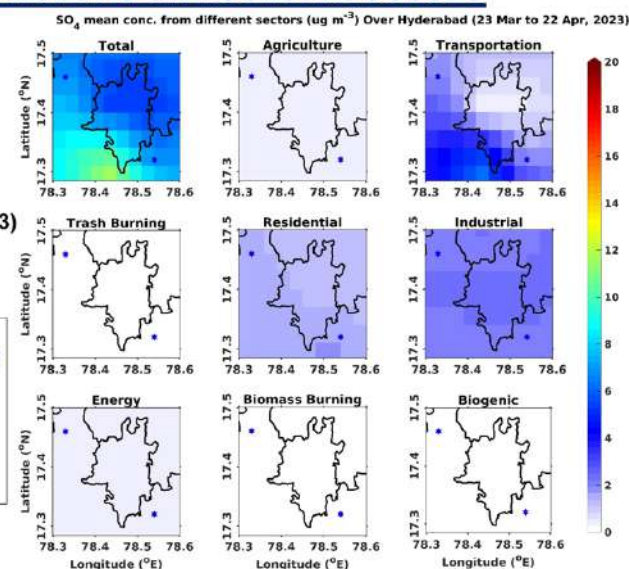
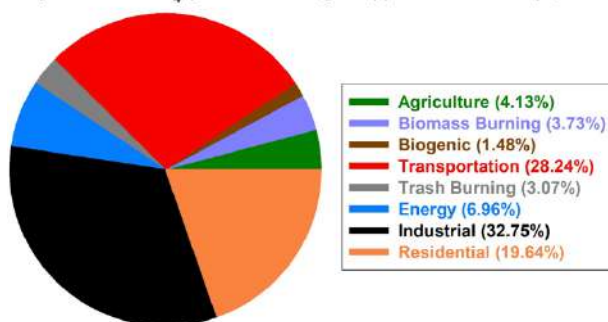


Figure 3.11: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category 1 City: Hyderabad

Hyderabad PM_{2.5} ($45.23 \pm 4.12 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

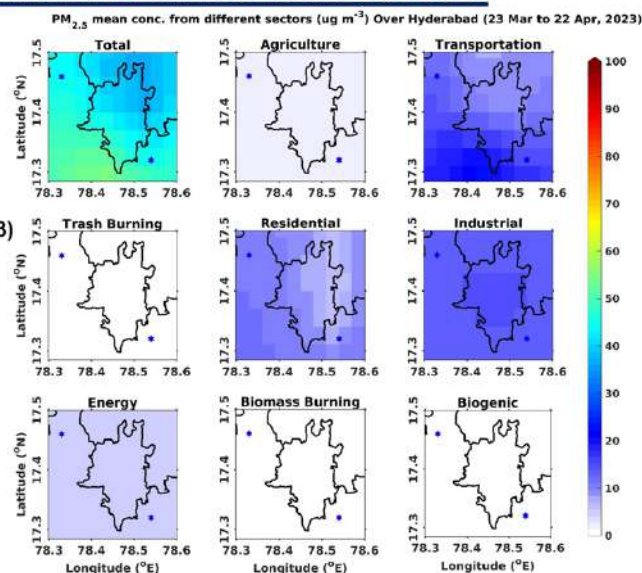
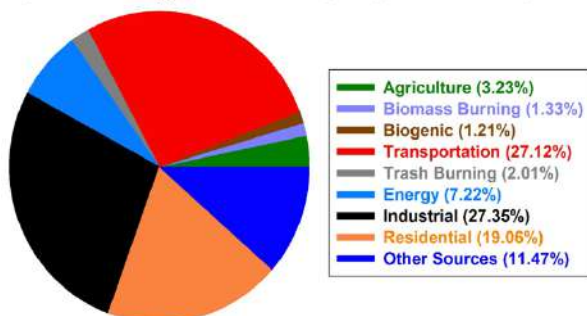


Figure 3.12: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category 1 City: Hyderabad

Hyderabad PM₁₀ ($85.18 \pm 6.54 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

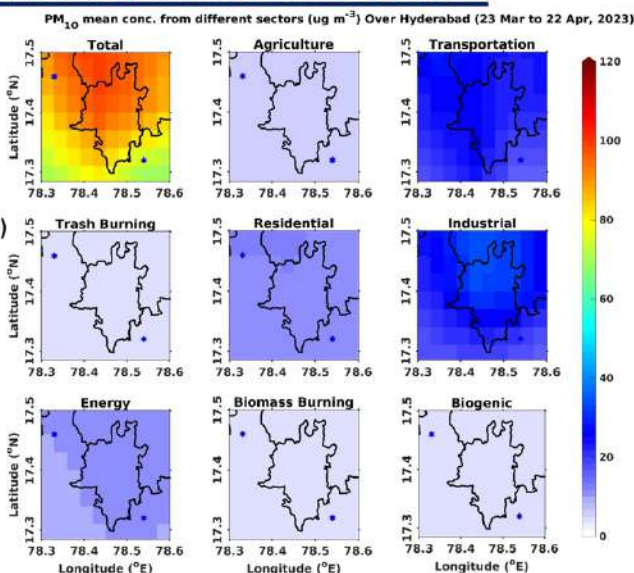
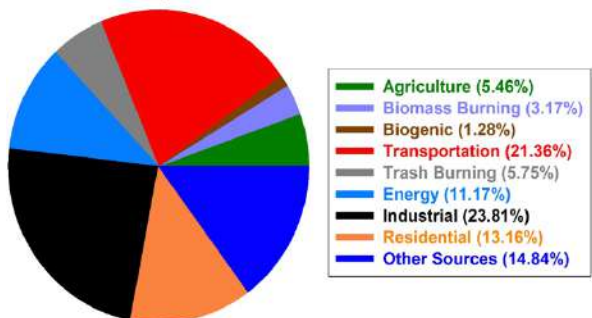


Figure 3.13: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Hyderabad during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category 1 City:
Hyderabad

Phase I
Pre-monsoon Season

Hyderabad PM_{2.5} ($45.23 \pm 4.12 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

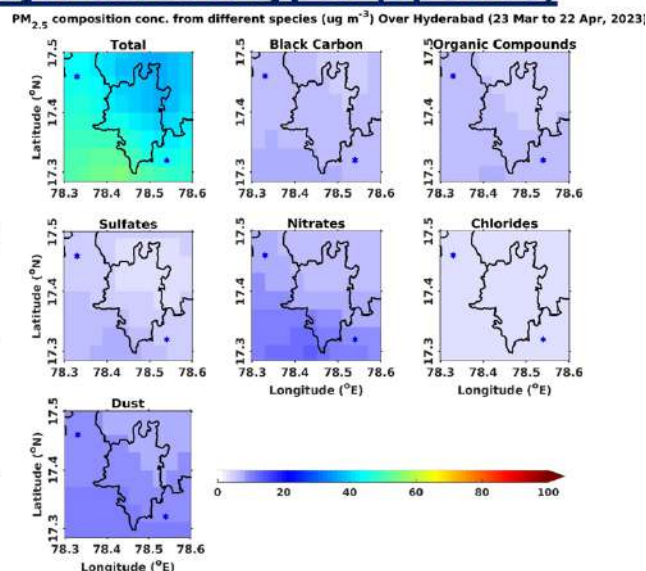
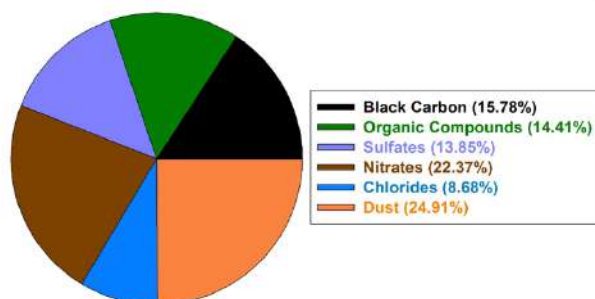


Figure 3.14: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category 1 City:
Hyderabad

Phase I
Pre-monsoon Season

Hyderabad PM₁₀ ($85.18 \pm 6.54 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

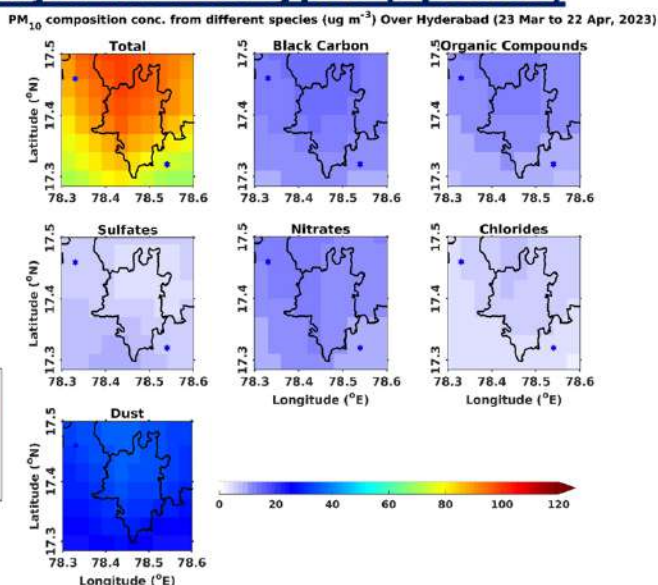
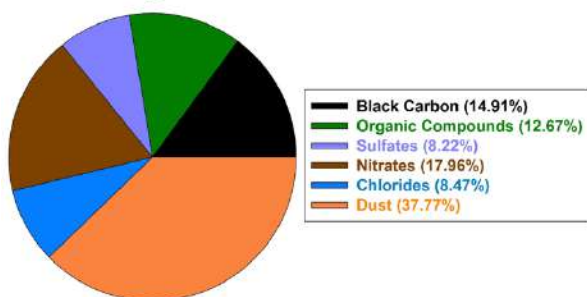


Figure 3.15: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from

thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category 1 City: Hyderabad

23rd March to 22 April 2023

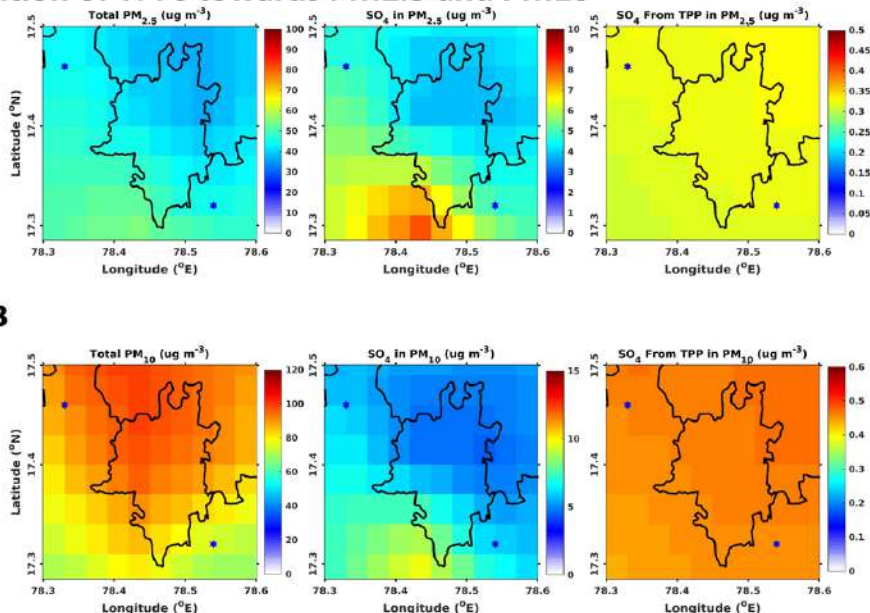


Figure 3.16: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Hyderabad during the simulation period from 23rd March to 22nd April 2023.

Next, we conducted another series of systematically designed WRF-Chem model simulations to determine the contributions of various sources to SO₂ and sulfate aerosols in Kolkata, the first Category-2 city considered during Phase-I of our survey. We also aimed to understand the power sector's impact on the ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in Kolkata during our survey. WRF-Chem version 4.2.2 was used to conduct a set of nine atmospheric chemistry simulations over Kolkata from March 23 to April 22, 2023. For this study, the model domains are centered at Kolkata (88.22° E and 22.34° N). Each simulation domain covers approximately 2,250,000 square kilometres with a horizontal resolution of 10 km², consisting of 150x150 grid cells in the outer domain. The inner domain has a horizontal resolution of 3 km² with 136x136 grid cells, following a nested WRF-Chem modeling setup with 44 vertical levels (using a hybrid-sigma coordinate system) extending from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis data (available at 6-hour intervals) with a resolution of 0.25°x0.25° were used to provide meteorological initial and lateral boundary conditions for the model simulations from March 23 to April 22, 2023. To estimate the sectoral emission contributions to the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Kolkata, we used an emission suppression method. We systematically designed a series of WRF-Chem model simulations where emissions from a particular sector were switched off in each simulation. The details of the simulation setup are described in Table 3.2.

Chemical Transport Modeling for Kolkata

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

Category 2 City:
Kolkata

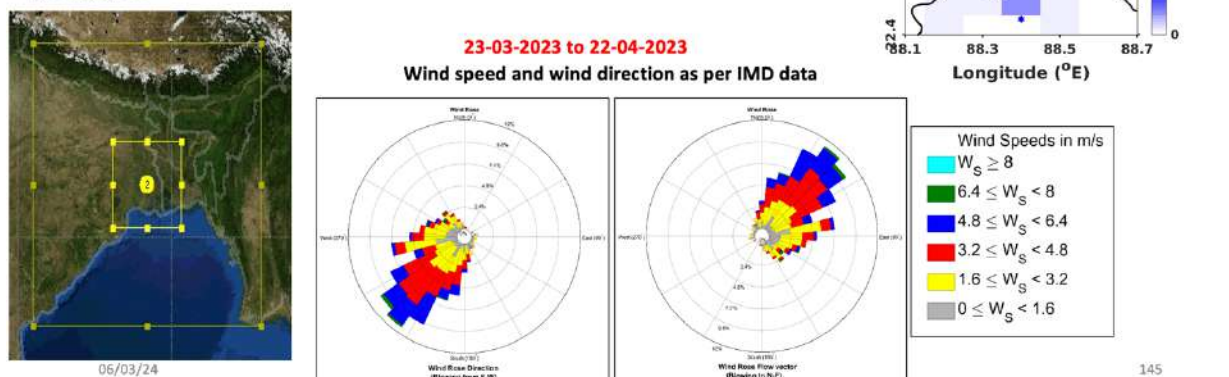


Figure 3.17: Simulation domain, gridded SO_2 emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Kolkata during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO_2

Category 2 City:
Kolkata

Kolkata SO_2 ($13.16 \pm 3.98 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

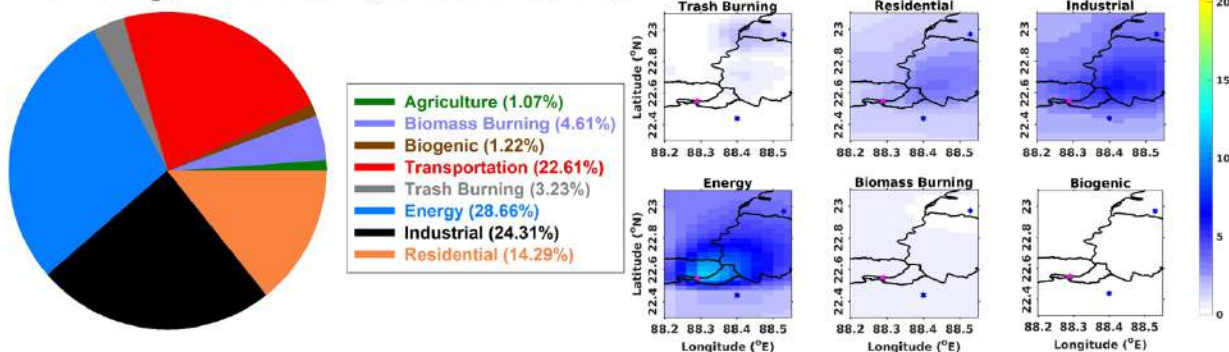


Figure 3.18: Contribution of different emission sectors towards ambient atmospheric SO_2 concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category 2 City:
Kolkata

Kolkata SO₄ ($8.28 \pm 1.97 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

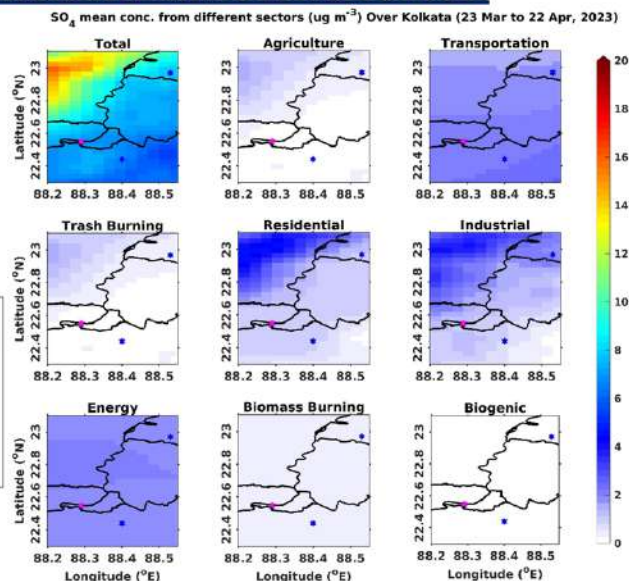
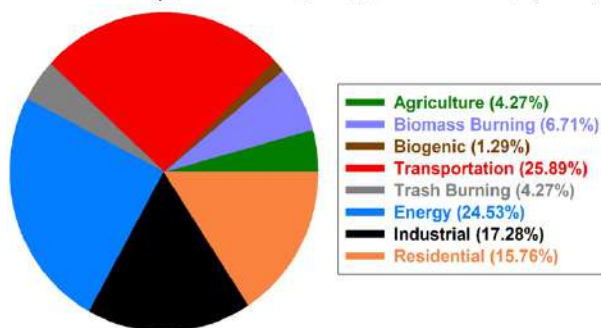


Figure 3.19: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category 2 City:
Kolkata

Kolkata PM_{2.5} ($31.53 \pm 7.75 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

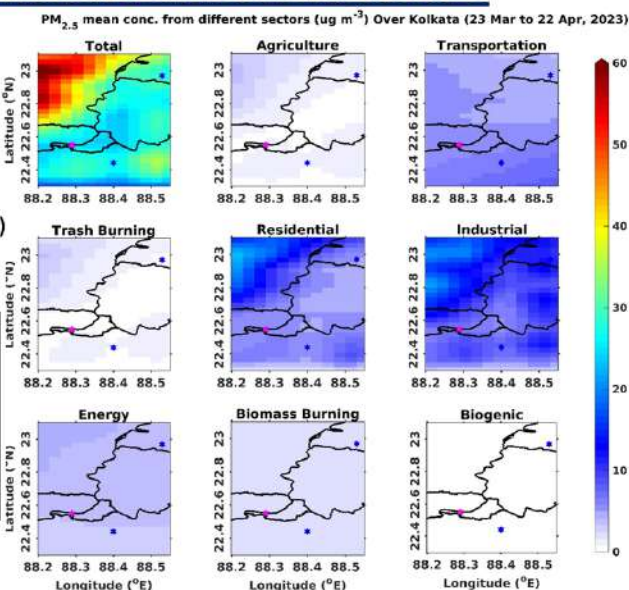
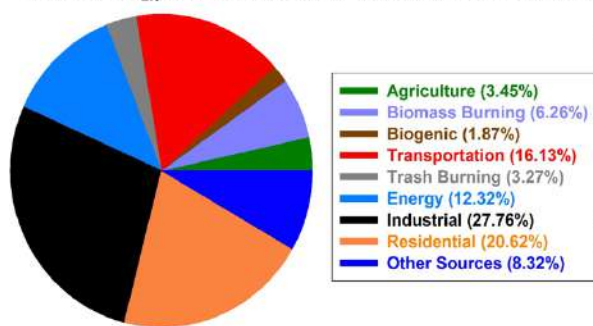


Figure 3.20: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category 2 City:
Kolkata

Kolkata PM₁₀ ($52.89 \pm 6.98 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

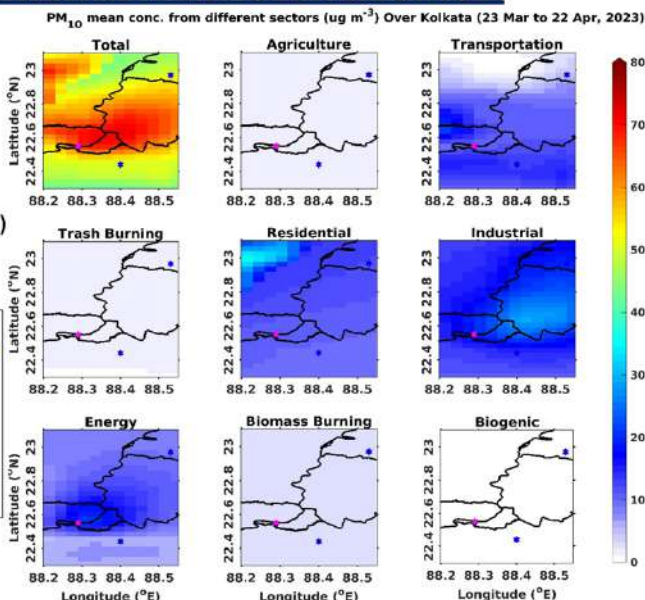
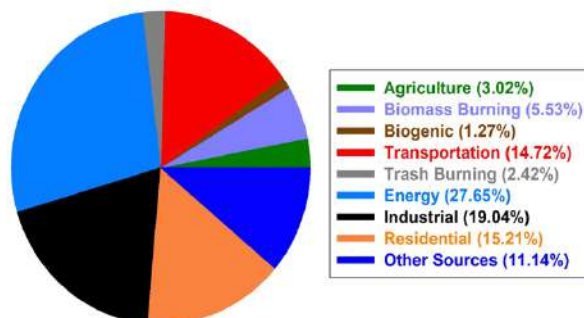


Figure 3.21: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Kolkata during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category 2 City:
Kolkata

Phase I
Pre-monsoon Season

Kolkata PM_{2.5} ($31.53 \pm 7.75 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

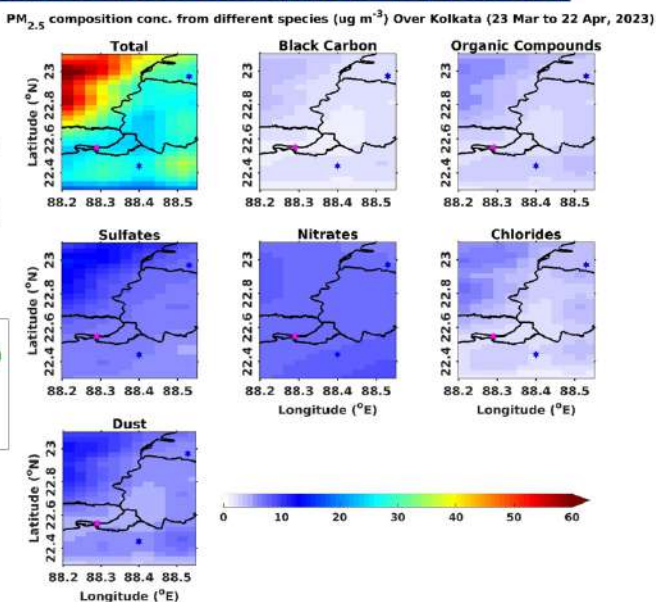
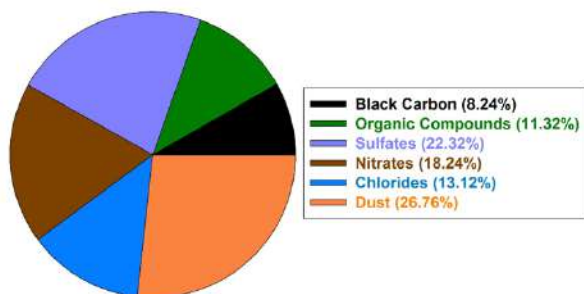


Figure 3.22: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category 2 City:
Kolkata

Phase I
Pre-monsoon Season

Kolkata PM₁₀ ($52.89 \pm 6.98 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

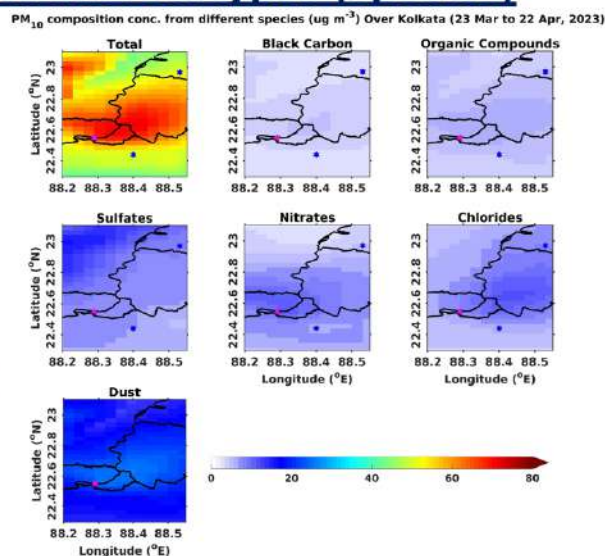
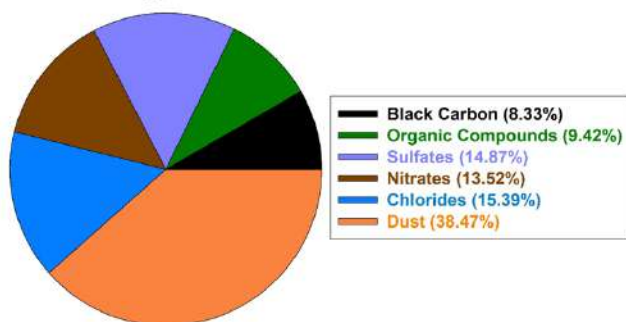


Figure 3.23: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Kolkata during the simulation period from 23 March to 22 April 2023.

By assessing the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of emissions from the energy sector, particularly SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ in the city of Kolkata that originated from SO₂ emissions from TPPs during our survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category 2 City:
Kolkata

23rd March to 22 April 2023

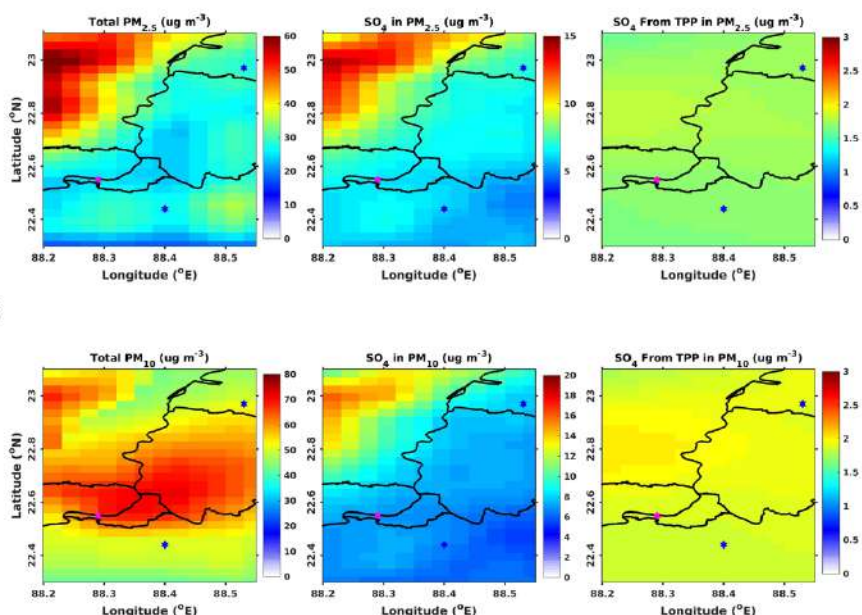


Figure 3.24: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Kolkata during the simulation period from 23rd March to 22nd April 2023.

Next, we conducted another series of systematically designed WRF-Chem model simulations to determine the contributions of different sources to SO₂ and sulfate aerosols in Nagpur, the second Category-2 city considered during Phase-I of our survey. Additionally, we aimed to understand the contribution of the power sector to the ambient atmospheric concentrations of SO₂, PM_{2.5}, and PM₁₀ in Nagpur during our survey. For this study, we used WRF-Chem version 4.2.2 to perform a set of nine atmospheric chemistry simulations over Nagpur from March 23 to April 22, 2023. The model domains are centered at Nagpur (79.04°E, 21.08°N). Each simulation domain covers approximately 2,250,000 square kilometres, with a horizontal resolution of 10x10 km² in the outer domain (150x150 grid cells) and 3x3 km² in the inner domain (136x136 grid cells), following a nested WRF-Chem modeling setup. The model uses 44 vertical levels (on a hybrid-sigma coordinate system) from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis data (available at six-hourly intervals) with a resolution of 0.25°x0.25° provided the meteorological initial and lateral boundary conditions for the simulation period. To estimate the sectoral emission contributions to the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Nagpur, we used an emission suppression method. This involved a series of systematically designed WRF-Chem model simulations in which emissions from specific sectors were switched off in each simulation. The details of the simulation setup are described in Table 3.2.

Chemical Transport Modeling for Nagpur

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

**Category 2 City:
Nagpur**

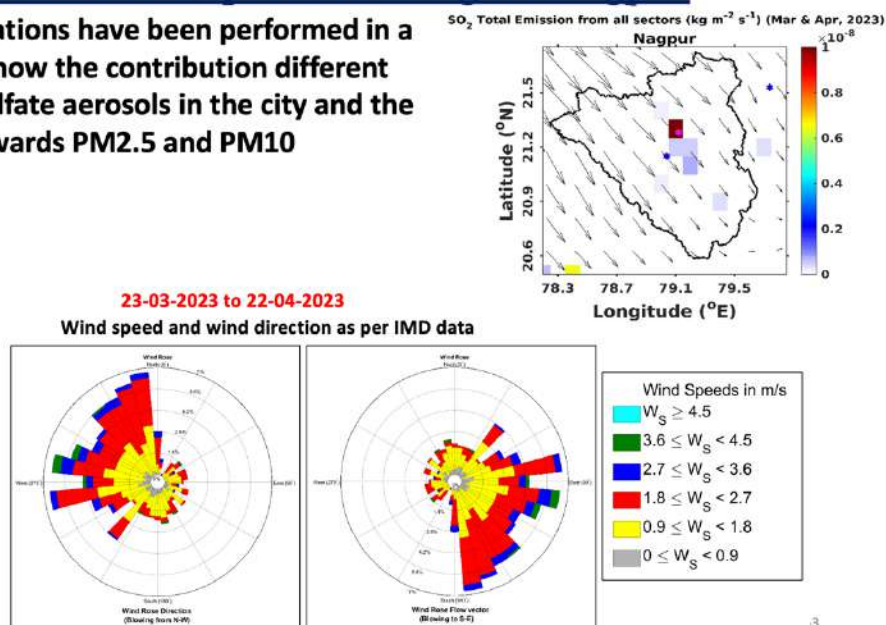
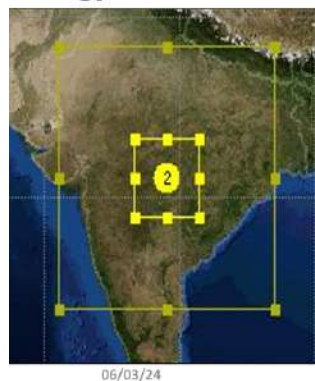


Figure 3.25: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Nagpur during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category 2 City:
Nagpur

Nagpur SO₂ ($14.28 \pm 6.27 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

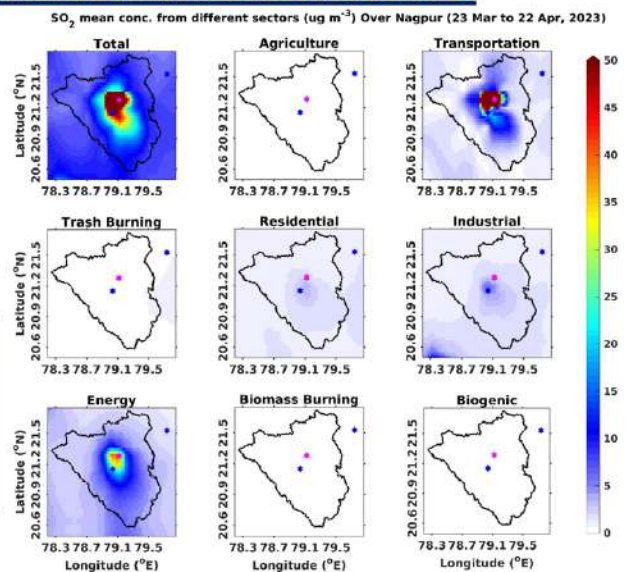
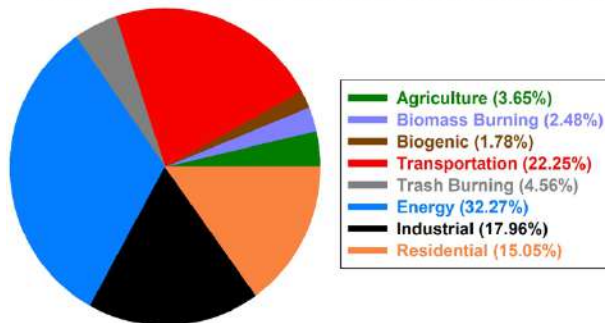


Figure 3.26: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category 2 City:
Nagpur

Nagpur SO₄ ($10.42 \pm 2.87 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

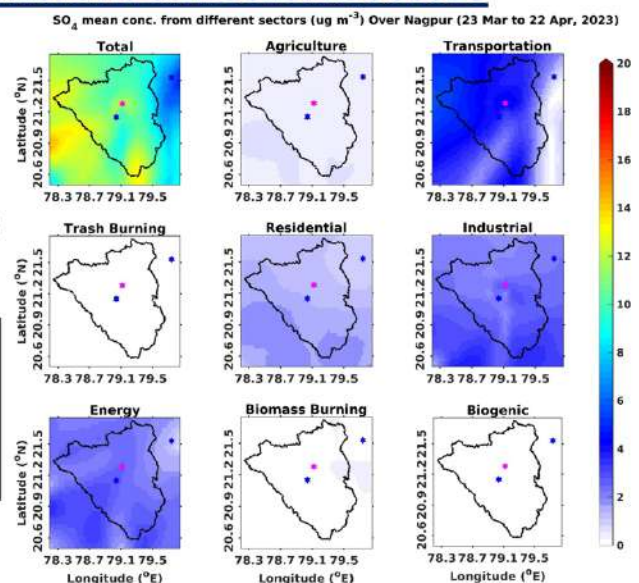
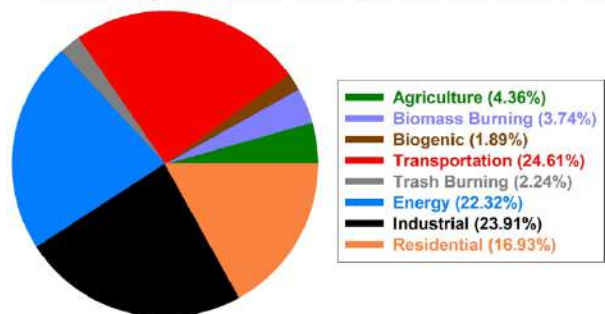


Figure 3.27: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category 2 City:
Nagpur

Nagpur PM_{2.5} ($62.53 \pm 6.06 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

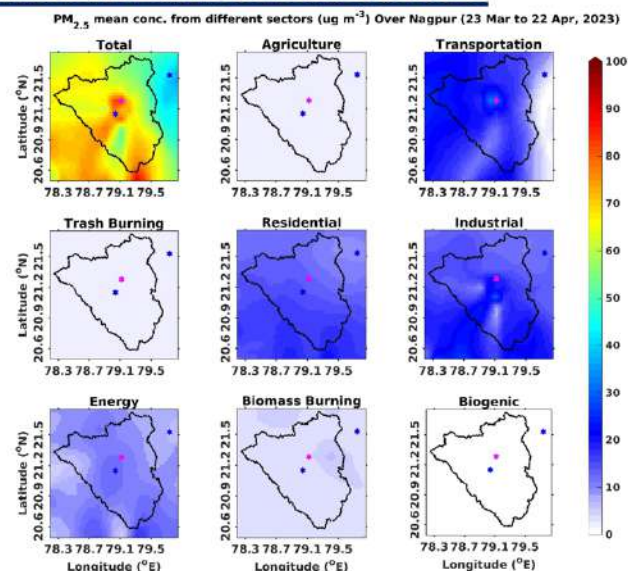
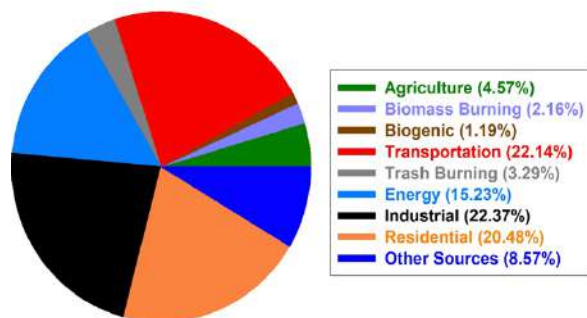


Figure 3.28: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category 2 City:
Nagpur

Nagpur PM₁₀ ($83.71 \pm 6.58 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

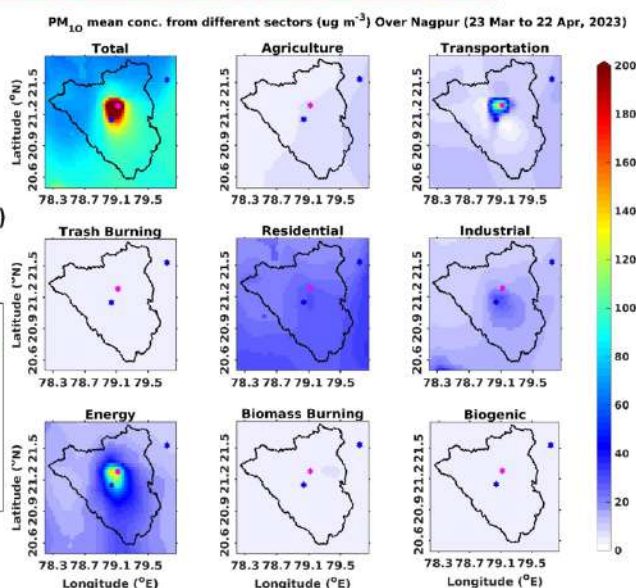
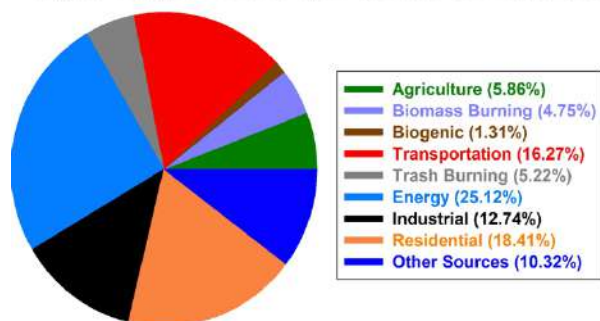


Figure 3.29: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

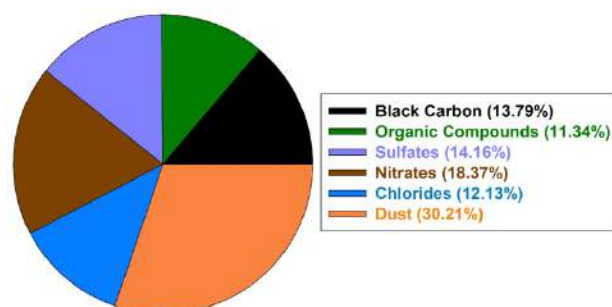
Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Nagpur during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category 2 City:
Nagpur

Phase I
Pre-monsoon Season

Nagpur PM_{2.5} ($62.53 \pm 6.06 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



PM_{2.5} composition conc. from different species (ug m^{-3}) Over Nagpur (23 Mar to 22 Apr, 2023)

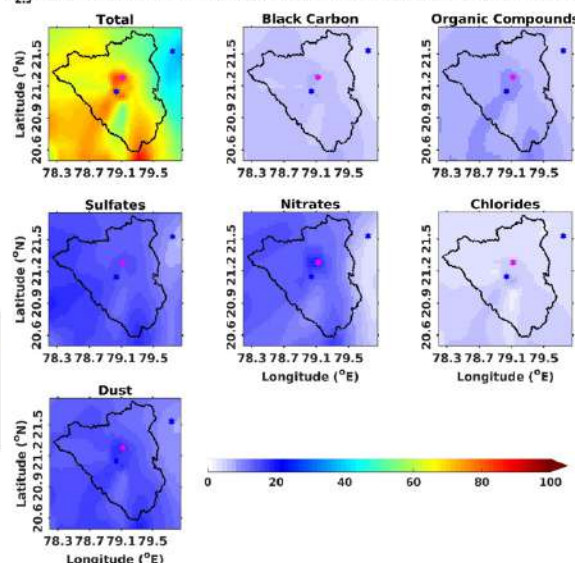


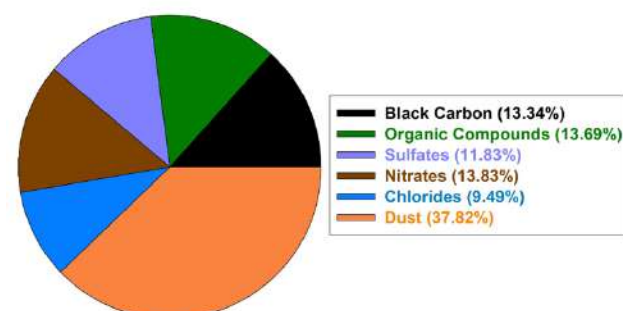
Figure 3.30: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category 2 City:
Nagpur

Phase I
Pre-monsoon Season

Nagpur PM₁₀ ($83.71 \pm 6.58 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



PM₁₀ composition conc. from different species (ug m^{-3}) Over Nagpur (23 Mar to 22 Apr, 2023)

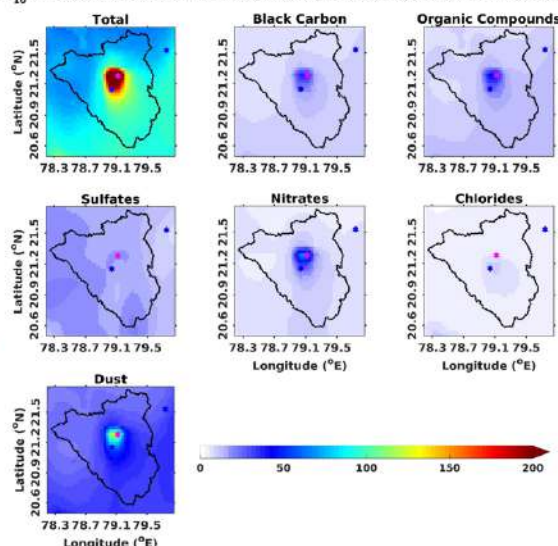


Figure 3.31: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

By assessing the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of emissions from the energy sector, particularly SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5}

and PM10 that originated from SO₂ emissions from TPPs in the city of Nagpur during the survey period.

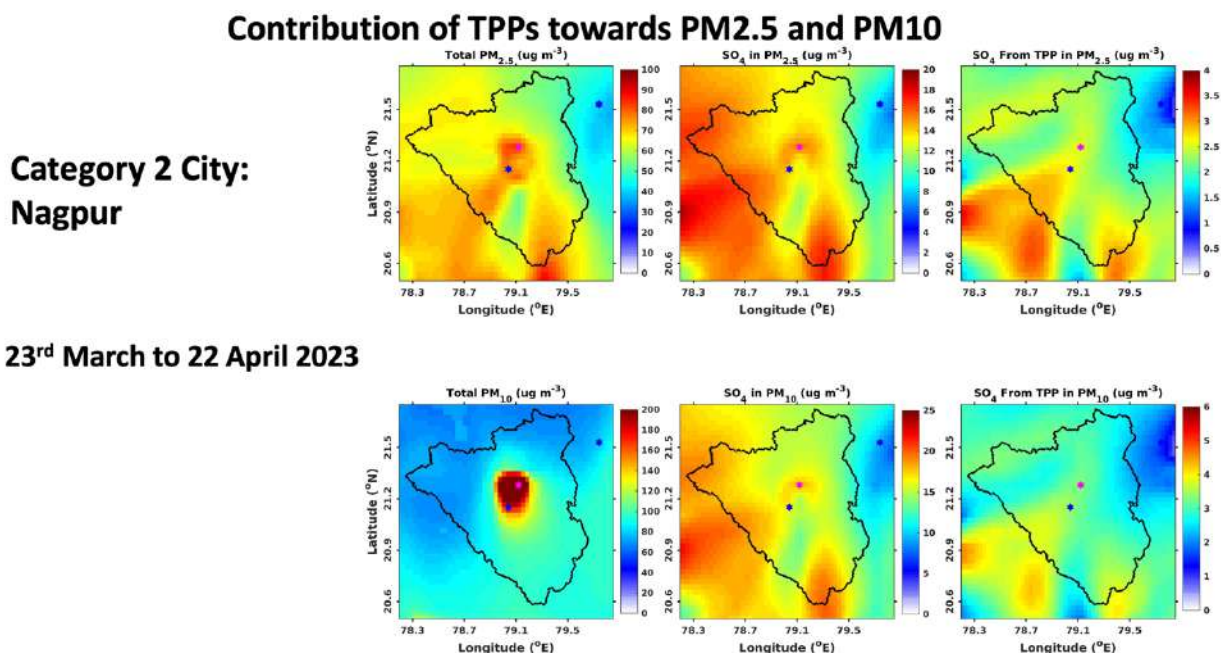


Figure 3.32: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Nagpur during the simulation period from 23rd March to 22nd April 2023.

Next, we conducted another series of systematically designed WRF-Chem model simulations to determine the contribution of different sources to SO₂ and sulfate aerosols in Gautam Buddha Nagar, the first Category-3 city considered during Phase-I of our survey. Additionally, we aimed to understand the impact of the power sector on ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in Gautam Buddha Nagar during the survey period. We used WRF-Chem version 4.2.2 to perform a set of nine atmospheric chemistry simulations over Gautam Buddha Nagar from March 23 to April 22, 2023. The model domains are centered at Gautam Buddha Nagar (77.61° E and 28.34° N). Each simulation domain covers approximately 2,250,000 square kilometers with a horizontal resolution of 10x10 km², consisting of 150x150 grid cells in the outer domain, and a horizontal resolution of 3x3 km² with 136x136 grid cells in the inner domain, following a nested WRF-Chem modeling setup. The model features 44 vertical levels on a hybrid-sigma coordinate system, starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis data (available at 6-hour intervals) with a resolution of 0.25°x0.25° were used to provide meteorological initial and lateral boundary conditions for the simulations. To estimate the sectoral emission contributions to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Gautam Buddha Nagar, we employed an emission suppression method. We modified the emissions assuming that FGD was operational in only two units of the NTPC Dadri TPP during Phase I of our survey. We systematically designed the WRF-

Chem simulations so that emissions from a particular sector were switched off in each simulation. The details of the simulation setup are described in Table 3.2.

Chemical Transport Modeling for GBN

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

Category-3 City:

Gautam Buddha

Nagar, Uttar

Pradesh

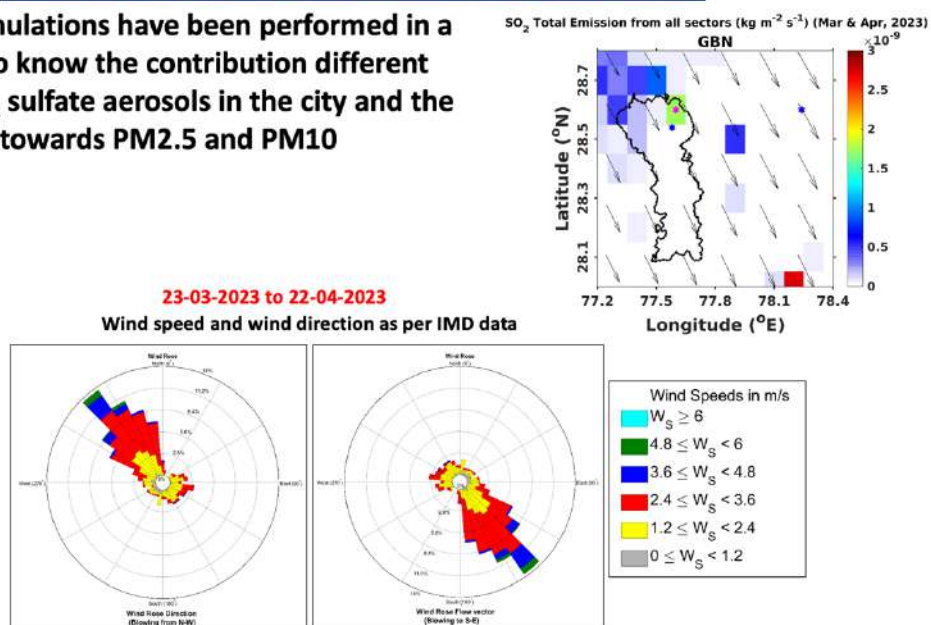


Figure 3.33: Simulation domain, gridded SO_2 emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Gautam Buddha Nagar during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO_2

Category-3 City:

Gautam Buddha

Nagar, Uttar

Pradesh

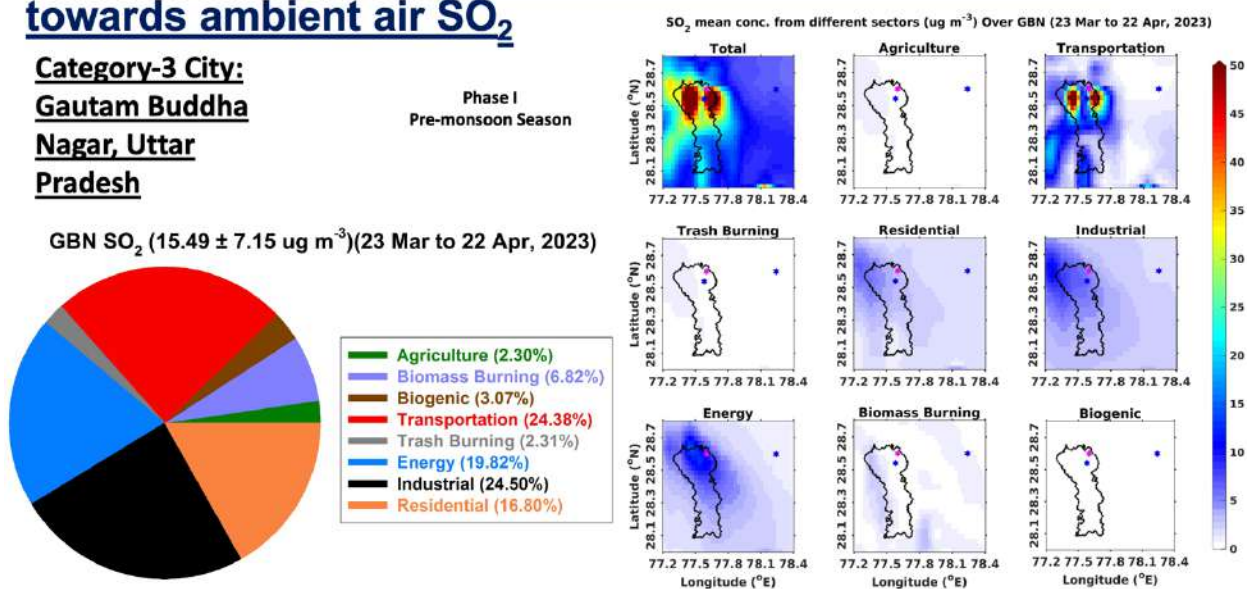


Figure 3.34: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in GBN during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

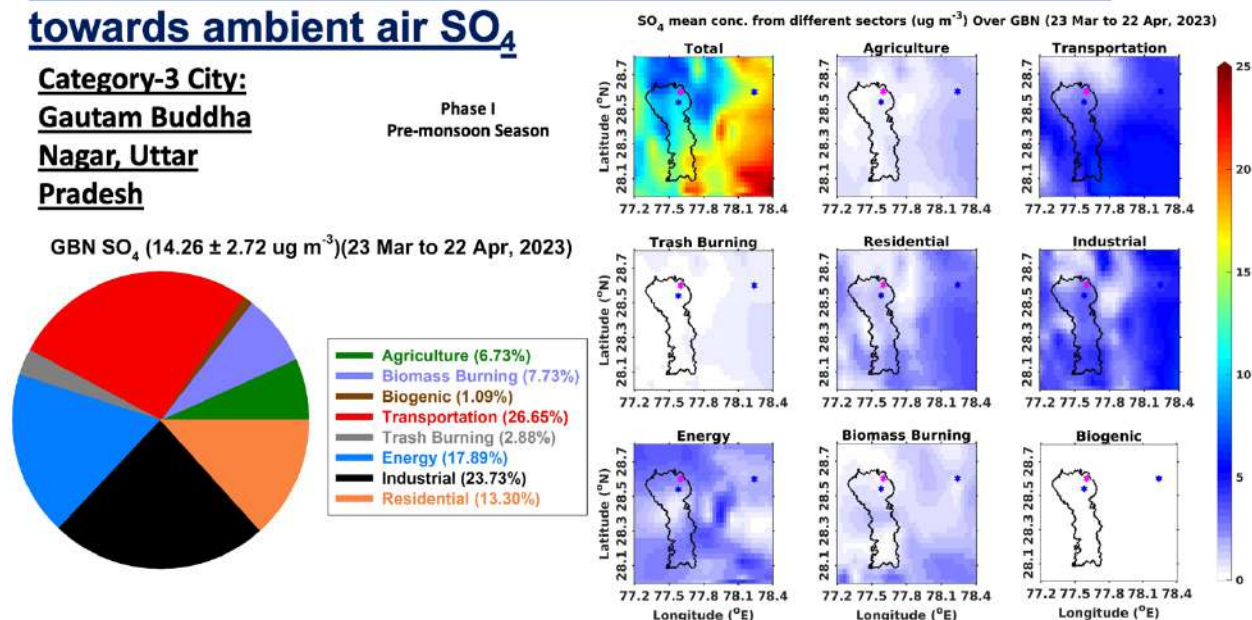


Figure 3.35: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in GBN during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM2.5

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

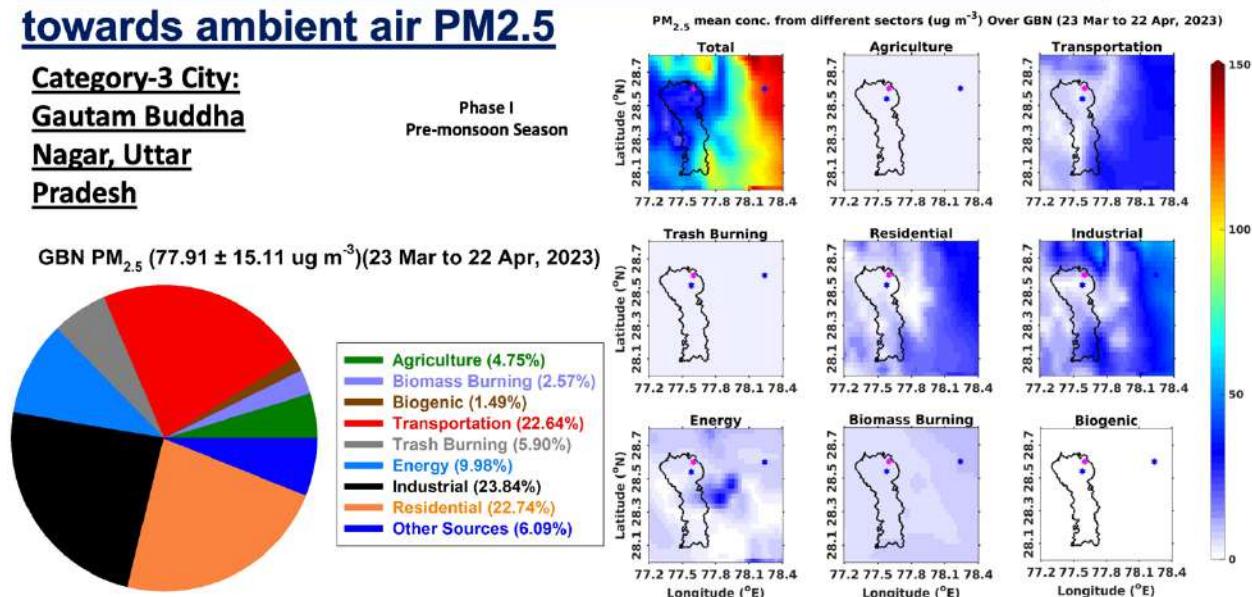


Figure 3.36: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in GBN during the simulation period from 23 March to 22 April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

Phase I
Pre-monsoon Season

GBN PM₁₀ ($131.35 \pm 16.21 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

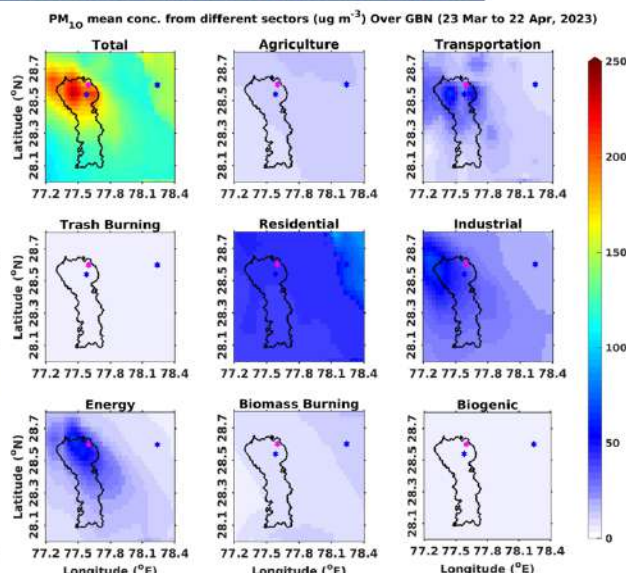
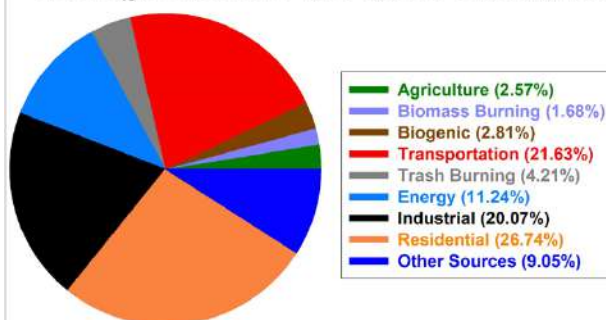


Figure 3.37: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 23rd March to 22nd April 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Gautam Buddha Nagar during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

Phase I
Pre-monsoon Season

GBN PM_{2.5} ($77.91 \pm 15.11 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

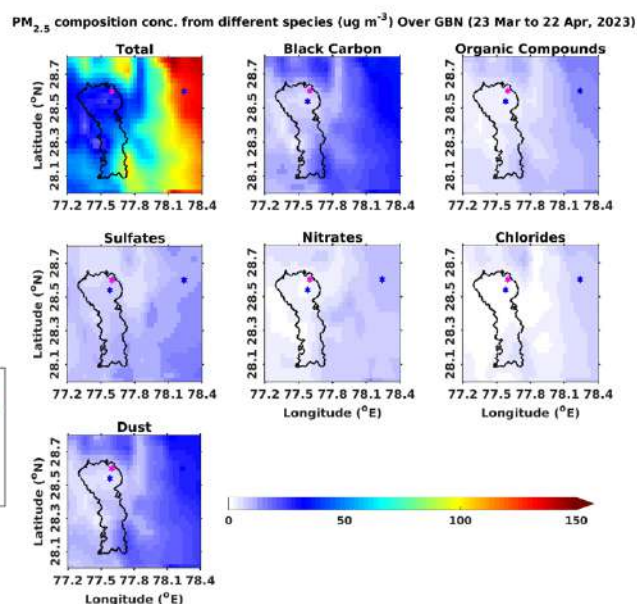
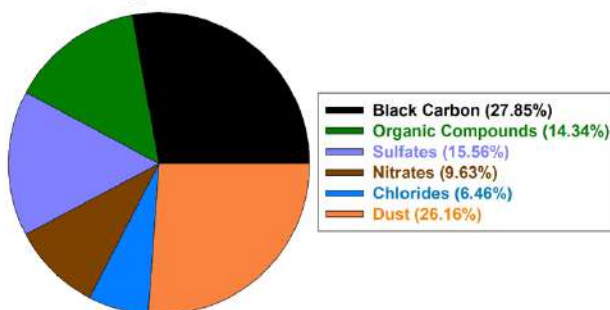
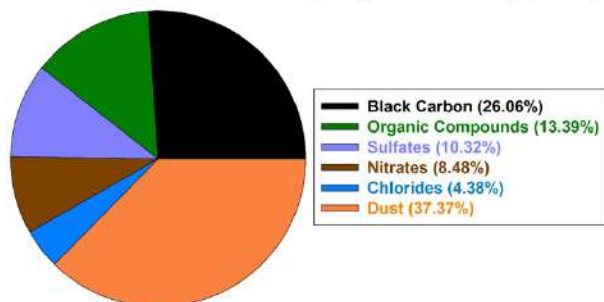


Figure 3.38: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in GBN during the simulation period from 23 March to 22 April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

GBN PM₁₀ (131.35 ± 16.21 ug m⁻³)(23 Mar to 22 Apr, 2023)



Phase I
Pre-monsoon Season

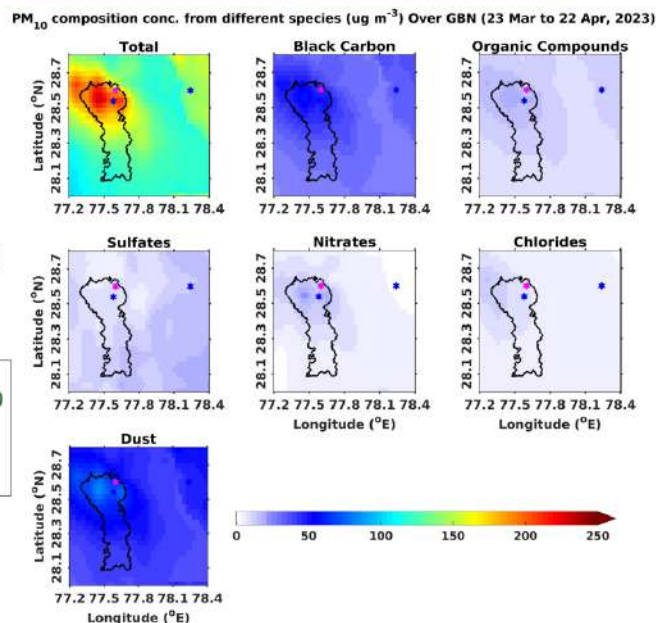
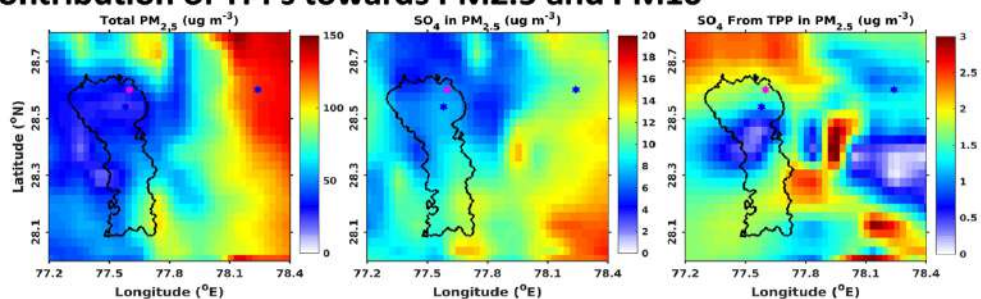


Figure 3.39: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 23rd March to 22nd April 2023. By assessing the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of emissions from the energy sector, particularly SO₂ emissions from TPPs, we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ in the city of Gautam Buddha Nagar that originated from SO₂ emissions from TPPs during the survey period.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh



23rd March to 22 April 2023

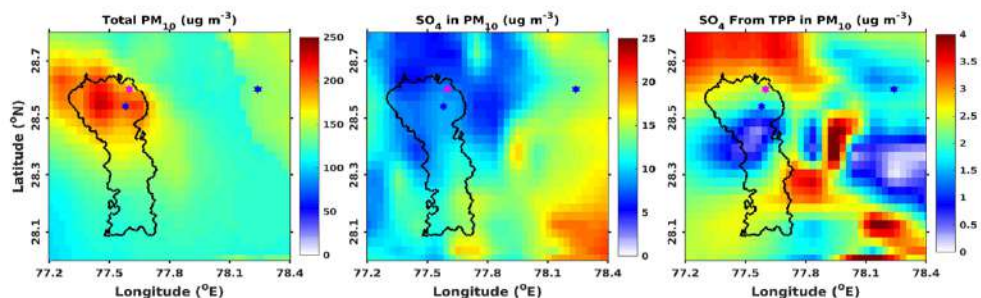


Figure 3.40: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in GBN during the simulation period from 23rd March to 22nd April 2023.

We conducted another series of systematically designed WRF-Chem model simulations to analyse the contribution of various sources to SO₂ and sulfate aerosols in Ghaziabad, the first Category-3 city in Phase-I of our survey. Additionally, we aimed to understand the influence of the power sector on ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in Ghaziabad during our survey. We utilized WRF-Chem version 4.2.2 to conduct a series of nine atmospheric chemistry simulations over Ghaziabad from March 23 to April 22, 2023. The model domains are centered at Ghaziabad (77.25° E and 28.40° N). Each simulation domain encompasses approximately 2,250,000 square kilometres with a horizontal resolution of 10x10 km², consisting of 150x150 grid cells in the outer domain, and a horizontal resolution of 3x3 km² with 136x136 grid cells in the inner domain following a nested WRF-Chem modeling setup. The model features 44 vertical levels on a hybrid-sigma coordinate system, extending from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis data (available at 6-hour intervals) with a resolution of 0.25°x0.25° were utilized to provide meteorological initial and lateral boundary conditions for the simulations. To estimate the sectoral emission contributions to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Ghaziabad, we implemented an emission suppression method. We modified the emissions assuming that FGD was operational in only two units of the NTPC Dadri TPP during Phase I of our survey. We conducted a series of systematically designed WRF-Chem model simulations by disabling emissions from a specific emission sector in each simulation. The simulation setup details are provided in Table 3.2.

Chemical Transport Modeling for Ghaziabad

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City:
Ghaziabad,
Uttar Pradesh

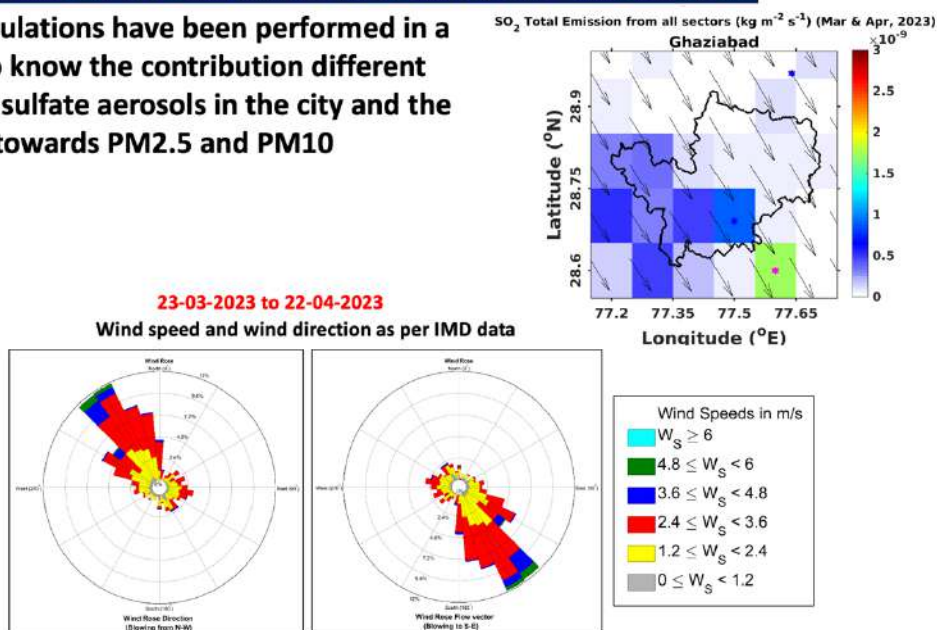


Figure 3.41: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-3 City:
Ghaziabad,
Uttar Pradesh

Ghaziabad SO₂ ($13.73 \pm 10.03 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

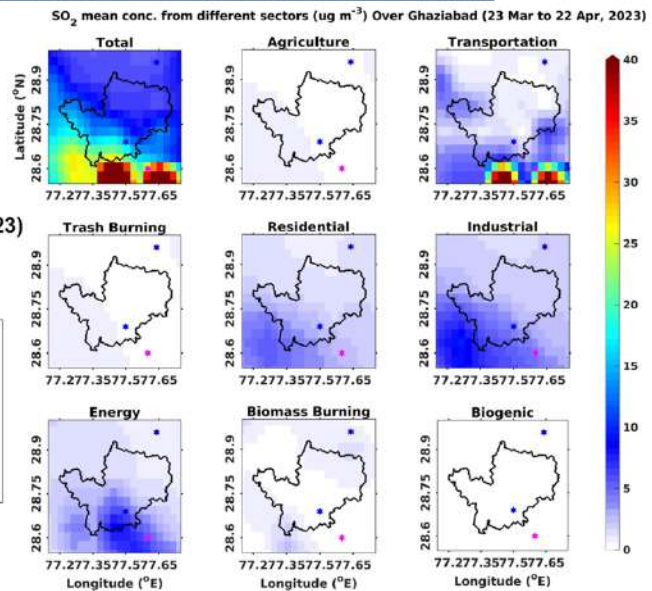
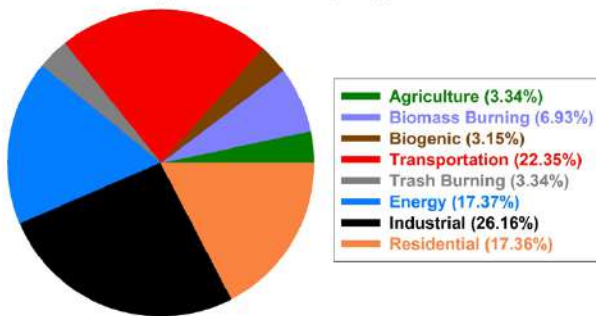


Figure 3.42: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-3 City:
Ghaziabad,
Uttar Pradesh

Ghaziabad SO₄ ($12.17 \pm 3.79 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)

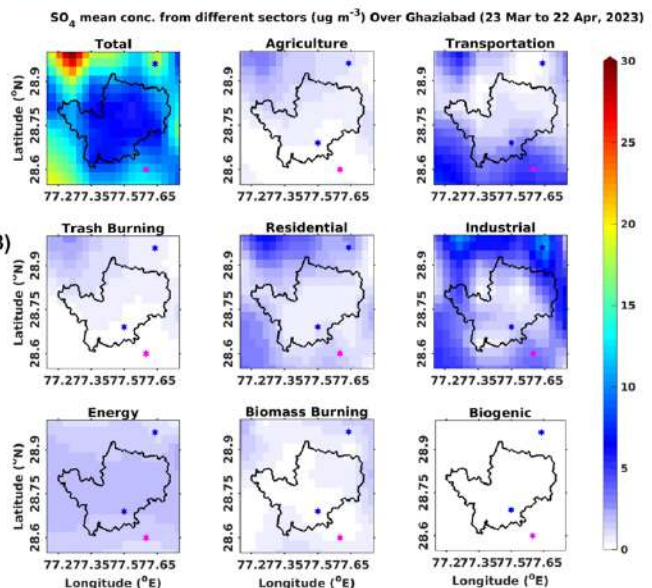
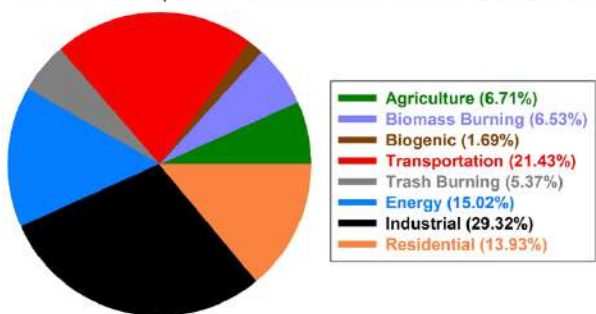
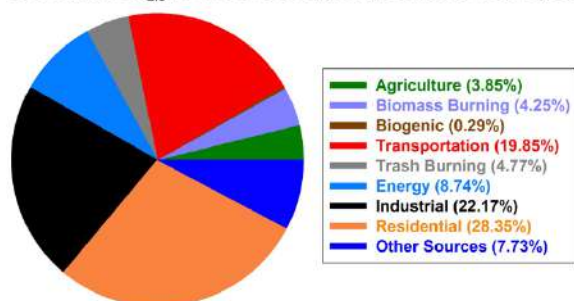


Figure 3.43: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category-3 City:
Ghaziabad,
Uttar Pradesh

Ghaziabad PM_{2.5} ($72.11 \pm 29.61 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



Phase I
Pre-monsoon Season

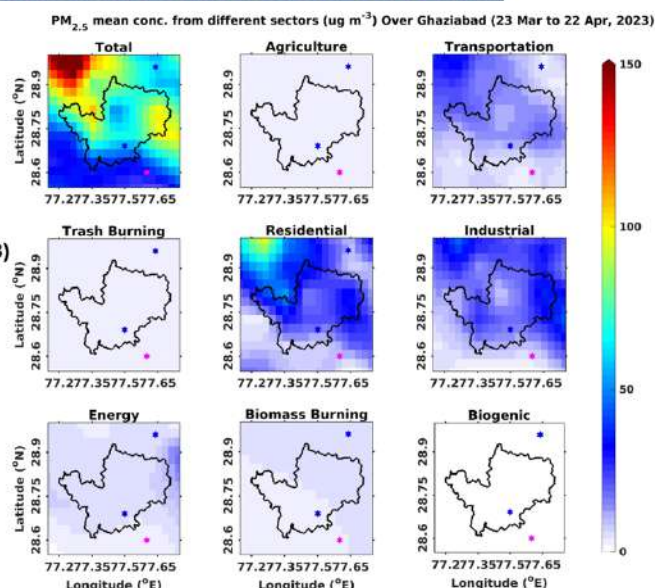
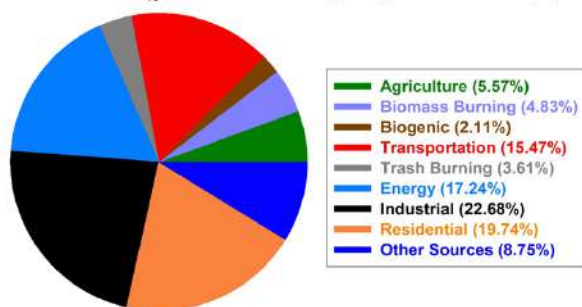


Figure 3.44: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category-3 City:
Ghaziabad,
Uttar Pradesh

Ghaziabad PM₁₀ ($122.89 \pm 25.99 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



Phase I
Pre-monsoon Season

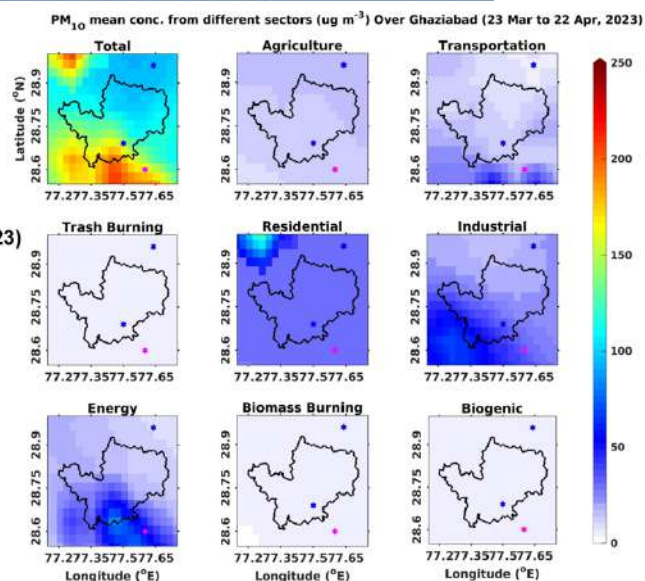


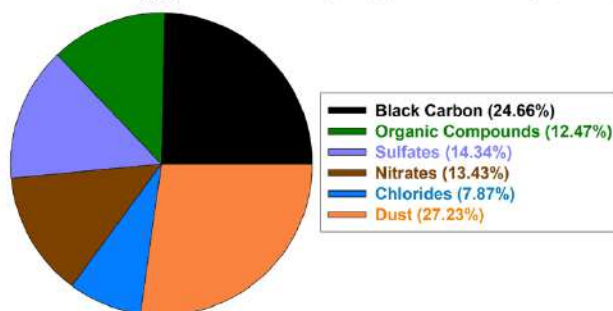
Figure 3.45: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023. Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Ghaziabad during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-3 City:
Ghaziabad,
Uttar Pradesh

Phase I
Pre-monsoon Season

Ghaziabad PM_{2.5} ($72.11 \pm 29.61 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



PM_{2.5} composition conc. from different species (ug m^{-3}) Over Ghaziabad (23 Mar to 22 Apr, 2023)

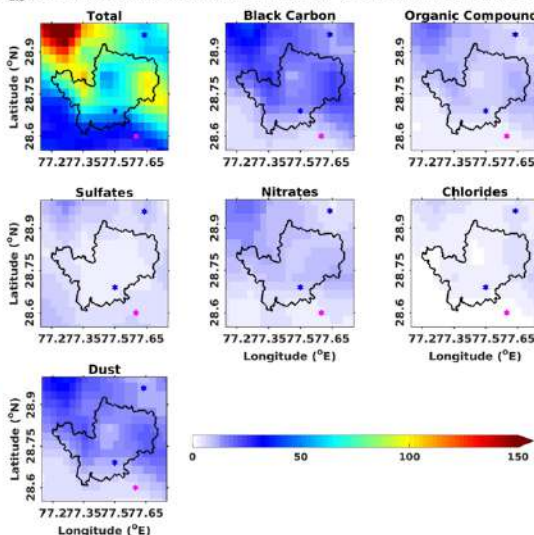


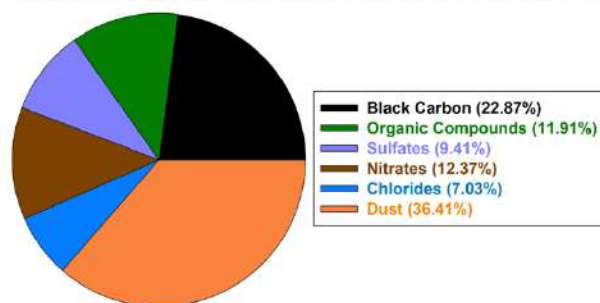
Figure 3.46: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-3 City:
Ghaziabad,
Uttar Pradesh

Phase I
Pre-monsoon Season

Ghaziabad PM₁₀ ($122.89 \pm 25.99 \text{ ug m}^{-3}$)(23 Mar to 22 Apr, 2023)



PM₁₀ composition conc. from different species (ug m^{-3}) Over Ghaziabad (23 Mar to 22 Apr, 2023)

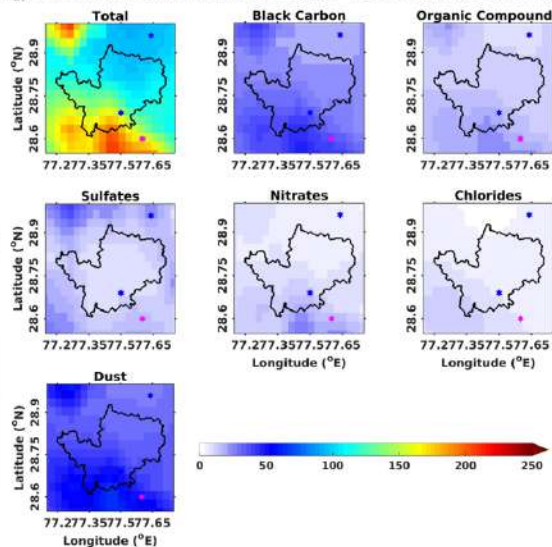


Figure 3.47: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

By assessing the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of emissions from the energy sector, particularly SO₂ emissions from TPPs,

we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the city of Ghaziabad during the survey period.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City:
Ghaziabad,
Uttar Pradesh

23rd March to 22 April 2023

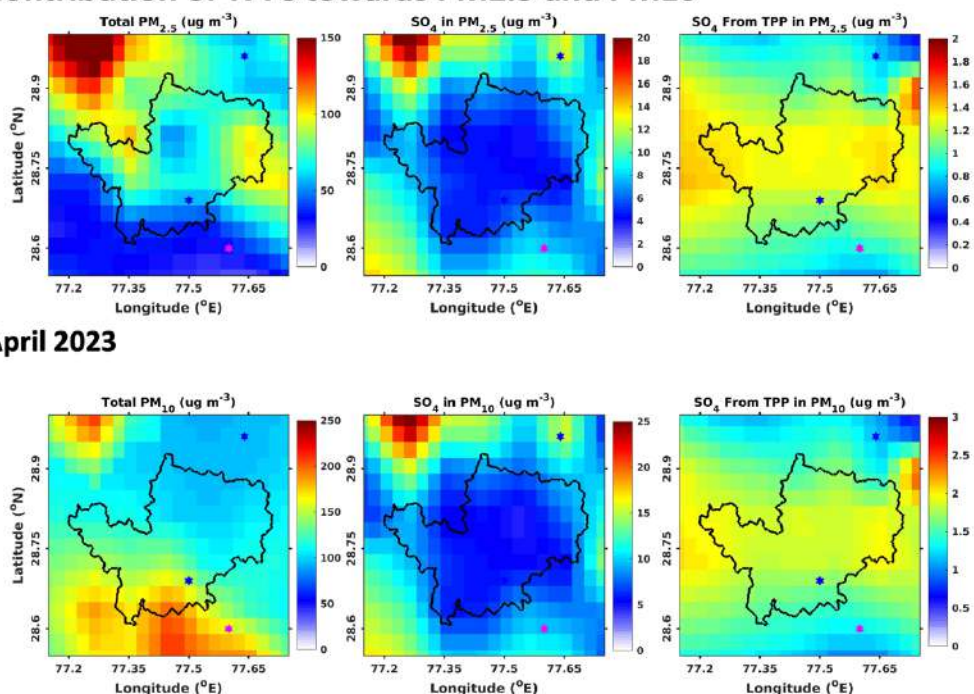


Figure 3.48: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Ghaziabad during the simulation period from 23rd March to 22nd April 2023.

Based on the results from a series of meticulously planned simulations, the contribution of SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric SO₂ concentrations during Phase I of the survey (Pre-monsoon season) exhibits significant spatial variability and distinct trends across all cities. Despite this variability, we analyse the average contribution of TPPs to ambient atmospheric SO₂ concentrations in each city and city category. In Category-1 cities, which have no coal-based TPPs, New Delhi and Hyderabad exhibit different contributions. In New Delhi, the power sector's contribution to ambient SO₂ concentrations is consistent at 16.53% across two survey periods. In Hyderabad, the power sector's contribution is lower, averaging 11.57%. In Category-2 cities, which have coal-based TPPs without installed FGD within 10 km of the city boundary, the average contribution of the power sector to ambient SO₂ concentrations is higher. Kolkata shows an average contribution of 28.66%, while Nagpur displays a slightly higher average contribution of 32.27%. In Category-3 cities, which have coal-based TPPs with installed FGD within 10 km of the city boundary, the contributions are lower than in Category-2 cities. In Ghaziabad, the average contribution from the power sector is 17.37%, while in Gautam Buddha Nagar, it is slightly higher at 19.82%. In summary, Category-2 cities, which have TPPs without FGD systems, exhibit the highest average contribution of TPPs to ambient SO₂ concentrations, followed by Category-3 cities, where TPPs have installed FGDs, and finally,

Category-1 cities, which have no coal-based TPPs. This pattern highlights the significant impact of TPPs, particularly those without FGDs, on the SO₂ levels in nearby cities.

After discussing the average contribution of TPPs to ambient atmospheric SO₂ concentrations in each city and city category, we examine the normalized contribution of the power sector, specifically coal-based thermal power plants (TPPs), to ambient atmospheric SO₂ concentrations at specific measurement locations across different cities during our survey period. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that ambient air SO₂ concentrations at all measurement locations across the six cities met the existing standards during the survey period. Examining the variability in the normalized contribution of the power sector, specifically coal-based thermal power plants (TPPs), to ambient atmospheric SO₂ concentrations reveals significant differences across various cities and city categories during our survey period. In Category-1 cities with no coal-based TPPs, the contribution of the power sector to ambient SO₂ concentrations is relatively low, ranging from 9% to 19%. For instance, New Delhi locations show SO₂ contributions of 18% and 19%, with absolute concentrations of 1.67 ± 0.93 µg/m³ and 1.37 ± 0.61 µg/m³, respectively. Hyderabad locations report contributions of 9% and 15%, with absolute concentrations of 0.42 ± 0.07 µg/m³ and 0.37 ± 0.03 µg/m³, respectively. In Category-2 cities, where TPPs without FGD installations are located within 10 km from the city boundary, the contributions are markedly higher. For instance, Kolkata locations show contributions of 23% and 25%, with absolute concentrations of 1.49 ± 0.09 µg/m³ and 1.08 ± 0.03 µg/m³, respectively, while Nagpur locations report even higher contributions of 39% and 22%, with absolute concentrations of 2.37 ± 0.31 µg/m³ and 0.78 ± 0.17 µg/m³, respectively. This indicates the significant impact of nearby TPPs without FGD systems on local air quality. Category-3 cities, with TPPs having FGD installations within 10 km, exhibit varied contributions. Ghaziabad locations show contributions of 33% and 13%, with absolute concentrations of 2.81 ± 0.72 µg/m³ and 1.03 ± 0.47 µg/m³, respectively, while Gautam Buddha Nagar locations have contributions of 26% and 17%, with absolute concentrations of 2.56 ± 0.62 µg/m³ and 1.41 ± 0.43 µg/m³, respectively. These findings highlight that the presence and proximity of TPPs, along with the implementation of FGD systems, play crucial roles in determining the extent of SO₂ emissions from the power sector, thereby influencing local air quality.

Table 3.5 summarizes the contribution of sulfate aerosols (SO₄) in PM_{2.5} and PM₁₀, as well as the specific contribution of sulfate aerosols originating from SO₂ emissions from the power sector (coal based TPPs) to ambient atmospheric PM_{2.5} and PM₁₀ concentrations across various cities during the Phase I survey period from March to April 2023.

	Name of City (Measurement Site, distance from TPP)	Period of Survey	Total SO ₂ (µg m ⁻³)	SO ₂ from Power Sector (µg m ⁻³)
Category-1	New Delhi Location-1	12-02-2023 to 14-03-2023	9.26 ± 3.28	1.67 ± 0.93
	New Delhi Location-2	23-03-2023 to 22-04-2023	7.22 ± 2.73	1.37 ± 0.61
	Hyderabad Location-1	23-03-2023 to 22-04-2023	4.65 ± 0.55	0.42 ± 0.07
	Hyderabad Location-2	29-04-2023 to 29-05-2023	2.48 ± 0.49	0.37 ± 0.03
Category-2	Kolkata Location-1 15 Km from SOUTHERN TPS	12-02-2023 to 14-03-2023 (One month)	6.48 ± 3.08	1.49 ± 0.09
	Kolkata Location-2 51 Km from SOUTHERN TPS	23-03-2023 to 22-04-2023 (One month)	4.32 ± 1.51	1.08 ± 0.03
	Nagpur Location-1 15 Km from KHAPARKHEDA TPS	23-03-2023 to 22-04-2023 (One month)	6.07 ± 2.83	2.37 ± 0.31
	Nagpur Location-2 57 Km from KHAPARKHEDA TPS	29-04-2023 to 29-05-2023 (One month)	3.55 ± 0.53	0.78 ± 0.17
Category-3	Ghaziabad Location-1 13 Km from DADRI TPP	23-03-2023 to 22-04-2023 (One month)	8.51 ± 2.56	2.81 ± 0.72
	Ghaziabad Location-2 42 Km from DADRI TPP	29-04-2023 to 29-05-2023 (One month)	7.87 ± 1.89	1.03 ± 0.47
	Gautam Buddha Nagar Location-1 10 Km from DADRI TPP	23-03-2023 to 22-04-2023 (One month)	9.86 ± 2.12	2.56 ± 0.62
	Gautam Buddha Nagar Location-2 53 Km from DADRI TPP	29-04-2023 to 29-05-2023 (One month)	8.31 ± 2.03	1.41 ± 0.43

Table 3.4: Normalized contribution of Power sector towards ambient atmospheric SO₂ concentrations at specific measurement locations in various cities during the period of our survey from 23rd March to 22nd April 2023.

Summary of results during Phase-I (March to April 2023)

City	Total PM _{2.5} (µg m ⁻³)	Total PM ₁₀ (µg m ⁻³)	Sulfate aerosols in PM _{2.5} (%)	Sulfate aerosols in PM _{2.5} (µg m ⁻³)	Sulfate aerosols in PM ₁₀ (%)	Sulfate aerosols in PM ₁₀ (µg m ⁻³)	Contribution of SO ₂ emissions from TPP towards Sulfate aerosols (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} (µg m ⁻³)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ (µg m ⁻³)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ (%)
Delhi	79.75 ± 19.04	137.56 ± 23.77	15.15	12.09 ± 2.73	9.82	13.51 ± 1.71	15.85	1.92 ± 0.61	2.25 ± 0.72	2.41 ± 0.81	1.64 ± 0.39
Hyderabad	45.23 ± 4.12	85.18 ± 6.54	13.85	6.26 ± 0.57	8.22	7.00 ± 0.54	6.96	0.44 ± 0.04	0.49 ± 0.04	0.96 ± 0.09	0.57 ± 0.04
Nagpur	62.53 ± 6.06	83.71 ± 6.58	14.16	8.85 ± 0.86	11.83	9.90 ± 0.78	22.32	1.98 ± 0.19	2.21 ± 0.17	3.16 ± 0.31	2.64 ± 0.21
Kolkata	31.53 ± 7.75	52.89 ± 6.98	22.32	7.04 ± 1.73	14.87	7.86 ± 1.04	24.53	1.73 ± 0.42	1.93 ± 0.25	5.48 ± 1.35	3.65 ± 0.48
Gautam Buddha Nagar	77.91 ± 11.81	131.35 ± 16.21	15.56	12.12 ± 2.12	10.32	13.55 ± 2.31	17.89	2.17 ± 0.55	2.55 ± 0.56	2.78 ± 0.63	1.94 ± 0.26
Ghaziabad	72.11 ± 22.39	122.89 ± 17.69	14.34	10.34 ± 3.11	9.41	11.56 ± 2.37	15.02	1.55 ± 0.43	1.83 ± 0.46	2.15 ± 0.78	1.49 ± 0.35

Table 3.5: Contribution of Power sector towards ambient atmospheric sulfate aerosols, PM_{2.5} and PM₁₀ concentrations in various cities during Phase I from 23 March to 22 April 2023.

In Category-1 cities like Delhi, sulfate aerosols contributed 15.15% (12.09 µg/m³) to PM_{2.5} and 9.82% (13.51 µg/m³) to PM₁₀. In Hyderabad, sulfate aerosols contributed 13.85% (6.26 µg/m³)

to PM_{2.5} and 8.22% (7.00 µg/m³) to PM₁₀. For Category-1 cities, the average contribution of sulfate aerosols in PM_{2.5} was 14.50% (9.18 µg/m³) and in PM₁₀, it was 9.02% (10.26 µg/m³). In Category-2 cities such as Nagpur, sulfate aerosols contributed 14.16% (8.85 µg/m³) to PM_{2.5} and 11.83% (9.90 µg/m³) to PM₁₀, whereas in Kolkata, the contributions were higher at 22.32% (7.04 µg/m³) to PM_{2.5} and 14.87% (7.86 µg/m³) to PM₁₀. For Category-2 cities, the average contribution of sulfate aerosols in PM_{2.5} was 18.24% (7.95 µg/m³) and in PM₁₀, it was 13.35% (8.88 µg/m³). For Category-3 cities like Gautam Buddha Nagar, sulfate aerosols contributed 15.56% (12.12 µg/m³) to PM_{2.5} and 10.32% (13.55 µg/m³) to PM₁₀, while in Ghaziabad, the contributions were 14.34% (10.34 µg/m³) to PM_{2.5} and 9.41% (11.56 µg/m³) to PM₁₀. For Category-3 cities, the average contribution of sulfate aerosols in PM_{2.5} was 14.95% (11.23 µg/m³) and in PM₁₀, it was 9.87% (12.56 µg/m³). Thus our study indicate a significant presence of sulfate aerosols in particulate matter across all city categories, with Category-2 cities showing the highest average contributions.

During the Phase-I survey, we also estimated the contribution of SO₂ emissions from the energy sector, specifically coal-based thermal power plants (TPPs), to the total ambient air SO₄ (sulfate aerosol) concentration and found that it varied significantly across different cities and city categories. In Category-1 cities (Delhi and Hyderabad), which do not have any coal-based TPPs, the contribution of the energy sector to ambient SO₄ levels was relatively low. Delhi exhibited a higher contribution at 15.85% (2.25 µg/m³), while Hyderabad had a much lower contribution of 6.96% (0.51 µg/m³). On average, Category-1 cities showed an energy sector contribution of 11.41% (1.38 µg/m³) to ambient SO₄ concentrations. In Category-2 cities (Nagpur and Kolkata), which are located near coal-based TPPs without flue-gas desulfurization (FGD) systems, the contributions were notably higher. Nagpur showed a contribution of 22.32% (2.33 µg/m³), and Kolkata had an even higher contribution of 24.53% (2.03 µg/m³). The average contribution of the energy sector in Category-2 cities was 23.43% (2.18 µg/m³). In Category-3 cities (Gautam Buddha Nagar and Ghaziabad), which are near coal-based TPPs with FGD systems, the contributions were significant but varied. Gautam Buddha Nagar had a contribution of 17.89% (2.55 µg/m³), and Ghaziabad showed a contribution of 15.02% (1.83 µg/m³). On average, the energy sector contributed 16.46% (2.19 µg/m³) to ambient SO₄ concentrations in Category-3 cities. Overall, the contribution of SO₂ emissions from coal-based TPPs to ambient SO₄ concentrations was higher in Category-2 cities, with an average contribution of 23.43% (2.18 µg/m³), compared to 16.46% (2.19 µg/m³) in Category-3 cities and 11.41% (1.38 µg/m³) in Category-1 cities. This indicates a significant impact of coal-based TPP emissions on sulfate aerosol levels, particularly in cities near TPPs without FGD systems.

The specific contribution of sulfate aerosols originating from SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric PM_{2.5} and PM₁₀ concentrations also varied across different cities and city categories. In Delhi, the contribution was 2.41% (1.92

$\mu\text{g}/\text{m}^3$) in PM_{2.5} and 1.64% ($2.25 \mu\text{g}/\text{m}^3$) in PM₁₀. In Hyderabad, the contributions were lower at 0.96% ($0.44 \mu\text{g}/\text{m}^3$) in PM_{2.5} and 0.57% ($0.49 \mu\text{g}/\text{m}^3$) in PM₁₀. For Category-1 cities, the average contribution to PM_{2.5} was 1.69% ($1.18 \mu\text{g}/\text{m}^3$) and to PM₁₀, it was 1.11% ($1.37 \mu\text{g}/\text{m}^3$). Nagpur had contributions of 3.16% ($1.98 \mu\text{g}/\text{m}^3$) in PM_{2.5} and 2.64% ($2.21 \mu\text{g}/\text{m}^3$) in PM₁₀, while Kolkata had 5.48% ($1.73 \mu\text{g}/\text{m}^3$) in PM_{2.5} and 3.65% ($1.93 \mu\text{g}/\text{m}^3$) in PM₁₀. For Category-2 cities, the average contribution to PM_{2.5} was 4.32% ($1.86 \mu\text{g}/\text{m}^3$) and to PM₁₀, it was 3.15% ($2.07 \mu\text{g}/\text{m}^3$). In Gautam Buddha Nagar, the contributions were 2.78% ($2.17 \mu\text{g}/\text{m}^3$) in PM_{2.5} and 1.94% ($2.55 \mu\text{g}/\text{m}^3$) in PM₁₀, whereas in Ghaziabad, they were 2.15% ($1.55 \mu\text{g}/\text{m}^3$) in PM_{2.5} and 1.49% ($1.83 \mu\text{g}/\text{m}^3$) in PM₁₀. For Category-3 cities, the average contribution to PM_{2.5} was 2.47% ($1.86 \mu\text{g}/\text{m}^3$) and to PM₁₀, it was 1.72% ($2.19 \mu\text{g}/\text{m}^3$). These figures indicate that SO₂ emissions from TPPs contribute a measurable but relatively small portion of sulfate aerosols in PM_{2.5} and PM₁₀, with Category-2 cities experiencing the highest average contributions.

Overall, the contribution of SO₂ emissions from the power sector, which convert to sulfate aerosols, ranged from 0.96% to 5.48% in PM_{2.5} and from 0.57% to 3.65% in PM₁₀ across the cities during Phase I of the survey. This indicates variability in the impact of power sector emissions on sulfate aerosol concentrations. While SO₂ emissions from TPPs do contribute to sulfate aerosol mass concentrations in PM_{2.5} and PM₁₀, their overall contribution remains a small fraction (less than 6%) of the total PM_{2.5} and PM₁₀ mass concentrations across various city categories, especially during the spring and pre-monsoon season, indicating that other sources are more significant contributors to ambient air PM levels.

CHAPTER-4: SURVEY OF AMBIENT ATMOSPHERIC SO₂ CONCENTRATIONS IN DIFFERENT CATEGORY OF CITIES: PHASE-II

In the first phase of this survey, measurements were conducted in six distinct cities: New Delhi, Kolkata, Ghaziabad, Gautam Buddha Nagar, Nagpur, and Hyderabad, with two cities from each category. Measurements were carried out at two separate locations within each city for a duration of one month. This survey yielded valuable data for understanding the baseline levels and variations in ambient atmospheric SO₂ concentrations across these cities. However, to enhance the robustness of our findings with statistically significant data, we decided to conduct simultaneous measurements at two different locations within each city, extend the survey to other seasons, and include additional cities. This expansion involved simultaneous measurements of SO₂ concentrations at two different locations in all three categories of cities during another season. Conducting simultaneous measurements from different locations allow us to compare ambient air SO₂ concentration values at varying distances from coal-based thermal power plants (TPPs) in Category-2 and Category-3 cities. Furthermore, this approach allowed us to assess the concentrations measured during the survey against the National Ambient Air Quality Standards (NAAQS) established by the Central Pollution Control Board (CPCB) to determine whether they complied with these standards. Thus, the second phase of the survey was undertaken with the objective of simultaneously measuring ambient atmospheric SO₂ concentrations at two different locations in all three categories of cities during another season.

Cities across the country were classified into three categories based on their proximity to coal-based thermal power plants (TPPs) and the implementation status of Flue Gas Desulfurization (FGD) systems in these TPPs. As mentioned earlier in Chapter-2, these categories are:

Category-1: Cities with no coal based TPP.

Category-2: Cities with a coal based TPP in which FGD has not been installed and the TPP is located within 10km from the boundary of the city.

Category-3: Cities with a coal based TPP in which FGD has been installed and the TPP is located within a distance of 10km from the boundary of the city.

The second phase of the survey started on 15th July 2023 and ended on 14th August 2023.

Cities and Measurement Sites Selected for Phase-II of the Survey

During Phase-II, we conducted the measurement-based survey in the following three cities corresponding to three different city categories.

Table 4.1: Cities selected for conducting the survey Phase-II

S. No.	City Name	City Category	Capacity of TPP	No. of Units	Population of the city
1	Lucknow	Category-1	-	-	4589838
2	Kota	Category-2	1240 MW	7	1951014
3	Gautam Buddha Nagar	Category-3	1820 MW	6	1648115

It is important to note that all the cities selected for our survey are classified as “non-attainment cities with million-plus populations” by the Central Pollution Control Board (CPCB). In each city, we conducted the survey by measuring ambient air SO₂ concentrations at two different locations for a period of one month at each site. For cities with TPPs in their vicinity, the survey was designed so that one measurement site was close to the TPP (approximately 1-10 km away), while the second site was located about 40-60 km from the TPP.

Identification of Measurement sites in each city

Category-1 city: Lucknow, Uttar Pradesh



Sampling height: 20m above ground

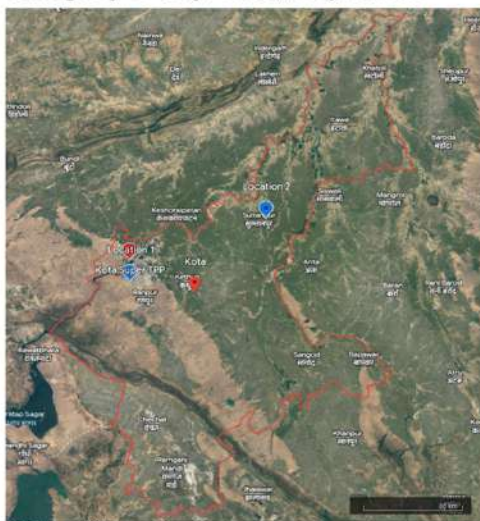
Location 1	Amity University Lucknow Campus, Malhaur (Near Railway Station), Gomti Nagar Extension, Lucknow, Uttar Pradesh 226028, India.
Location 2	Babasaheb Bhimrao Ambedkar University, Vidya Vihar, Raebareli Road, Lucknow, Uttar Pradesh 226025, India.

Distance between Location-1 and Location-2 is 18 Km

Figure 4.1: Satellite image (google earth) showing location of the measurement sites for Category-1 city Lucknow considered during Phase-II of the survey

Identification of Measurement sites in each city

Category-2 City: Kota, Rajasthan



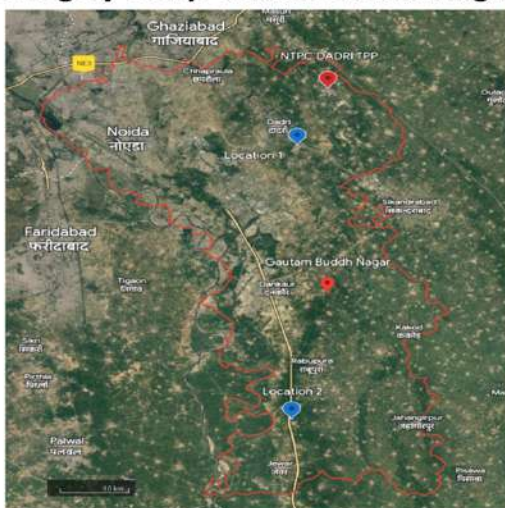
Sampling height: 20m above ground

KOTA Super TPP	TPP Developer: Rajasthan Rajya Vidyut Utpadan Nigam.
Location 1	University of Kota, Kota city, Rajasthan (6 Km from Kota Super TPP)
Location 2	Government ITI college Sultanpur, Kota, Rajasthan (40 Km from Kota Super TPP)

Figure 4.2: Satellite image (google earth) showing location of the measurement sites for Category-2 city Kota considered during Phase-II of the survey

Identification of Measurement sites in each city

Category-3 City: Gautam Buddha Nagar, Uttar Pradesh



Sampling height: 20m above ground

NTPC DADRI TPP	Developer: NTPC
Location 1	Shiv Nadar University 9 Km from NTPC DADRI TPP
Location 2	Maharaja Agrasen Polytechnic College 46 Km from NTPC DADRI TPP

Figure 4.3: Satellite image (google earth) showing location of the measurement sites for Category-3 city Gautam Buddha Nagar considered during Phase-II of the survey

Measurement Plan for Phase-II of the Survey

We conducted simultaneous measurements at two pre-identified locations in each of the three cities to avoid biases in our SO₂ concentration data due to seasonal variations in temperature,

wind, relative humidity, and other meteorological factors that influence the transport, removal, and lifetime of SO₂ in the atmosphere. Measurements in all three cities were conducted during the same period.

Continuous measurements were taken every 10 minutes at two different locations in each city for at least 30 days during the survey period. It was crucial to perform simultaneous measurements across the six different locations in the three cities within the same month or season to ensure that our data accurately represented SO₂ concentrations for that specific season. This approach eliminated any potential bias due to seasonal variability in meteorological conditions.

In total, we collected at least 4320 air samples at each location, resulting in a minimum of 8640 samples per city. Therefore, ambient SO₂ concentrations in three different cities were surveyed during Phase II of our study.

Measurement technique and equipment involved:

We used the same equipment and followed the same measurement techniques as described in Chapter 2; therefore, those details are not repeated here.

Measurement data from Phase-II of the Survey

This section presents the results of the measurements conducted in various category cities across the country during Phase II of our survey. In this phase, measurements commenced simultaneously at all locations across three cities on July 15, 2023, and concluded on August 14, 2023. Table 4.2 summarizes the maximum instantaneous, minimum instantaneous, and daily mean values of ambient air SO₂ concentrations measured at two different locations in each of the three category cities selected for Phase II of our survey during the summer monsoon season. In the Category 1 city of Lucknow, the maximum instantaneous ambient air SO₂ concentration was 11.92 µg/m³, the minimum was 2.83 µg/m³, and the daily mean values ranged from 5.62 ± 1.14 µg/m³ to 5.95 ± 1.56 µg/m³. In the Category 2 city of Kota, the maximum ambient air SO₂ concentration was 18.65 µg/m³, the minimum was 0.75 µg/m³, and the daily mean values ranged from 3.12 ± 0.81 µg/m³ to 5.15 ± 1.75 µg/m³. In the Category 3 city of Gautam Buddha Nagar, the maximum instantaneous ambient air SO₂ concentration was 16.61 µg/m³, the minimum was 1.45 µg/m³, and the daily mean values ranged from 5.89 ± 1.65 µg/m³ to 6.15 ± 2.56 µg/m³. Summarizing by city categories, Category 1 cities had maximum instantaneous ambient air SO₂ concentrations of up to 11.92 µg/m³ and minimum concentrations down to 2.83 µg/m³, with daily mean values ranging from 5.62 to 5.95 µg/m³. Category 2 cities had maximum concentrations of up to 18.65 µg/m³ and minimum concentrations down to 0.75 µg/m³, with daily mean values ranging from 3.12 to 5.15 µg/m³. Category 3 cities had maximum concentrations of up to 16.61 µg/m³ and minimum concentrations down to 1.45 µg/m³, with

daily mean values ranging from 5.89 to 6.15 $\mu\text{g}/\text{m}^3$. Thus our survey results highlight the variability in ambient air SO_2 concentrations across different locations and city categories, with Category 2 and Category 3 cities generally showing higher SO_2 levels. As the National Ambient Air Quality Standards (NAAQS) or the maximum permissible limit of ambient air SO_2 concentrations based on 24 hours average measurements for industrial, residential, rural, and other areas as notified by the MoEF&CC, Govt. of India is 80 $\mu\text{g}/\text{m}^3$, results of our survey confirm that the ambient air SO_2 concentrations in all cities are meeting the existing standards during the period of our survey.

As evident from Table 4.2, the daily mean values of ambient air SO_2 concentrations measured at various locations in all three cities during Phase II of our survey are comparable to the SO_2 data from the CPCB/SPCB/PCC measurement sites in those cities (<https://cpcb.nic.in/air-pollution/>), thereby validating the robustness of our collected data.

Summary of survey results from Phase-II

	Name of City (Measurement Site, distance from TPP)	Data Analysis Duration	This Study SO_2 Concentration ($\mu\text{g m}^{-3}$)			CPCB/SPCB measurements (μgm^{-3})
			Maximum (Instantaneous)	Minimum (Instantaneous)	Daily Mean $\pm 1\sigma$ (NAAQS = 80 $\mu\text{g m}^{-3}$)	
Category-1	Lucknow Location-1		10.86	3.79	5.62 $\pm$ 1.14	3.21 $\pm$ 1.03
	Lucknow Location-2		11.92	2.83	5.95 $\pm$ 1.56	
Category-2	Kota Location-1 7 Km from Kota Super TPP	15-07-2023 to	18.65	0.95	5.15 $\pm$ 1.75	4.48 $\pm$ 1.17
	Kota Location-2 40 Km from Kota Super TPP	14-08-2023	9.74	0.75	3.12 $\pm$ 0.81	
Category-3	Gautam Buddha Nagar Location-1 9 Km from DADRI TPP		16.61	1.45	6.15 $\pm$ 2.56	5.74 $\pm$ 0.91
	Gautam Buddha Nagar Location-2 46 Km from DADRI TPP		12.51	2.65	5.89 $\pm$ 1.65	

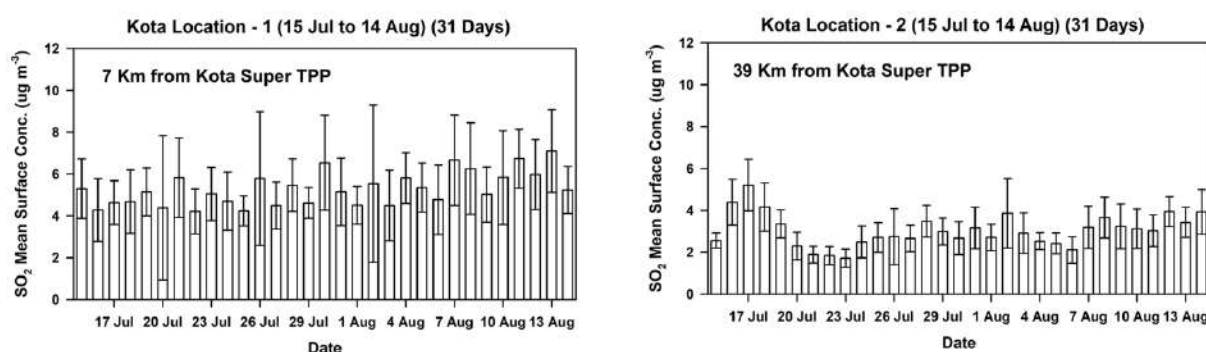
Table 4.2: Daily mean, maximum, and minimum values of ambient air SO_2 concentration ($\mu\text{g}/\text{m}^3$) measured at two different locations of three different cities classified under three different categories from across the country during Phase-II of our survey are listed here. SO_2 concentrations data from CPCB/SPCB measurements sites from each city are also mentioned.

Next, we discuss the findings from our survey in the Category-2 city of Kota, which has a coal-based TPP without an installed FGD in more detail. Figure 4.4 presents the time series of daily mean ambient air SO_2 concentrations ($\mu\text{g}/\text{m}^3$) measured on various days at two different sites in Kota. Figure 4.5 shows the diurnal variation of ambient air SO_2 concentrations ($\mu\text{g}/\text{m}^3$) recorded at these sites on different days. Both figures illustrate significant diurnal variations and notable intra-day fluctuations in ambient air SO_2 concentrations at both measurement locations in Kota. The maximum instantaneous values of ambient air SO_2 concentrations recorded at Location 1 and Location 2 in Kota during Phase II were 18.65 $\mu\text{g}/\text{m}^3$ and 9.74 $\mu\text{g}/\text{m}^3$, respectively. The

minimum instantaneous values of ambient air SO₂ concentrations recorded at Location 1 and Location 2 in Kota during Phase I were 0.95 µg/m³ and 0.75 µg/m³, respectively. The monthly average daily mean values of ambient air SO₂ concentrations at Location 1 and Location 2 in Kota during Phase II were 5.15 ± 1.75 µg/m³ and 3.12 ± 0.81 µg/m³, respectively.

According to the National Ambient Air Quality Standards (NAAQS), the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas, as notified by the MoEF&CC, Government of India, is 80 µg/m³. The results of our survey confirm that the ambient air SO₂ concentrations in Kota were within the permissible limits during the period of our survey.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in Kota



National Ambient Air Quality Standards (NAAQS)

[NAAQS Notification dated 18th November, 2009]

S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (notified by Central Government)	
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual	50	20	1. Improved West and Gaeke 2. Ultraviolet Fluorescence
		24 Hours	80	80	

Figure 4.4: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (15th July to 14th August 2023) as measured in Location-1 of Kota (upper left panel) and in Location-2 of Kota (upper right panel). Vertical lines on each bar represents the ±1σ standard deviation variation around the daily mean values for each day.

As mentioned earlier in Chapter-2 that the diurnal variations in ambient air SO₂ concentrations are influenced by a combination of several factors such as variability in SO₂ emission flux from different sources, variations in atmospheric boundary (or mixed) layer height throughout the day, changes in wind patterns or air circulation, and other meteorological conditions. In general, potential sources of SO₂ over any location include emissions from energy sector, transportation sector (burning of fossil fuel), industries (such as petroleum refineries, cement manufacturing, paper pulp manufacturing, iron and steel, and metal smelting, processing facilities, brick kilns,

etc.), residential sector (involving burning of fossil fuel or biomass for various purposes including usage of diesel/petrol generators), agricultural waste burning, solid waste treatment etc. SO₂ is also used in bleaching materials, as a fumigant, preserving dry fruits to prevent discoloration. In the residential sector SO₂ gas can be emitted from tobacco smoke, improperly or inadequately vented solid/gas fuel appliances (such as biomass or fossil fuel-based cooking stoves, furnaces, heaters), as well as kerosene or wood or cooking coal stoves or burning of these things for any other household purposes.

In general, we observed that the ambient air SO₂ concentrations at both measurement locations in Kota exhibit weaker diurnal variability compared to the variations noted in different cities during Phase-I of the survey. However, we did observe occasional spikes in SO₂ concentrations, primarily during the daytime at Location-1. These spikes, typically lasting 1-2 hours, suggest the influence of local sources within the city affecting the ambient air SO₂ levels at Location-1. Interestingly, there are significant differences in diurnal variations of ambient air SO₂ concentrations between the two locations. Unlike Location-1, Location-2 did not experience major spikes in SO₂ concentrations, indicating that it is less influenced by local sources. Consequently, location-2 exhibited very minimal diurnal variability throughout the survey period. While some weak spikes were also observed at location-2 on certain days, they were much smaller in magnitude compared to those at location-1. The randomness in the occurrence of these spikes at both locations suggests they are primarily caused by emissions from nearby local sources, other than the TPP, with a shorter distance of influence, less than the approximate 50 km distance between the two measurement locations.

The monthly mean pattern of diurnal variation in ambient air SO₂ concentration at both measurement locations in Kota showed minimal diurnal variability. At Location-1, the monthly mean pattern indicated slightly higher values during the forenoon hours, likely due to spikes caused by local sources other than TPP emissions. Generally, ambient air SO₂ concentrations were marginally higher during the nighttime, likely due to a shallower boundary layer at night, resulting in a smaller volume for air pollutants to disperse vertically.

Next, we discuss the findings from our survey in Lucknow, a Category-1 city selected for Phase II, which does not have any coal-based TPP within 10 km of its boundary. Figure 4.6 presents the time series of daily mean ambient air SO₂ concentrations (µg/m³) measured on various days at two different sites in Lucknow. Figure 4.7 shows the diurnal variation of ambient air SO₂ concentrations (µg/m³) recorded at these sites on different days. The maximum instantaneous values of ambient air SO₂ concentrations recorded at Location 1 and Location 2 in Lucknow during Phase II were 10.86 µg/m³ and 11.92 µg/m³, respectively. The minimum instantaneous values of ambient air SO₂ concentrations recorded at Location 1 and Location 2 in Delhi during Phase I were 3.79 µg/m³ and 2.83 µg/m³, respectively.

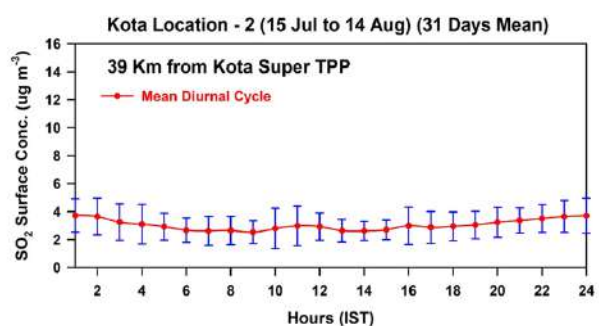
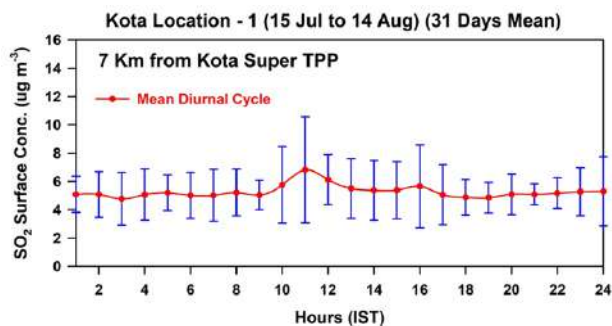
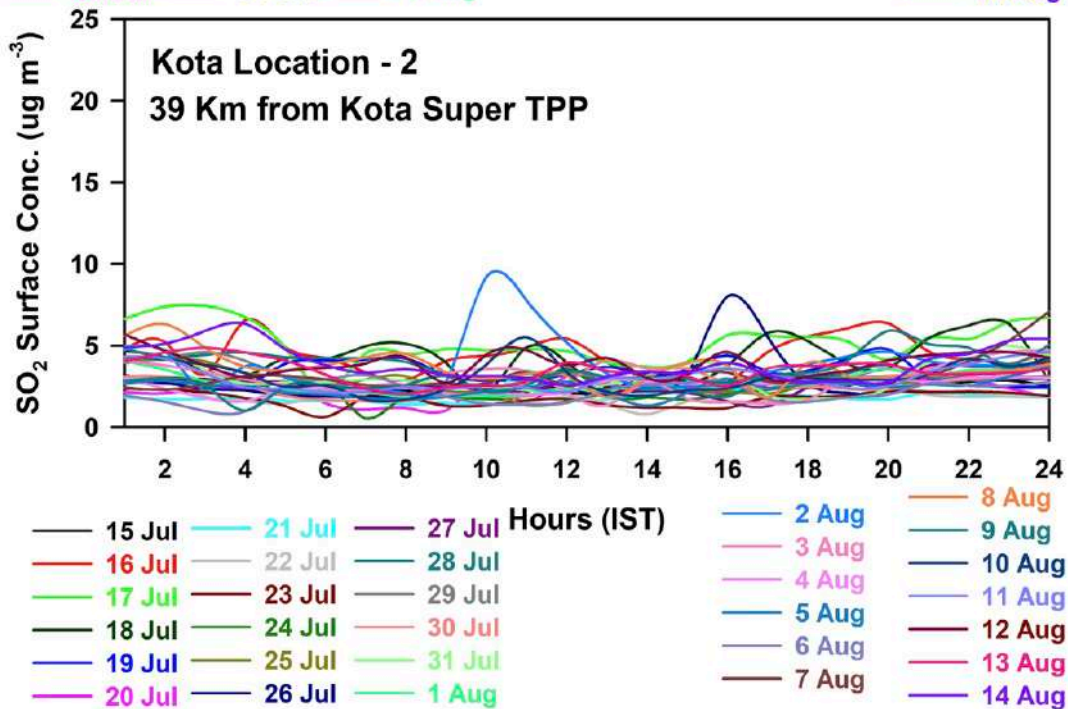
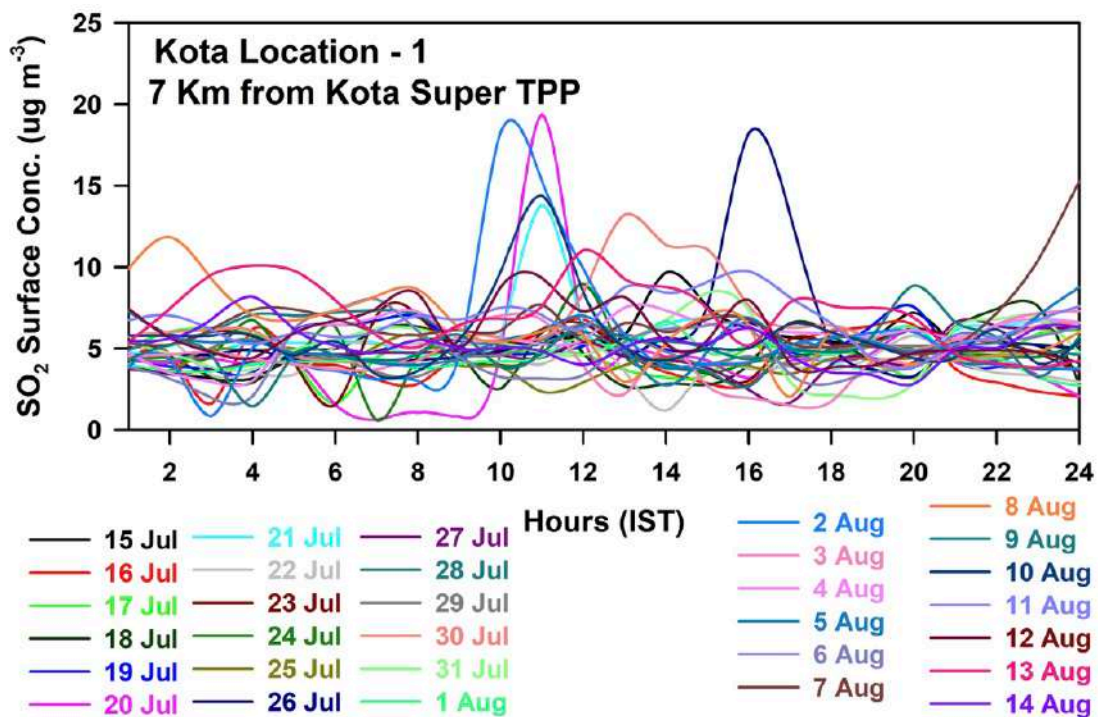


Figure 4.5: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (15 July to 14 August 2023) as measured in Location-1 of Kota (upper panel) and Location-2 of Kota (middle panel). Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) derived from measurements made at both locations of Kota are also shown. Vertical lines in lower panels represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

The monthly average daily mean values of ambient air SO₂ concentrations at Location 1 and Location 2 in Lucknow during Phase II were $5.62 \pm 1.14 \mu\text{g}/\text{m}^3$ and $5.95 \pm 1.56 \mu\text{g}/\text{m}^3$, respectively.

According to the National Ambient Air Quality Standards (NAAQS), the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas, as notified by the MoEF&CC, Government of India, is 80 µg/m³. The results of our survey confirm that the ambient air SO₂ concentrations in Lucknow were within the permissible limits during the period of our survey.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in Lucknow

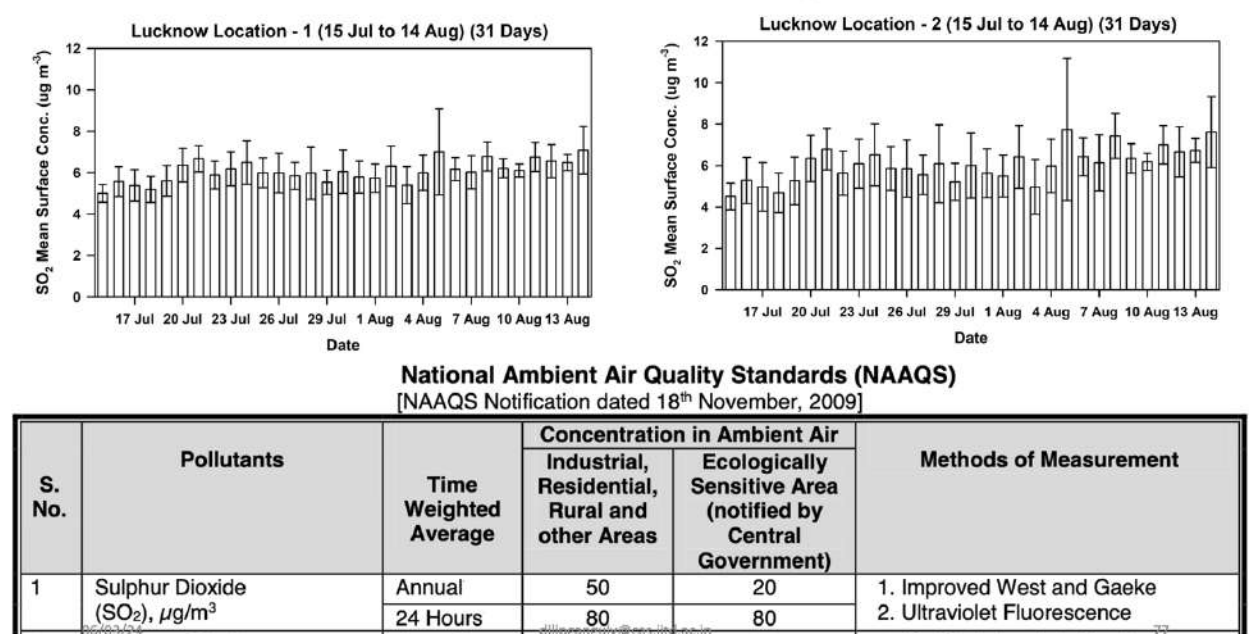


Figure 4.6: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (15 July to 14 August 2023) as measured in Location-1 of Lucknow (upper left panel) and for the period 15th July to 14th August 2023 in Location-2 of Lucknow (upper right panel). Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

During Phase II of our survey in Lucknow, we observed occasional spikes in ambient air SO₂ concentrations at both measurement locations of Lucknow. However, no clear pattern in the diurnal variability of SO₂ was noted at either of the measurement locations. These spikes,

typically lasting for 1-2 hours and occurring at different times throughout the day, suggest that local sources within the city are independently influencing the ambient air SO₂ levels at both sites. Notably, there were no systematic differences in the diurnal variations of SO₂ concentrations between the two locations. The randomness in the occurrence of these spikes at both locations indicates that they are primarily caused by emissions from nearby local sources, which have a shorter range of influence than the approximate 50 km distance between the two measurement sites. This variability underscores the complex interplay of local emission sources in shaping the ambient air quality in Lucknow, highlighting the need for more detailed investigations to identify and mitigate these sources.

The monthly mean pattern of diurnal variation in ambient air SO₂ concentration at both measurement locations in Lucknow shows minimal diurnal variability, as depicted in figure 4.7. Although occasional spikes in SO₂ concentrations were observed, no distinct diurnal pattern was evident at either site. These spikes, typically lasting 1-2 hours and occurring at various times throughout the day, indicate that local sources within the city independently influence SO₂ levels at both locations, in addition to contributing to the background SO₂ level as part of regional air pollution. Notably, there were no systematic differences in the diurnal variations of SO₂ concentrations between the two sites. The randomness of these spikes indicates that they are primarily caused by emissions from nearby local sources, rather than a consistent, time-of-day dependent pattern. Despite the lack of a clear diurnal pattern, these spikes illustrate the influence of local activities and sources on ambient air SO₂ levels. For instance, traffic emissions, industrial activities, or other urban processes could be contributing to these sporadic increases in SO₂ concentrations. The absence of a significant difference between the two locations further suggests that these local sources are dispersed across the city, affecting both measurement sites similarly. This randomness underscores the complex nature of urban air quality, where multiple, variable factors can influence pollutant levels at any given time.

Next, we discuss the findings of our survey from Gautam Buddha Nagar in Uttar Pradesh, the Category-3 city selected for Phase II, having a coal-based Thermal Power Plant (TPP) equipped with FGD, situated within 10 kilometres of the city boundary. Figure 4.8 presents the time series of daily mean ambient air SO₂ concentrations measured on various days at two different sites in Gautam Buddha Nagar. Figure 4.9 shows the diurnal variation of ambient air SO₂ concentrations recorded at these sites on different days. The maximum instantaneous values of ambient air SO₂ concentrations recorded at Location 1 and Location 2 in Gautam Buddha Nagar during Phase II were 16.61 µg/m³ and 12.51 µg/m³, respectively. The minimum instantaneous values of ambient air SO₂ concentrations recorded at Location 1 and Location 2 in Gautam Buddha Nagar during Phase II were 1.45 µg/m³ and 2.65 µg/m³, respectively. The monthly average daily mean values of ambient air SO₂ concentrations at Location 1 and Location 2 during Phase II were 6.15 ± 2.56 µg/m³ and 5.89 ± 1.65 µg/m³, respectively.

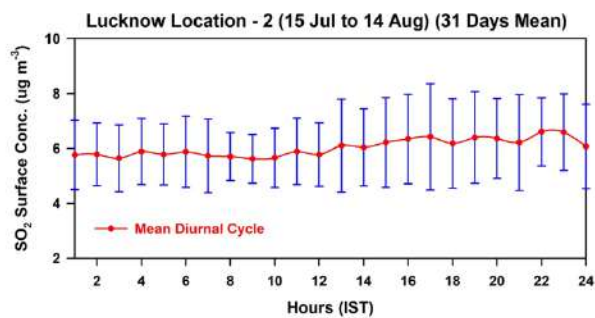
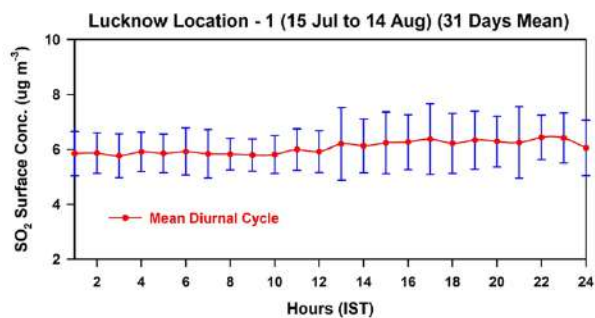
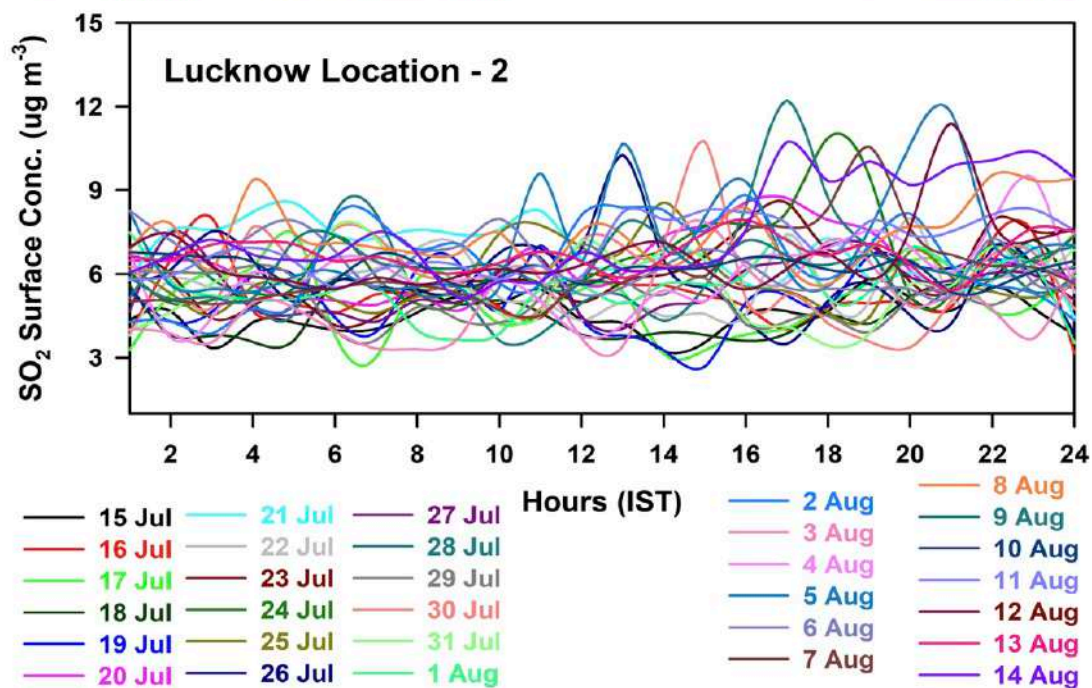
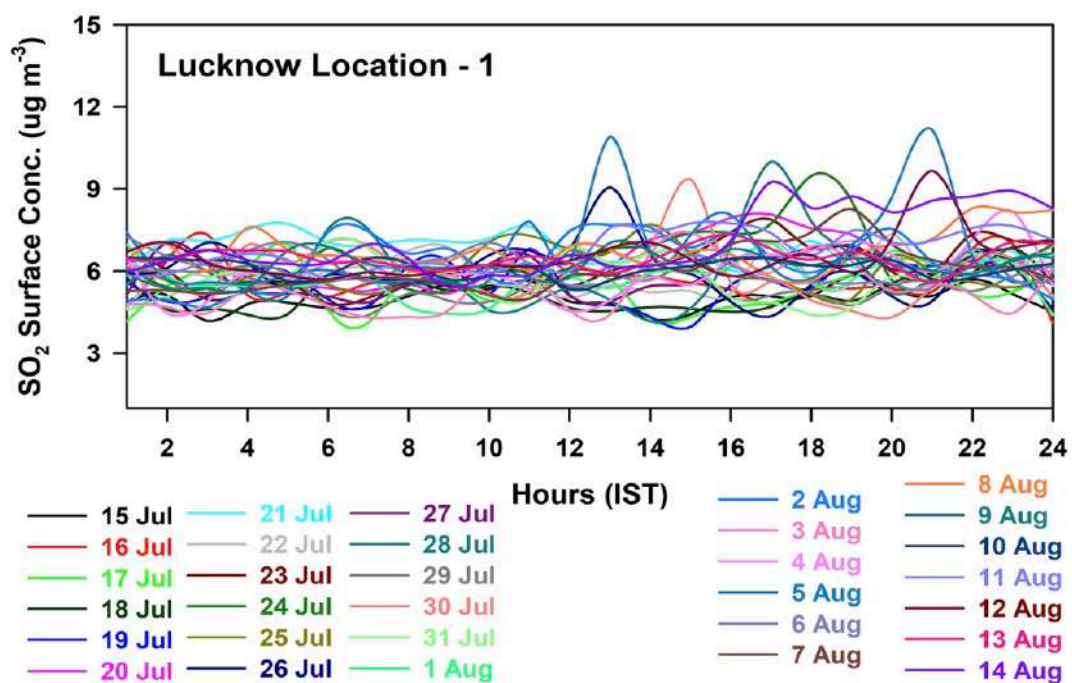
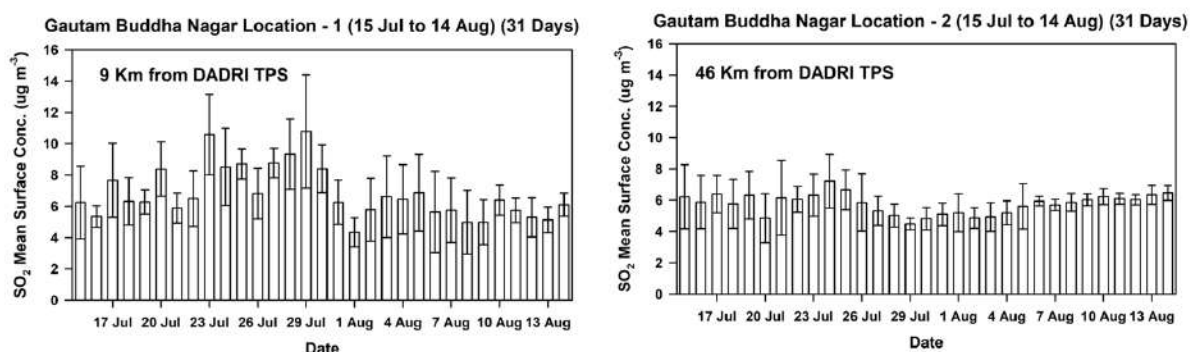


Figure 4.7: Diurnal variation of ambient air SO₂ concentration for all days (15 July to 14 August 2023) as measured in Location-1 (upper panel) and Location-2 (middle panel) of Lucknow. Monthly mean pattern of diurnal variation of ambient air SO₂ concentration derived from measurements made at both locations are also shown. Vertical lines in lower panels represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in GBN



National Ambient Air Quality Standards (NAAQS)

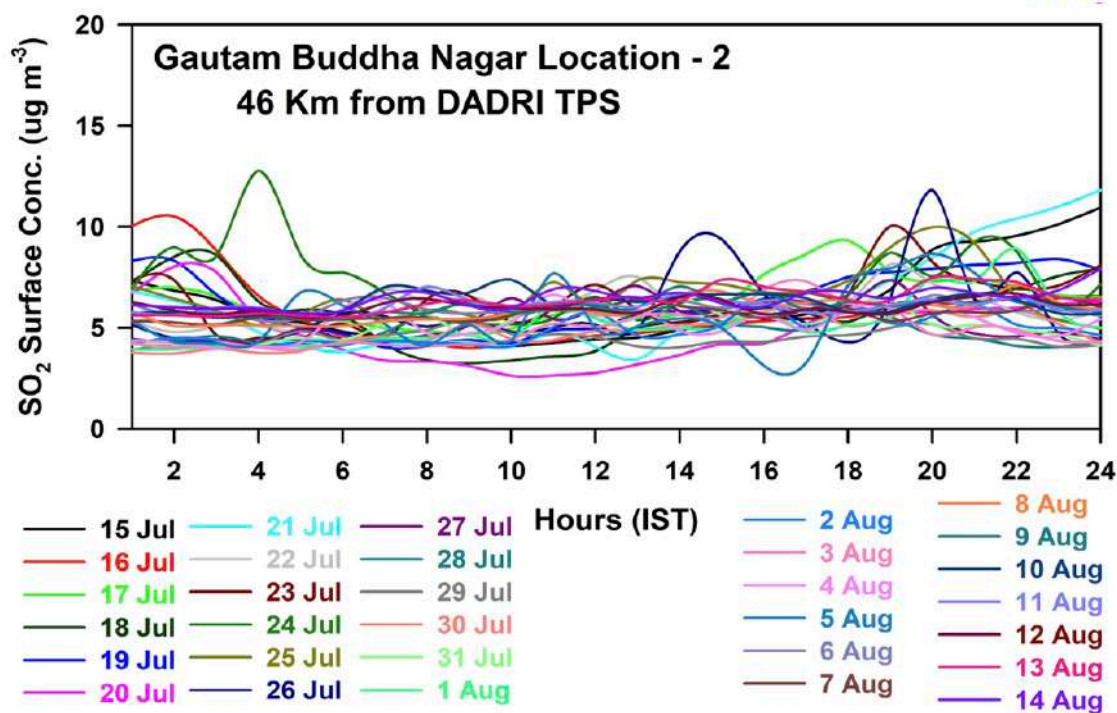
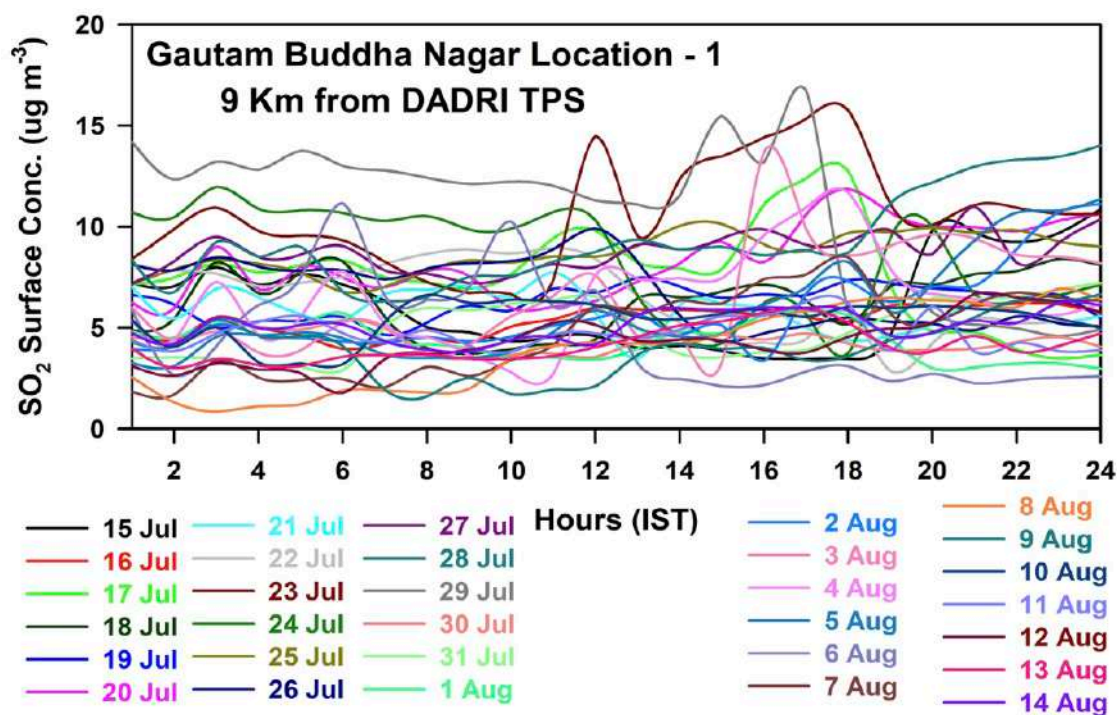
[NAAQS Notification dated 18th November, 2009]

S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (notified by Central Government)	
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual	50	20	1. Improved West and Gaeke 2. Ultraviolet Fluorescence
		24 Hours	80	80	

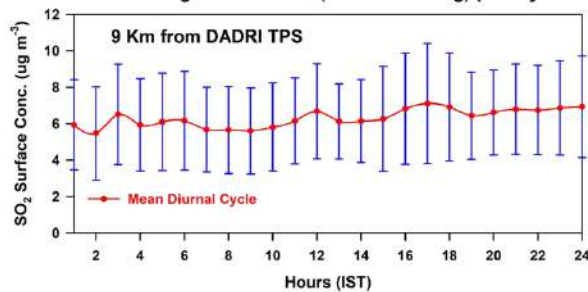
Figure 4.8: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (15th July to 14th August 2023) as measured in Location-1 of Gautam Buddha Nagar (upper left panel) and for the period 15th July to 14th August 2023 in Location-2 of Gautam Buddha Nagar (upper right panel). Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

As per the National Ambient Air Quality Standards (NAAQS), the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas, as notified by the MoEF&CC, Government of India, is 80 µg/m³. The results of our survey confirm that the ambient air SO₂ concentrations in Gautam Buddha Nagar were within the permissible limits during the period of our survey.

Figure 4.9 illustrates the diurnal variation of ambient air SO₂ concentrations (in µg/m³) on different days of the month, based on measurements at two locations in Gautam Buddha Nagar. At Location 1, SO₂ concentrations exhibit greater variability throughout the day, with some peaks reaching up to 15 µg/m³.



Gautam Buddha Nagar Location - 1 (15 Jul to 14 Aug) (31 Days Mean)



Gautam Buddha Nagar Location - 2 (15 Jul to 14 Aug) (31 Days Mean)

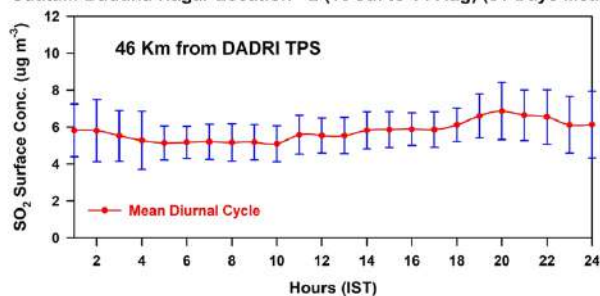


Figure 4.9: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (15th July to 14th August 2023) as measured in Location-1 (upper panel) and Location-2 (middle panel) of Gautam Buddha Nagar. Monthly mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) derived from measurements made at both locations are also shown. Vertical lines in lower panels represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

The diurnal patterns at Location 1 show multiple fluctuations, with concentrations generally oscillating between 0 and 10 µg/m³ and occasionally rising above this range. This suggests significant day-to-day variations and potentially stronger influences from dominant SO₂ sources, such as the NTPC Dadri TPP, as well as various other local sources within the city. These sources independently influence SO₂ levels at both locations and contribute to the background SO₂ levels as part of regional air pollution, affected by varying meteorological conditions on different days. In contrast, Location 2 shows more consistent and lower SO₂ concentrations, predominantly staying between 0 and 10 µg/m³, with fewer peaks above this range. The patterns here appear smoother and less volatile, indicating a more stable ambient air quality regarding SO₂ levels, possibly due to the greater distance from major emission sources like NTPC Dadri TPP. Both locations share a general range of SO₂ concentrations, typically between 0 and 10 µg/m³. However, Location 1 exhibits higher peak values and more pronounced fluctuations, while Location 2 demonstrates steadier and lower concentrations. These differences highlight the impact of proximity to pollution sources and potentially differing local activities on ambient air quality, including SO₂ concentrations.

Figure 4.9 also presents the mean diurnal patterns of ambient air SO₂ concentrations obtained from measurements at two different locations in Gautam Buddha Nagar during Phase II of our survey. Location 1, situated approximately 9 km from the NTPC Dadri TPS, shows ambient air SO₂ concentrations generally ranging between 5 and 7 µg/m³ throughout the day, with some fluctuations and intra-day variability indicated by the vertical bars. Concentrations peak slightly in the early morning and late evening. In contrast, Location 2, 46 km from the NTPC Dadri TPS, displays more stable ambient air SO₂ concentrations, primarily varying between 4 and 6 µg/m³, with minimal fluctuations and overall lower levels compared to Location 1. Both locations exhibit similar overall diurnal trends, with concentrations remaining relatively stable throughout the day and minor increases during specific periods. However, Location 1 experiences higher mean concentrations and greater variability, likely due to its proximity to the NTPC Dadri TPS and other local sources of SO₂ in Gautam Buddha Nagar and Ghaziabad. These differences highlight the impact of distance from major emission sources on ambient air quality and SO₂ concentrations, with closer proximity leading to higher and more variable SO₂ levels.

CHAPTER-5: CONTRIBUTION OF SO₂ EMISSIONS FROM COAL-BASED TPPS TOWARDS AMBIENT ATMOSPHERIC SO₂, SULFATE AEROSOLS, PM_{2.5}, AND PM₁₀ MASS CONCENTRATIONS IN DIFFERENT CATEGORY CITIES DURING PHASE II OF SURVEY

To understand the contribution of SO₂ emissions from the power sector, specifically coal-based thermal power plants (TPPs), on ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in various cities selected for Phase II of the survey, we conducted a series of meticulously planned simulations using the WRF-Chem chemical transport model. These simulations aimed to delineate the contributions of various sources, particularly TPP emissions, to ambient air SO₂ and sulfate aerosols as components of PM_{2.5} and PM₁₀ mass concentrations across the surveyed cities. Additionally, we aimed to determine the contributions of major aerosol types, including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust, to the ambient air concentrations of PM_{2.5} and PM₁₀ in these cities. Specifically, we sought to quantify the impact of SO₂ emissions from TPPs on the ambient air concentrations of sulfate aerosols, PM_{2.5} and PM₁₀ mass concentrations in the cities included in the Phase II of this survey.

Model setup and Simulation Details

The Weather Research and Forecasting model coupled with a chemistry module (WRF-Chem) is a regional system designed for both operational weather forecasting and atmospheric chemistry research (Skamarock, 2008; Powers et al., 2017). In this study, WRF-Chem version 4.2.2 was utilized to conduct nine sets of atmospheric chemistry simulations over the city of interest (Lucknow, Kota, and Gautam Buddha Nagar during Phase II of the survey) spanning from 15th July to 14th August 2023. For the first set of simulations, the model domains were centered at Kota (75.84° E and 25.18° N), each covering approximately 2,250,000 square kilometres at a horizontal resolution of 10 km, with 150x150 grid cells in the outer domain and a horizontal resolution of 3 km, with 136x136 grid cells in the inner domain, following a nested WRF-Chem modeling setup. The model included 44 vertical levels on a hybrid-sigma coordinate system, extending from the surface to about 10 hPa as the model top pressure.

The NCEP GDAS Final Analysis data, available at 6-hour intervals and with a resolution of 0.25°x0.25°, provided the meteorological initial and lateral boundary conditions for the model simulations covering the period from 15th July to 14th August 2023. Anthropogenic emissions were based on the EDGAR-v6.1 (2023) dataset. ERA5 Temperature, Water Vapor, and Wind data were used for both the WRF-Chem simulations and the Four-Dimensional Data Assimilation (FDDA) approach. Initial and lateral chemical boundary conditions for the WRF-Chem model

simulations were obtained from previously available results from the Community Atmospheric Model With Chemistry (CAM-Chem) simulations.

To evaluate the sectoral contributions to ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in the selected cities of Lucknow, Kota, and Gautam Buddha Nagar during Phase II of the survey, we utilized an emission suppression method. This approach involved conducting a series of systematically designed simulations using the WRF-Chem model, where emissions from specific sectors were disabled in each simulation. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

Chemical Transport Modeling for Kota, Rajasthan

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

Category-2 City:
Kota, Rajasthan

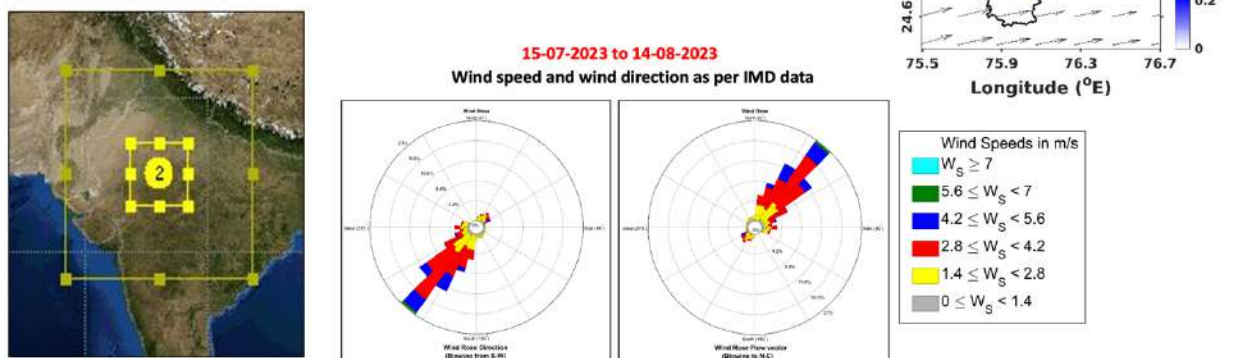


Figure 5.1: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Kota during the simulation period from 15th July to 14th August 2023.

First, we present the results of our simulations, detailing the contributions of major emission sectors to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ mass concentrations in the city of Kota during Phase II of our survey.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-2 City:
Kota, Rajasthan

Kota SO₂ ($7.67 \pm 2.85 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

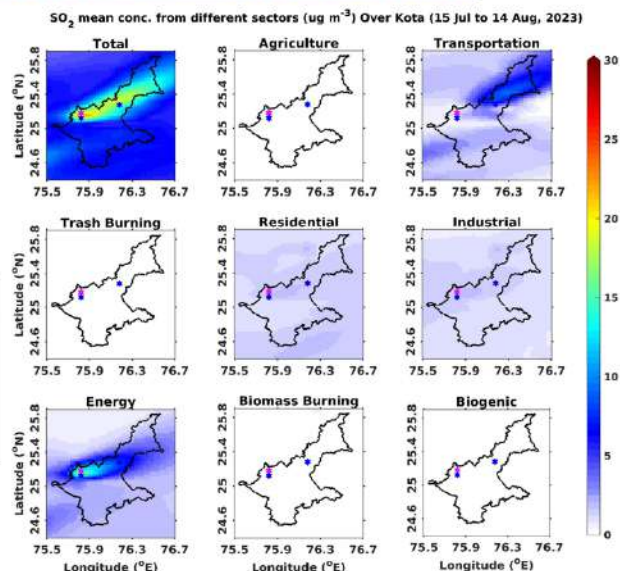
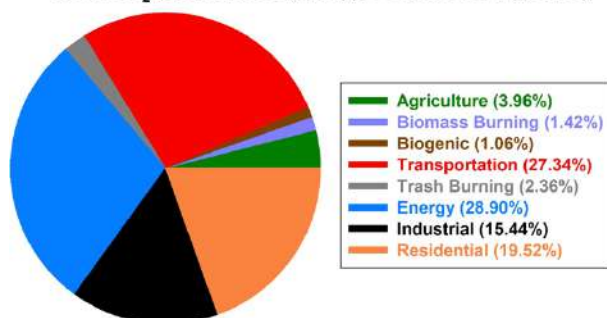


Figure 5.2: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-2 City:
Kota, Rajasthan

Kota SO₄ ($6.72 \pm 2.41 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

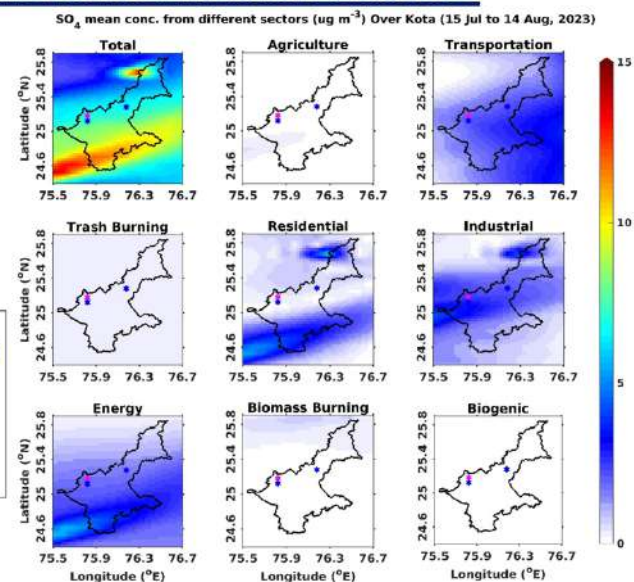
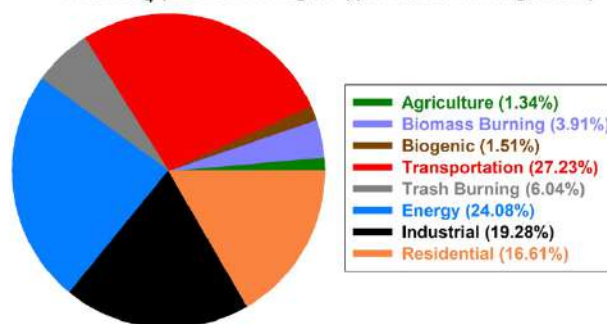


Figure 5.3: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category-2 City:
Kota, Rajasthan

Kota PM_{2.5} ($48.69 \pm 6.14 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

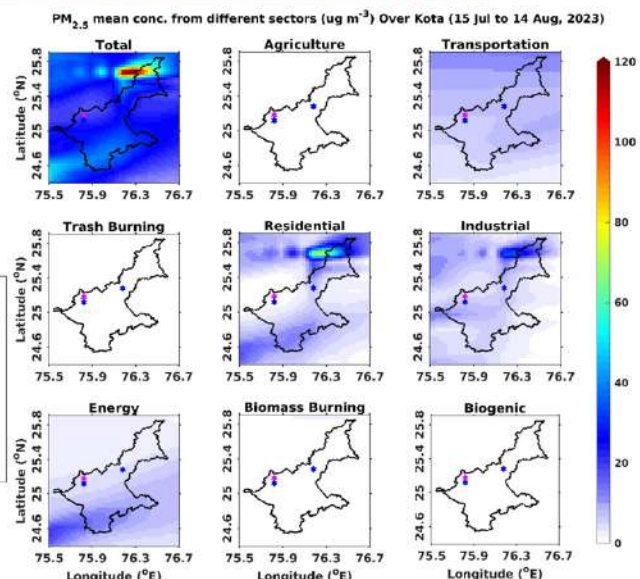
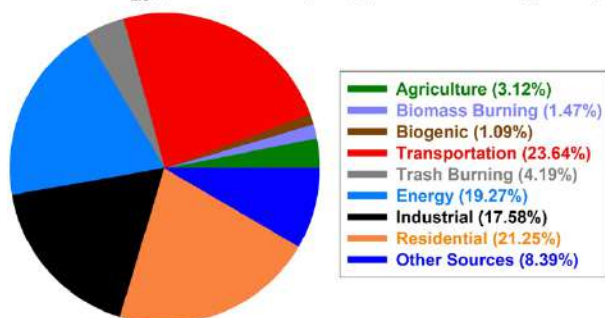


Figure 5.4: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category-2 City:
Kota, Rajasthan

Kota PM₁₀ ($65.74 \pm 6.47 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

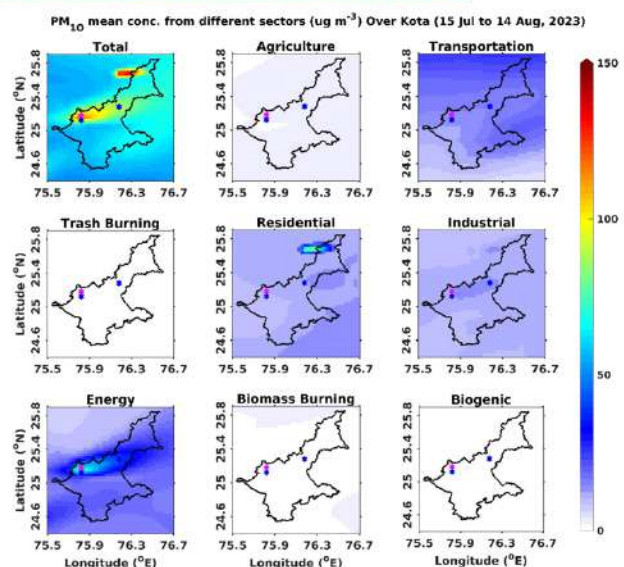
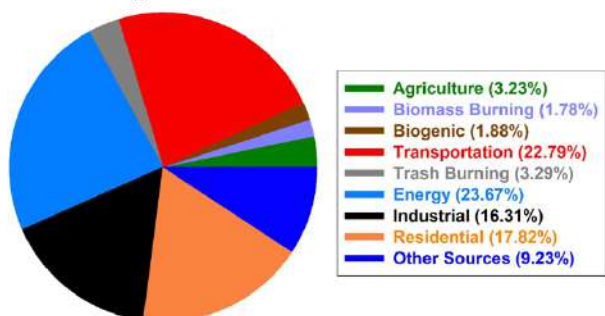


Figure 5.5: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Kota during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-2 City:
Kota, Rajasthan

Phase II
Monsoon Season

Kota PM_{2.5} ($48.69 \pm 6.14 \text{ ug m}^{-3}$) (15 Jul to 14 Aug, 2023)

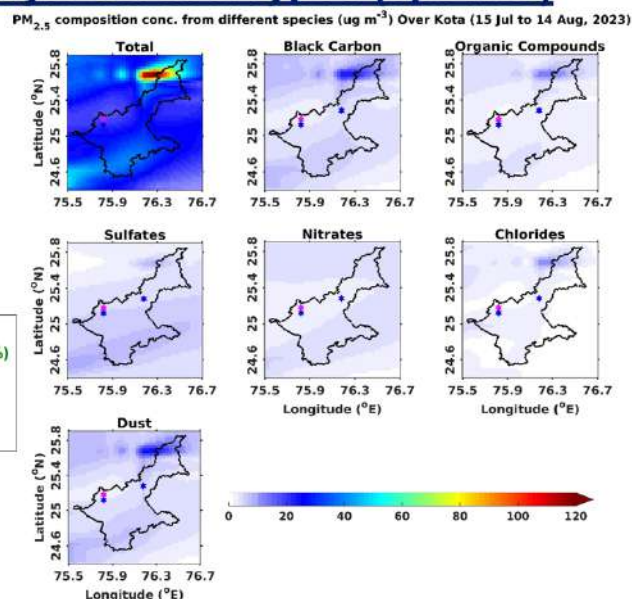
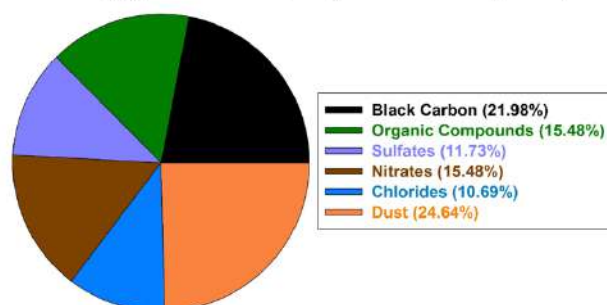


Figure 5.6: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-2 City:
Kota, Rajasthan

Phase II
Monsoon Season

Kota PM₁₀ ($65.74 \pm 6.47 \text{ ug m}^{-3}$) (15 Jul to 14 Aug, 2023)

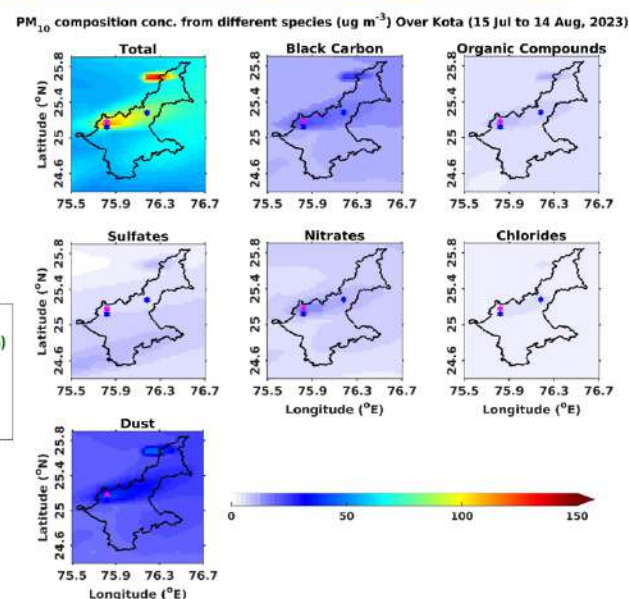
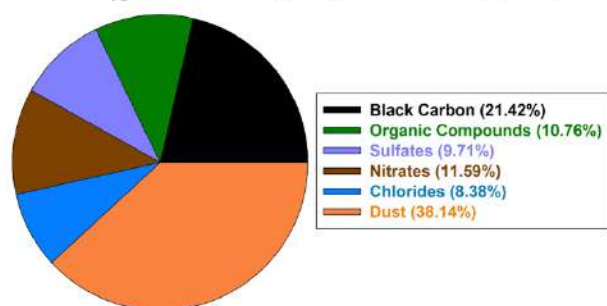


Figure 5.7: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Kota during the simulation period from 15th July to 14th August 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

**Category-2 City:
Kota, Rajasthan**

15th July to 14th Aug 2023

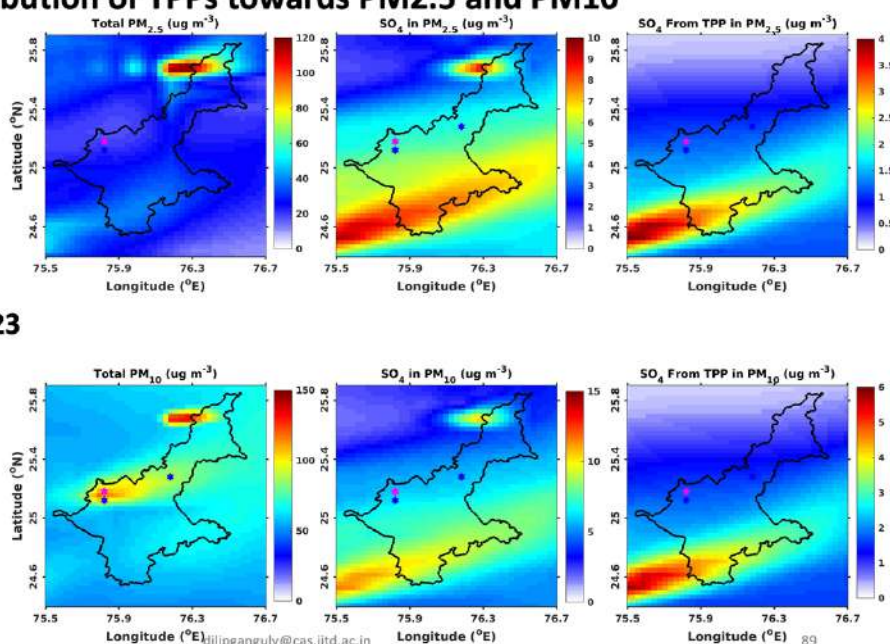


Figure 5.8: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Kota during the simulation period from 15th July to 14th August 2023.

Next we performed another series of systematically designed WRF-Chem model simulations to know the contribution different sources towards SO₂ and sulfate aerosols in Lucknow, which is a Category-1 city considered during the Phase-II of our survey. We also wanted to understand the contribution of Power sector towards the ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in the city of Lucknow during our survey. WRF-Chem version 4.2.2 has been used to perform a set of nine atmospheric chemistry simulations over Lucknow for 15th July to 14th August 2023. For this study, the model domains are centered at Lucknow (80.57° E and 26.51° N). Each of the simulation domain covers approximately 2250000 square Km area at a horizontal resolution of 10x10 Km², with 150x150 grid cells in the outer domain and horizontal resolution of 3x3 Km², with 136x136 grid cells in the inner domain following nested WRF-Chem modeling setup and 44 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis (available at 6 hourly intervals) with a resolution of 0.25°x0.25° have been used to provide meteorological initial and lateral boundary conditions to the model simulation of 15th July to 14th August 2023. To estimate the sectoral emission contribution towards the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Lucknow, we followed an emission suppression method. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

Chemical Transport Modeling for Lucknow

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

Category-1 city:

Lucknow, Uttar Pradesh

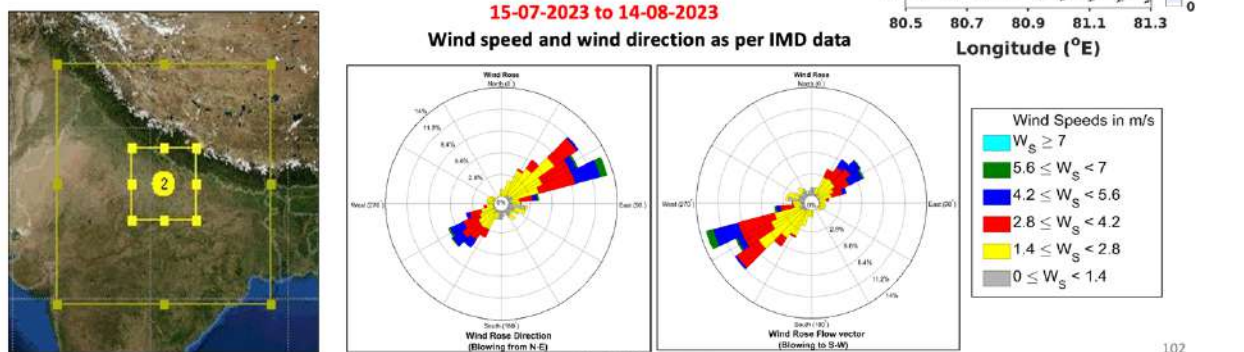


Figure 5.9: Simulation domain, gridded SO_2 emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Lucknow during the simulation period from 15th July to 14th August 2023.

First, we present the results of our simulations, detailing the contributions of major emission sectors to ambient atmospheric SO_2 , sulfate aerosols, $\text{PM}_{2.5}$, and PM_{10} mass concentrations in the city of Lucknow during Phase II of our survey.

Normalized Contribution of different emission sectors towards ambient air SO_2

Category-1 city:

Lucknow, Uttar Pradesh

Lucknow SO_2 ($6.64 \pm 1.09 \text{ ug m}^{-3}$) (15 Jul to 14 Aug, 2023)

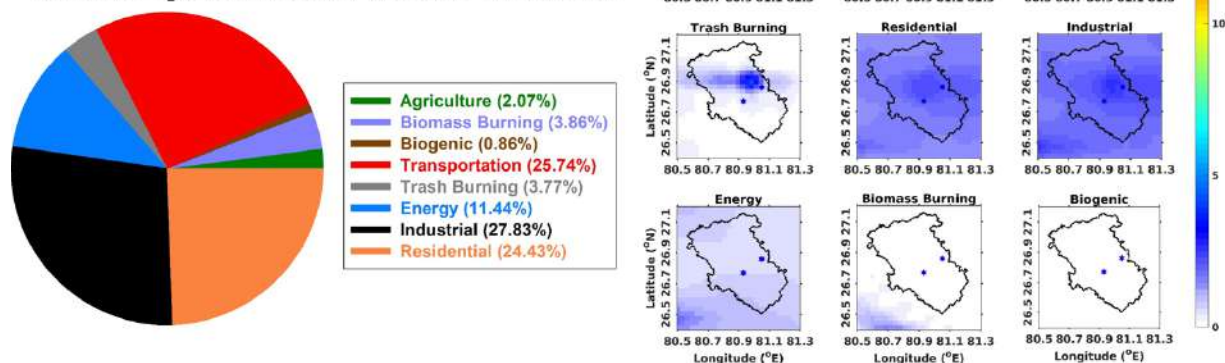


Figure 5.10: Contribution of different emission sectors towards ambient atmospheric SO_2 concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-1 city:

Lucknow, Uttar Pradesh

Lucknow SO₄ ($4.73 \pm 1.27 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

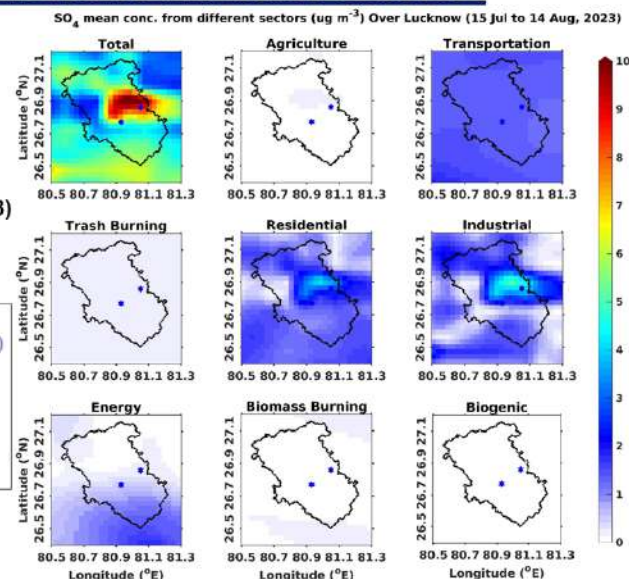
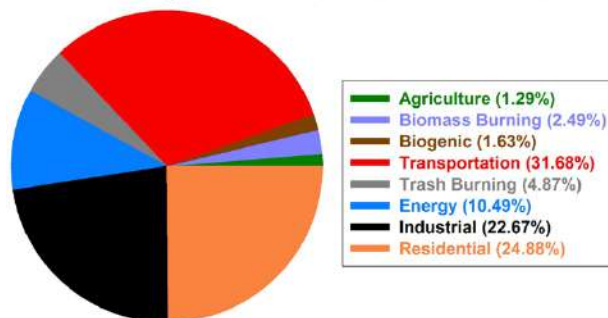


Figure 5.11: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category-1 city:

Lucknow, Uttar Pradesh

Lucknow PM_{2.5} ($34.59 \pm 7.99 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

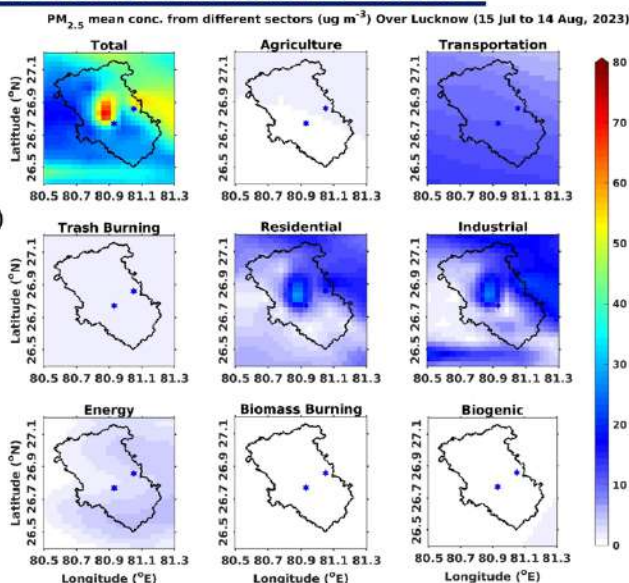
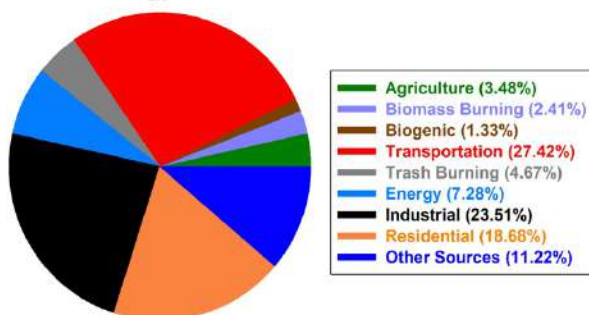


Figure 5.12: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category-1 city:

Lucknow, Uttar Pradesh

Lucknow PM₁₀ ($52.57 \pm 3.14 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

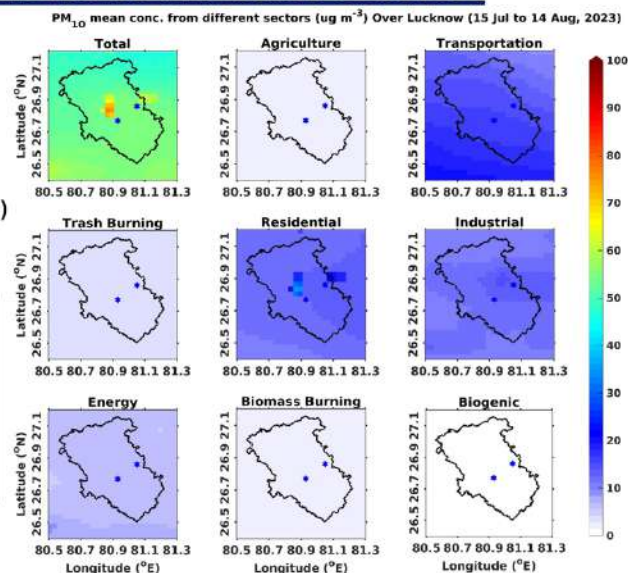
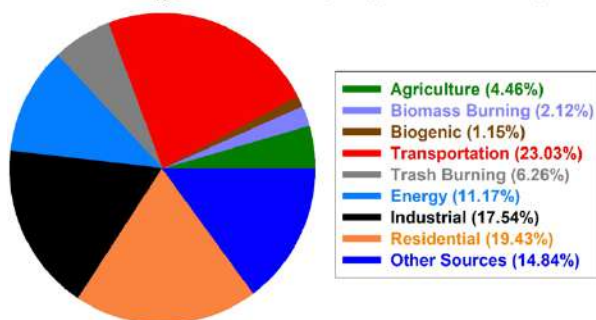


Figure 5.13: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Lucknow during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-1 city:

Lucknow, Uttar Pradesh

Phase II
Monsoon Season

Lucknow PM_{2.5} ($34.59 \pm 7.99 \text{ ug m}^{-3}$)(15 Jul to 14 Aug, 2023)

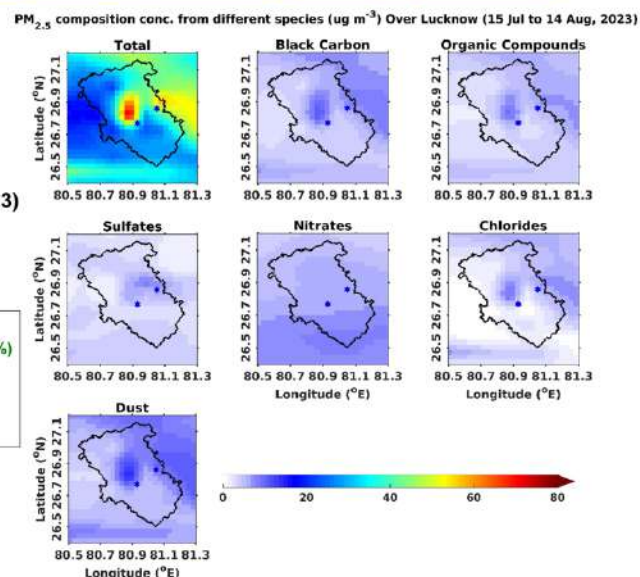
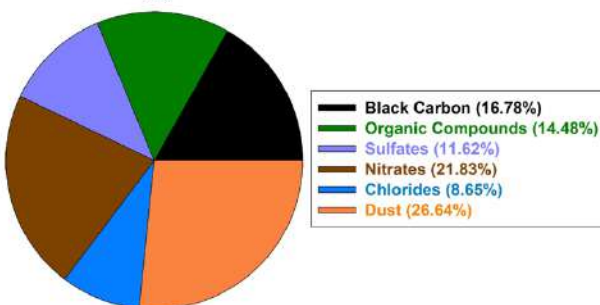


Figure 5.14: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

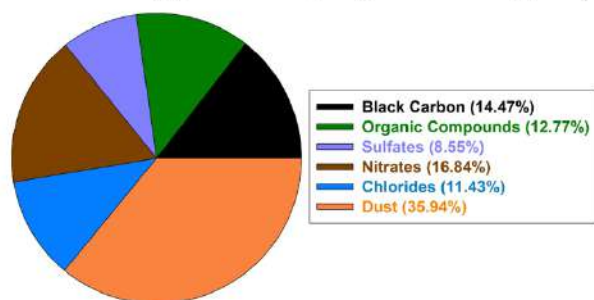
Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-1 city:

Lucknow, Uttar Pradesh

Phase II
Monsoon Season

Lucknow PM₁₀ ($52.57 \pm 3.14 \text{ ug m}^{-3}$) (15 Jul to 14 Aug, 2023)



PM₁₀ composition conc. from different species (ug m^{-3}) Over Lucknow (15 Jul to 14 Aug, 2023)

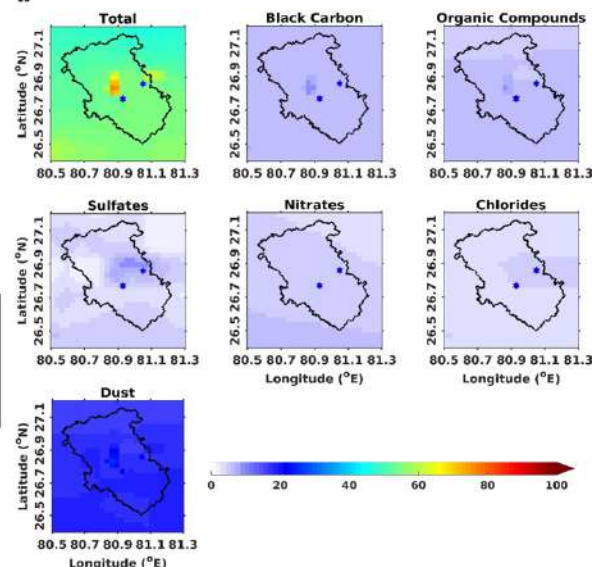


Figure 5.15: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-1 city:

Lucknow, Uttar Pradesh

15th July to 14th Aug 2023

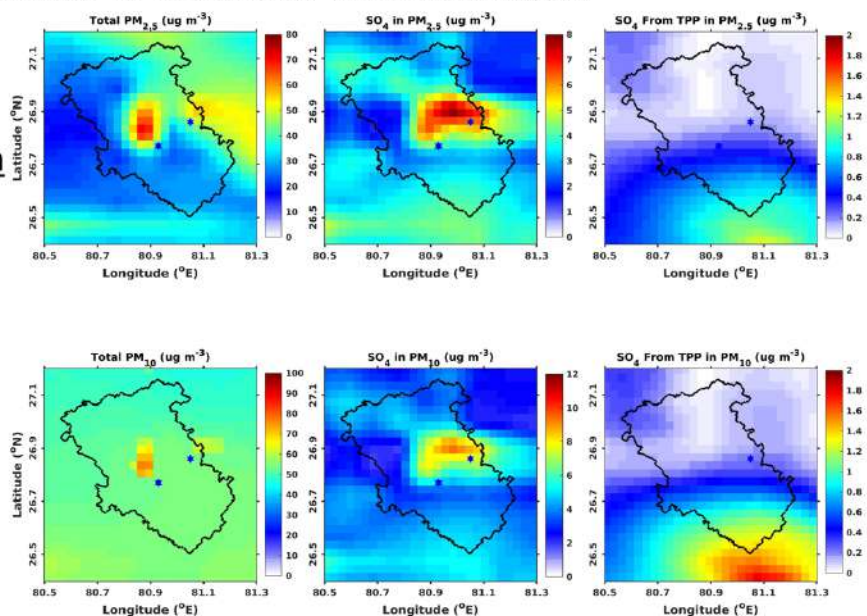


Figure 5.16: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Lucknow during the simulation period from 15th July to 14th August 2023.

Next, we performed another series of systematically designed WRF-Chem model simulations to know the contribution different sources towards SO_2 and sulfate aerosols in Gautam Buddha Nagar, which is a Category-3 city considered during the Phase-II of our survey. We also wanted to understand the contribution of SO_2 emissions from the power sector, specifically coal-based thermal power plants (TPPs), on ambient atmospheric concentrations of SO_2 , sulfate aerosols, $\text{PM}_{2.5}$, and PM_{10} in the city of Gautam Buddha Nagar during our survey. WRF-Chem version 4.2.2 has been used to perform a set of nine atmospheric chemistry simulations over Gautam Buddha Nagar for 15th July to 14th August 2023. For this study, the model domains are centered at Gautam Buddha Nagar (77.61° E and 28.34° N). Each of the simulation domain covers approximately 2250000 square Km area at a horizontal resolution of $10 \times 10 \text{ Km}^2$, with 150×150 grid cells in the outer domain and horizontal resolution of $3 \times 3 \text{ Km}^2$, with 136×136 grid cells in the inner domain following nested WRF-Chem modeling setup and 44 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis (available at 6 hourly intervals) with a resolution of $0.25^\circ \times 0.25^\circ$ have been used to provide meteorological initial and lateral boundary conditions to the model simulation of 15th July to 14th August 2023. To estimate the sectoral emission contribution towards the ambient atmospheric SO_2 , sulfate aerosols, $\text{PM}_{2.5}$, and PM_{10} concentrations in Gautam Buddha Nagar, we followed an emission suppression method. We modified the emissions assuming that FGD was operational in two units of the NTPC Dadri TPP during Phase II of our survey. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

Chemical Transport Modeling for GBN, Uttar Pradesh

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

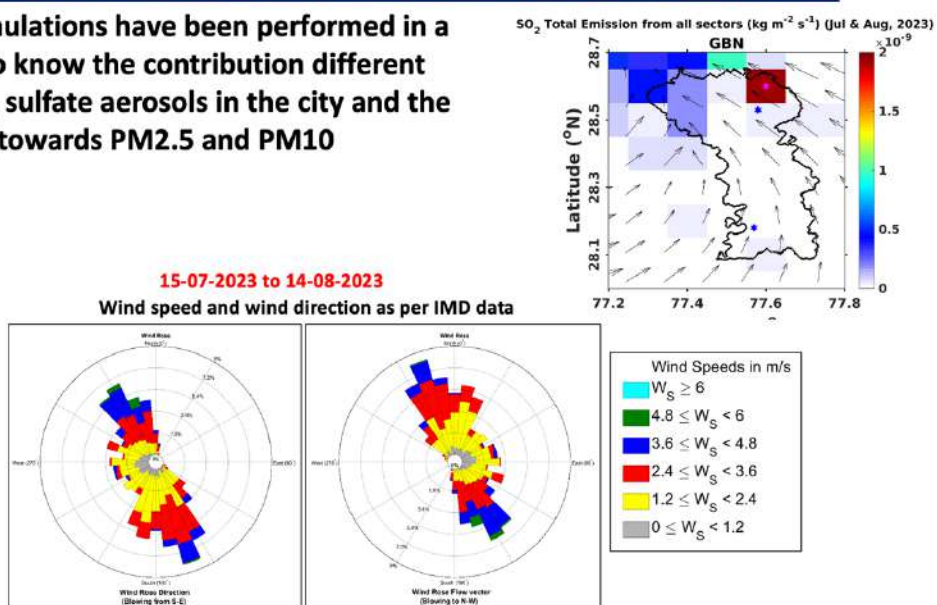


Figure 5.17: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over GBN during the simulation period from 15th July to 14th August 2023.

First, we present the results of our simulations, detailing the contributions of major emission sectors to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ mass concentrations in the city of Gautam Buddha Nagar during Phase II of our survey.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

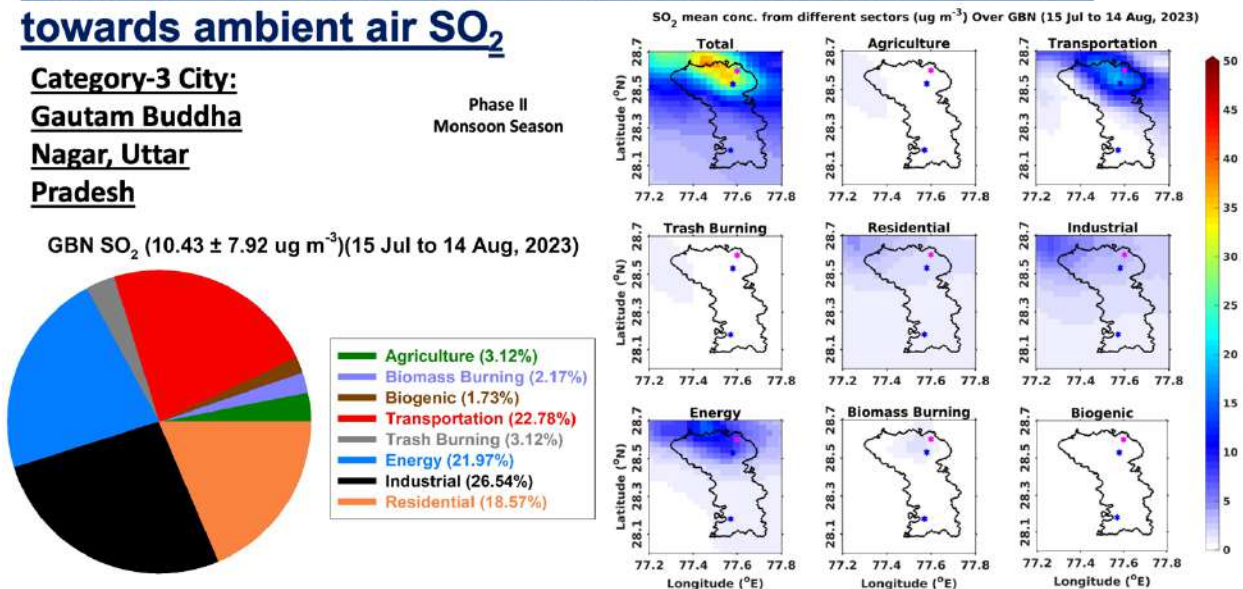


Figure 5.18: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

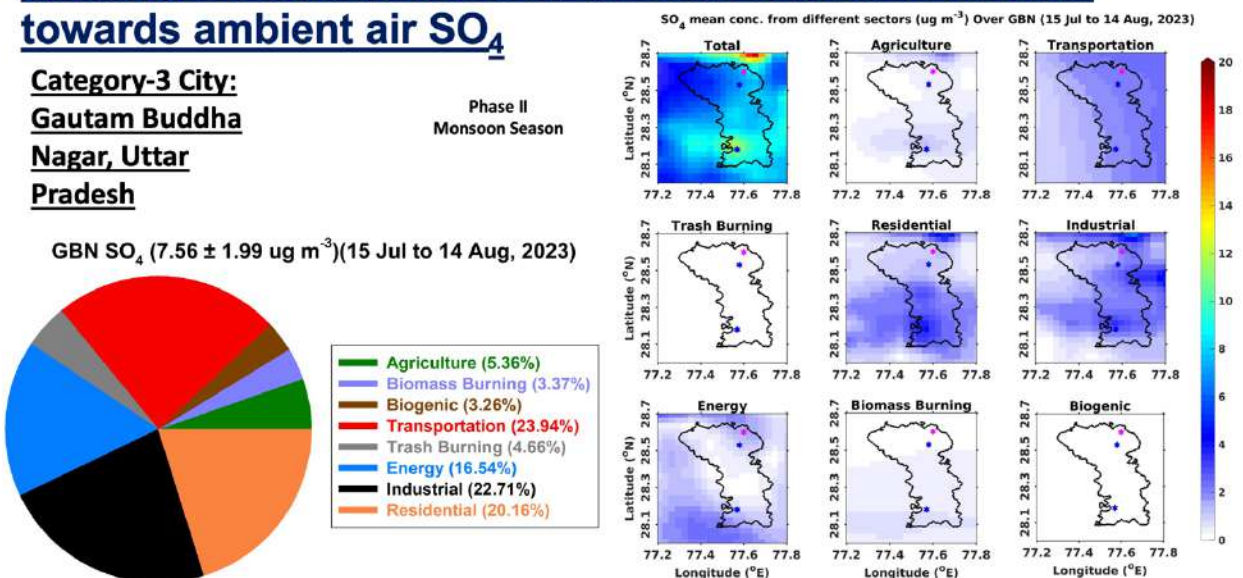


Figure 5.18: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM2.5

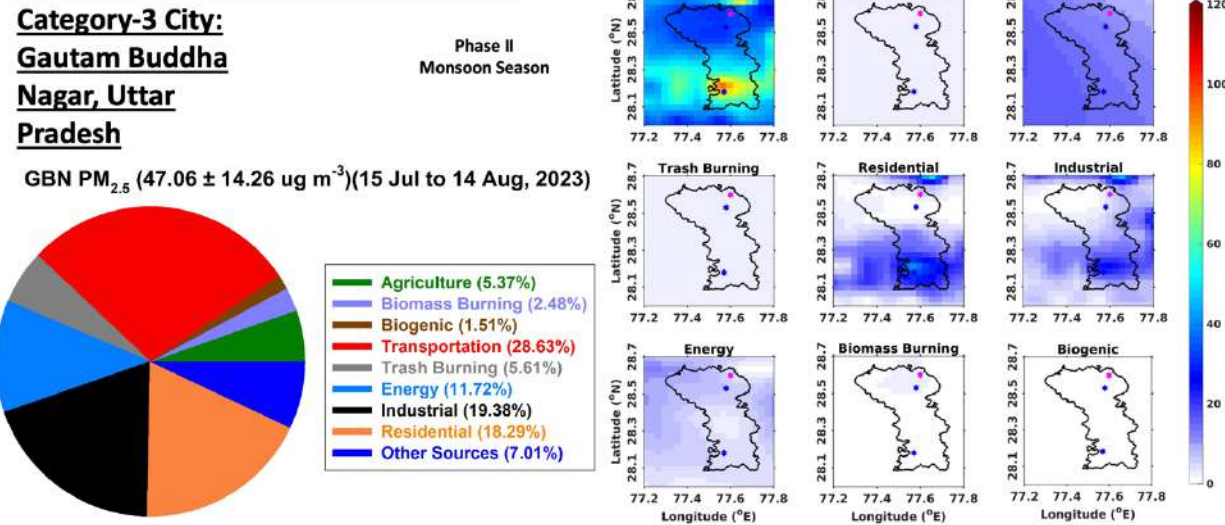


Figure 5.19: Contribution of different emission sectors towards ambient atmospheric PM2.5 concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of different emission sectors towards ambient air PM10

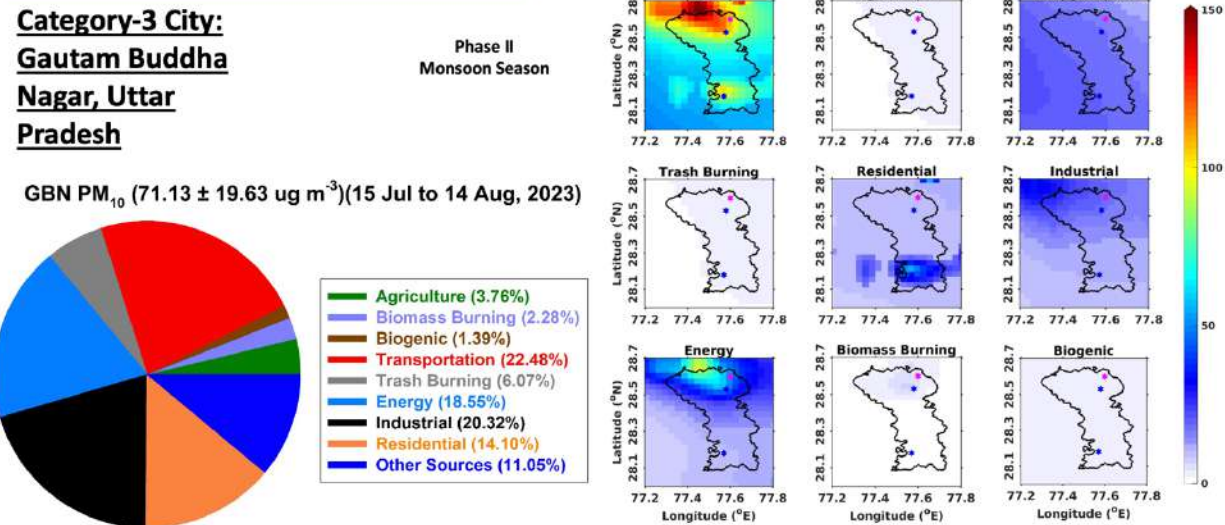


Figure 5.20: Contribution of different emission sectors towards ambient atmospheric PM10 concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates,

chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Gautam Buddha Nagar during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

Phase II
Monsoon Season

GBN PM_{2.5} (47.06 ± 14.26 ug m⁻³)(15 Jul to 14 Aug, 2023)

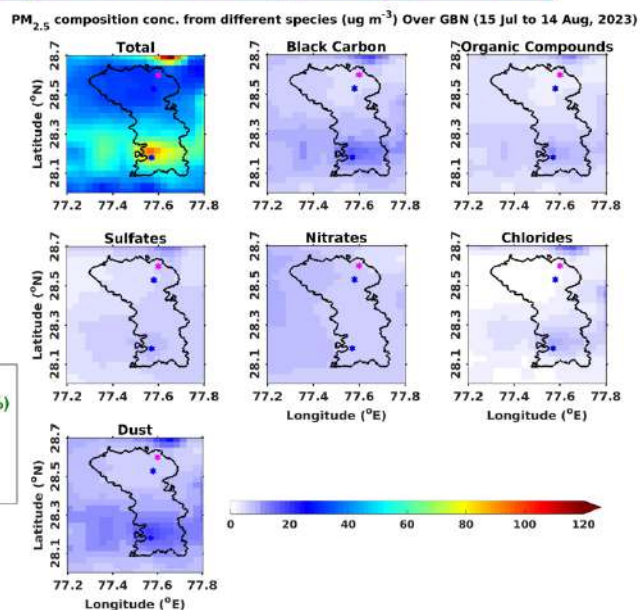
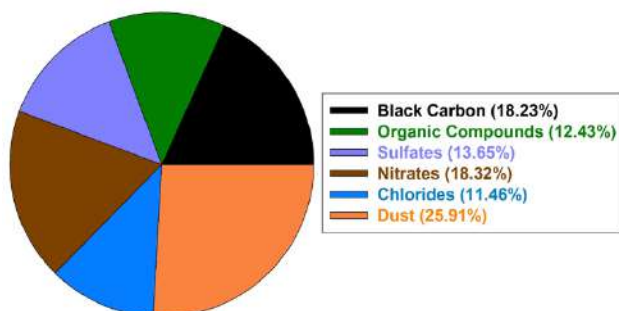


Figure 5.21: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

Phase II
Monsoon Season

GBN PM₁₀ (71.13 ± 19.63 ug m⁻³)(15 Jul to 14 Aug, 2023)

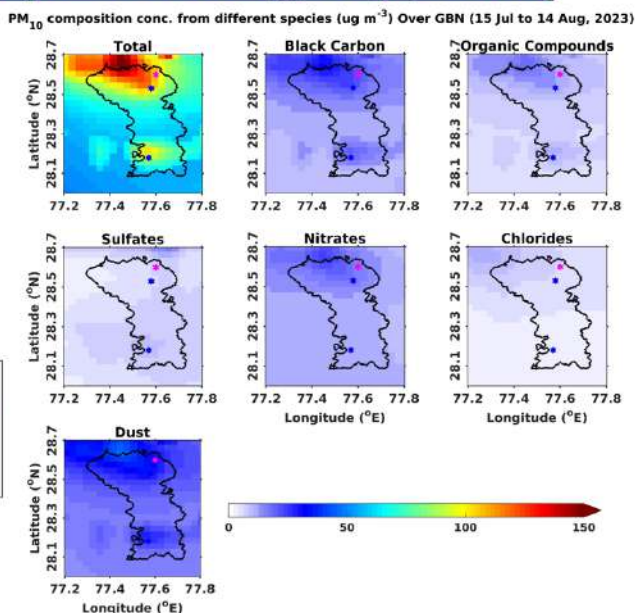
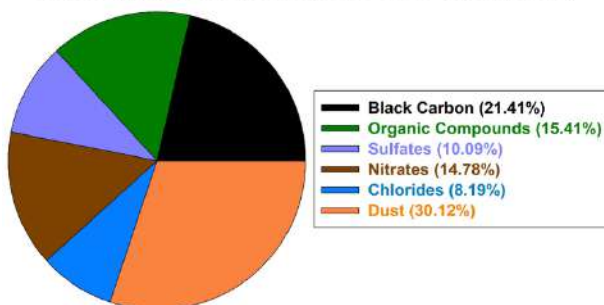


Figure 5.22: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 15th July to 14th August 2023. By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from

thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City:
Gautam Buddha
Nagar, Uttar
Pradesh

15th July to 14th Aug 2023

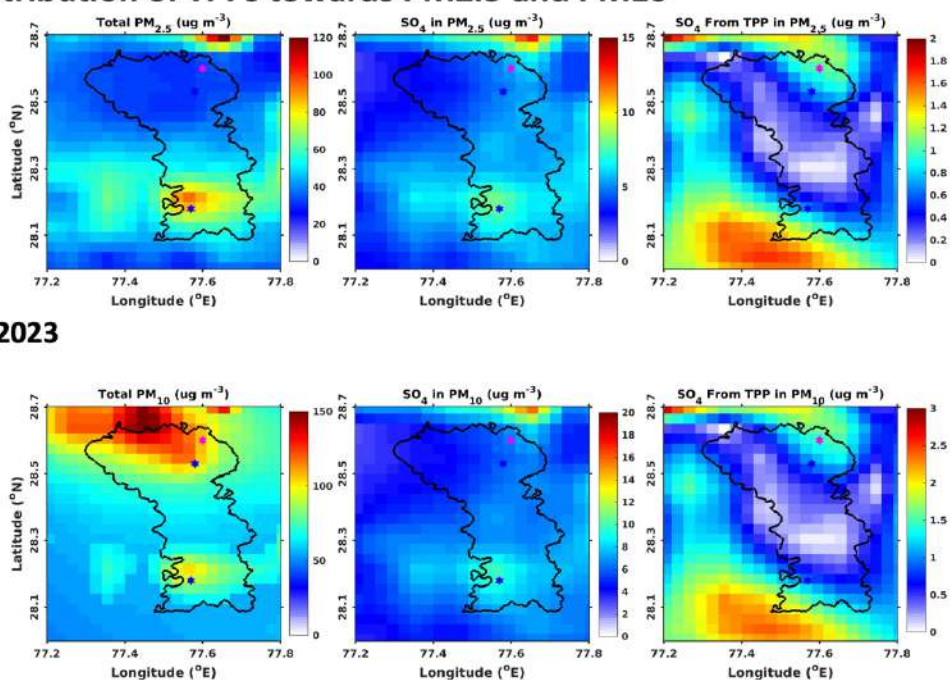


Figure 5.23: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in GBN during the simulation period from 15th July to 14th August 2023.

Based on the results from a series of meticulously planned simulations, the contribution of SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric SO₂ concentrations during Phase II of the survey (summer monsoon season) exhibits significant spatial variability across all cities. Despite this variability, we analyse the average contribution of TPPs to ambient atmospheric SO₂ concentrations in each city and city category. In Category-1 cities, which include cities with no coal-based TPP, the average contribution of TPPs to ambient SO₂ concentrations was 11.44% in Lucknow. For Category-2 cities, which have a coal-based TPP without FGD installed and located within 10km from the city boundary, Kota exhibited an average contribution of 28.9% from TPPs to ambient SO₂ levels. In Category-3 cities, which include a coal-based TPP with FGD installed and located within 10km from the city boundary, Gautam Buddha Nagar showed an average TPP contribution of 21.97%. These findings illustrate that the presence and operational status of FGDs in TPPs significantly influence the contribution of power sector emissions to ambient SO₂ levels. Category-2 cities, which lack FGD installations, displayed higher contributions compared to Category-1 and Category-3 cities, emphasizing the efficacy of FGDs in mitigating SO₂ emissions. Thus, our analysis highlights the varying impact of coal-based thermal power plants on ambient SO₂ levels during the summer monsoon season, with significant differences noted among city categories.

Summary of results from Phase-II of survey (Jul to Aug 2023)

	Name of City (Measurement Site, distance from TPP)	Period of Survey	Total SO ₂ (µg m ⁻³) (NAAQS = 80 µg m ⁻³)	SO ₂ from Power Sector (µg m ⁻³)
Category-1	Lucknow Location-1		5.62 ± 1.14	0.45±0.03
	Lucknow Location-2		5.95 ± 1.56	0.55±0.07
Category-2	Kota Location-1 7 Km from Kota Super TPP	15-07-2023 to 14-08-2023	5.15 ± 1.75	3.35±1.21
	Kota Location-2 40 Km from Kota Super TPP		3.12 ± 0.81	1.28±0.21
Category-3	Gautam Buddha Nagar Location-1 9 Km from DADRI TPP		6.15 ± 2.56	1.41±0.43
	Gautam Buddha Nagar Location-2 46 Km from DADRI TPP		5.89 ± 1.65	1.24±0.31

Table 5.4: Normalized contribution of Power sector towards ambient atmospheric SO₂ concentrations at specific measurement locations in various cities during the period of our survey from 15th July to 14th August 2023.

After discussing the average contribution of TPPs to ambient atmospheric SO₂ concentrations in each city and city category, we examine the normalized contribution of the power sector, specifically coal-based thermal power plants (TPPs), to ambient atmospheric SO₂ concentrations at specific measurement locations across different cities during the Phase II of our survey. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. As evident from the data presented in Table 5.3, our survey results confirm that ambient air SO₂ concentrations at all measurement locations across the six cities met the existing standards during the survey period. In Category-1 city Lucknow, the contribution of TPPs to SO₂ levels was relatively low, ranging from 8% to 9%, with absolute concentrations of 0.45 ± 0.03 µg/m³ and 0.55 ± 0.07 µg/m³. Conversely, in Category-2 city Kota, TPPs had a significantly higher impact, contributing 65% and 41% to SO₂ levels, with absolute concentrations of 3.35 ± 1.21 µg/m³ and 1.28 ± 0.21 µg/m³. In Category-3 city Gautam Buddha Nagar, the contribution was moderate, at 23% and 21%, with absolute concentrations of 1.41 ± 0.43 µg/m³ and 1.24 ± 0.31 µg/m³. This variability highlights the substantial influence of TPPs on local SO₂ concentrations, especially in cities with TPPs near their boundaries. The data suggests that while other sources of SO₂ emissions might be more prevalent in Category-1 cities, TPPs are a primary contributor in Category-2 cities. Overall, the findings indicate that the proximity to thermal power plants and the status of FGD implementation significantly affect SO₂ concentrations, with locations closer to TPPs showing higher contributions from the power sector.

Summary of results from Phase-II of survey (Jul to Aug 2023)

City	Total PM _{2.5} ($\mu\text{g m}^{-3}$)	Total PM ₁₀ ($\mu\text{g m}^{-3}$)	Sulfate aerosols in PM _{2.5} (%)	Sulfate aerosols in PM _{2.5} ($\mu\text{g m}^{-3}$)	Sulfate aerosols in PM ₁₀ (%)	Sulfate aerosols in PM ₁₀ ($\mu\text{g m}^{-3}$)	Contribution of SO ₂ emissions from TPP towards Sulfate aerosols (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} ($\mu\text{g m}^{-3}$)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ ($\mu\text{g m}^{-3}$)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ (%)
Gautam Buddha Nagar	47.06 $\pm$ 11.49	71.13 $\pm$ 15.68	13.65	6.42 $\pm$ 1.31	10.09	7.18 $\pm$ 1.69	16.54	1.06 $\pm$ 0.43	1.25 $\pm$ 0.43	2.26 $\pm$ 0.80	1.76 $\pm$ 0.52
Kota	48.69 $\pm$ 6.14	65.74 $\pm$ 6.47	11.73	5.71 $\pm$ 0.72	9.71	6.38 $\pm$ 0.63	24.08	1.38 $\pm$ 0.17	1.54 $\pm$ 0.15	2.82 $\pm$ 0.36	2.34 $\pm$ 0.23
Lucknow	34.59 $\pm$ 7.99	52.57 $\pm$ 3.14	11.62	4.02 $\pm$ 0.93	8.55	4.49 $\pm$ 0.27	10.49	0.42 $\pm$ 0.10	0.47 $\pm$ 0.03	1.22 $\pm$ 0.28	0.90 $\pm$ 0.05

Table 5.4: Contribution of Power sector towards ambient atmospheric sulfate aerosols, PM_{2.5} and PM₁₀ concentrations in various category cities during the period of our survey from 15th July to 14th August 2023.

Table 5.4 summarizes the contribution of sulfate aerosols (SO₄) in PM_{2.5} and PM₁₀, as well as the specific contribution of sulfate aerosols originating from SO₂ emissions from the power sector (coal based TPPs) to ambient atmospheric PM_{2.5} and PM₁₀ concentrations across various cities during the survey period from 15th July to 14th August 2023. In Category-1 cities, such as Lucknow, sulfate aerosols contributed 11.62% (4.02 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 8.55% (4.49 $\mu\text{g}/\text{m}^3$) to PM₁₀. In Category-2 cities, such as Kota, sulfate aerosols contributed 11.73% (5.71 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 9.71% (6.38 $\mu\text{g}/\text{m}^3$) to PM₁₀. In Category-3 cities, such as Gautam Buddha Nagar, sulfate aerosols contributed 13.65% (6.42 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 10.09% (7.18 $\mu\text{g}/\text{m}^3$) to PM₁₀. On average, the contributions of sulfate aerosols to PM_{2.5} were 13.65% (6.42 $\mu\text{g}/\text{m}^3$) in Category-3 cities, 11.73% (5.71 $\mu\text{g}/\text{m}^3$) in Category-2 cities, and 11.62% (4.02 $\mu\text{g}/\text{m}^3$) in Category-1 cities. For PM₁₀, the average contributions were 10.09% (7.18 $\mu\text{g}/\text{m}^3$) in Category-3 cities, 9.71% (6.38 $\mu\text{g}/\text{m}^3$) in Category-2 cities, and 8.55% (4.49 $\mu\text{g}/\text{m}^3$) in Category-1 cities. These figures indicate a significant presence of sulfate aerosols in particulate matter across all city categories, with Category-3 cities showing the highest contributions.

During the Phase-II survey, we also estimated the contribution of SO₂ emissions from the energy sector, specifically coal-based thermal power plants (TPPs), to the total ambient air SO₄ (sulfate aerosol) concentration and found that it varied significantly across different cities and city categories. In the Category-1 city of Lucknow, the contribution of SO₂ emissions from TPPs towards the total ambient air SO₄ concentration was 10.49%, corresponding to an absolute concentration of 0.50 $\mu\text{g}/\text{m}^3$. For the Category-2 city of Kota, the contribution of SO₂ emissions from TPPs towards the total ambient air SO₄ concentration was 24.08%, equating to an absolute concentration of 1.62 $\mu\text{g}/\text{m}^3$. In the Category-3 city of Gautam Buddha Nagar, the contribution of SO₂ emissions from TPPs towards the total ambient air SO₄ concentration was 16.54%, translating to an absolute concentration of 1.25 $\mu\text{g}/\text{m}^3$. Thus, Category-2 cities, with coal-based

TPPs without FGD systems, exhibit the highest contributions of SO₂ emissions from TPPs towards the total ambient air SO₄ concentration. In contrast, Category-1 cities, which have no coal-based TPPs, show the lowest contributions, while Category-3 cities, which have TPPs with FGD systems, have intermediate contributions.

The specific contribution of sulfate aerosols originating from SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric PM_{2.5} and PM₁₀ concentrations also varied across different cities and city categories. In Lucknow, the contribution was 1.22% (0.42 µg/m³) in PM_{2.5} and 0.90% (0.47 µg/m³) in PM₁₀. In Kota, the contributions were 2.82% (1.38 µg/m³) in PM_{2.5} and 2.34% (1.54 µg/m³) in PM₁₀. In Gautam Buddha Nagar, the contributions were 2.26% (1.06 µg/m³) in PM_{2.5} and 1.76% (1.25 µg/m³) in PM₁₀. On average, the contributions of sulfate aerosols originating from SO₂ emissions from TPPs to PM_{2.5} were 2.26% (1.06 µg/m³) in Category-3 cities, 2.82% (1.38 µg/m³) in Category-2 cities, and 1.22% (0.42 µg/m³) in Category-1 cities. For PM₁₀, the average contributions were 1.76% (1.25 µg/m³) in Category-3 cities, 2.34% (1.54 µg/m³) in Category-2 cities, and 0.90% (0.47 µg/m³) in Category-1 cities. These figures indicate that SO₂ emissions from TPPs contribute a measurable, but relatively small portion of sulfate aerosols in PM_{2.5} and PM₁₀.

Overall, the contribution of SO₂ emissions from the power sector, which convert to sulfate aerosols, ranged from 1.22% to 2.82% in PM_{2.5} and from 0.90% to 2.34% in PM₁₀ across the cities during Phase II of the survey. This indicates variability in the impact of power sector emissions on sulfate aerosol concentrations. While SO₂ emissions from TPPs do contribute to sulfate aerosol mass concentrations in PM_{2.5} and PM₁₀, their overall contribution remains a small fraction (less than 3%) of the total PM_{2.5} and PM₁₀ mass concentrations, especially during the summer monsoon season, indicating that other sources are more significant contributors to ambient air PM levels.

CHAPTER-6: SURVEY OF AMBIENT ATMOSPHERIC SO₂ CONCENTRATIONS IN DIFFERENT CATEGORY OF CITIES: PHASE-III

In the first phase of this survey, measurements were conducted in six distinct cities: New Delhi, Kolkata, Ghaziabad, Gautam Buddha Nagar, Nagpur, and Hyderabad, with two cities from each category. These measurements were carried out at two different locations within each city for a one-month period during the spring and pre-monsoon season (February to May). This phase provided valuable data for understanding the baseline levels and variations in ambient atmospheric SO₂ concentrations across these cities during the spring and pre-monsoon seasons. To enhance the robustness of our findings with statistically significant data, we decided to conduct simultaneous measurements at two different locations within each city, extend the survey to other seasons, and include additional cities. Therefore, Phase II of this survey involved simultaneous measurements of SO₂ concentrations at two different locations in three cities: Lucknow, Kota, and Gautam Buddha Nagar, during the monsoon season. Conducting simultaneous measurements from different locations allowed us to compare ambient air SO₂ concentration values at varying distances from coal-based thermal power plants (TPPs) in Category-2 and Category-3 cities. Additionally, it enabled us to assess whether the measured concentrations complied with the National Ambient Air Quality Standards (NAAQS) established by the Central Pollution Control Board (CPCB).

To further enhance the robustness and statistical significance of our findings, we extended the survey to additional cities and conducted simultaneous SO₂ concentration measurements at different locations within these cities during the other seasons. Therefore, the second phase of the survey aimed to measure ambient atmospheric SO₂ concentrations simultaneously at two different locations in cities from all three categories during the monsoon season. In the third phase, we extended these measurements to more cities during the winter season.

Thus, Phase III of the survey was designed with the objective of measuring SO₂ concentrations during the winter season in (a) cities/towns with FGD installed in TPPs, and (b) cities/towns with TPPs without FGD installed. Additionally, the survey aimed to assess the contribution of SO₂ emissions from TPPs to sulfate aerosols present in PM₁₀ and PM_{2.5} in both types of cities. We also sought to determine, based on our measurement-based survey, whether FGD installations were making a difference in ambient air SO₂ concentrations with FGD-equipped TPPs.

Cities across the country were classified into three categories based on their proximity to coal-based thermal power plants (TPPs) and the implementation status of Flue Gas Desulfurization (FGD) systems in these TPPs. As mentioned earlier in Chapter-2, these categories are:

Category-1: Cities with no coal based TPP.

Category-2: Cities with a coal based TPP in which FGD has not been installed and the TPP is located within 10km from the boundary of the city.

Category-3: Cities with a coal based TPP in which FGD has been installed and the TPP is located within a distance of 10km from the boundary of the city.

The third phase of the survey started on 8th November 2023 and ended on 21st February 2024.

Cities and Measurement Sites Selected for Phase-III of the Survey

Survey of ambient atmospheric SO₂ concentrations in different category of cities have been conducted in three phases to cover different cities in different geographical locations of the country and different seasons.

In the first phase of this survey, measurements have been conducted in six different cities namely, New Delhi, Kolkata, Ghaziabad, Gautam Buddha Nagar, Nagpur, and Hyderabad (two cities from each category). Measurements during the first phase of the survey were conducted at two different locations for one month period each in all six cities during spring and pre-monsoon season (February to May). In the second phase of this survey, simultaneous measurements have been conducted in three different cities namely, Lucknow, Kota, and Gautam Buddha Nagar (one city from each category). During the second phase of our survey, simultaneous measurements were conducted at two different locations in all three cities during monsoon season (July- August).

To make the findings of our survey more robust with statistically significant data, it was decided to extend this survey to a few more cities by conducting simultaneous measurements of SO₂ concentrations at different locations in these cities during the winter season as well. We conducted measurement-based survey in the following four cities corresponding to category-2 and category-3 during winter season.

Table 6.1: Cities selected for conducting the survey Phase-III

S. No.	City/District Name	City Category	Capacity of TPP	No. of Units	Population of the city
1	Kota (Rajasthan)	Category-2	1240 MW	7	1951014
2	Gautam Buddha Nagar (U.P.)	Category-3	1820 MW	6	1648115
3	Shahdol (M. P.)	Category-2	1340 MW	5	86681
4	Khargone (M. P.)	Category-3	1320 MW	2	116150

It is worth mentioning here that two (Kota and Gautam Buddha Nagar) out of the four cities chosen for our survey fall under the category of "non-attainment cities with a million-plus population" according to the Central Pollution Control Board (CPCB) classification. In all four

cities, we conducted the survey by performing simultaneous measurements at three different locations for a one-and-a-half-month period at each site.

For cities with TPPs in their vicinity, we designed the survey to measure ambient air SO₂ concentrations at two sites close to the TPP (approximately 1-10 km away), one in the upwind direction and the other in the downwind direction. Additionally, we conducted measurements at a third site located in the downwind direction of the TPP, at a distance of about 40-60 km from the TPP. We first conducted simultaneous measurements at three sites each in Kota and Gautam Buddha Nagar from November 8th to December 24th 2023. Subsequently, we performed simultaneous measurements at three sites each in Shahdol and Khargone from January 8th to February 21st 2024.

Dispersion Modeling (using AERMOD) of SO₂ from Thermal Power Plants (TPPs) to understand the distance of influence of TPPs towards ambient SO₂ concentration and identification of measurement sites for the survey

The AERMOD Dispersion Model Version 9 was employed to understand and quantify the dispersion characteristics of SO₂ from various TPPs based on their operational capacity during the survey period. Dispersion models like AERMOD, which are typically Lagrangian models, use mathematical formulations to characterize the atmospheric processes dispersing pollutants emitted by a source. With emissions and meteorological inputs, a dispersion model can predict concentrations at selected downwind receptor locations. Our goal was to use the results of our dispersion modelling to understand the extent of TPP SO₂ emission influence on ambient air concentrations of SO₂ and to identify suitable measurement sites for Phase III of our survey. In this study, the horizontal resolution of the dispersion modelling simulations was set to 500m x 500m, and the simulations were performed over a model domain area of 300km x 300km, with the thermal power plant location as the centre of the model domain in each simulation.

Figure 6.1 displays the spatial pattern of the highest hourly, 24-hourly, and monthly dispersion of SO₂ from the Dadri TPP during the simulation period from November 8th to December 24th, 2023. Figure 6.2 presents the results of our AERMOD simulation, showing SO₂ concentrations as a function of distance from the Dadri TPP in the direction of maximum dispersion during the simulation period. The graphs illustrate how SO₂ concentrations decrease with increasing distance from the TPP. With a horizontal resolution of 500m, all concentrations plotted in Figures 6.1 and 6.2 represent an area of 500m x 500m around each receptor point. This means that the SO₂ concentrations corresponding to the 0 km label on the X-axis in various panels of Figure 6.2 refer to the average surface concentration of SO₂ over an area of 500m x 500m around the TPP. Similarly, concentrations at any distance from the TPP, as marked on the X-axis in Figure 6.2, refer to the average surface concentration over an area of 500m x 500m around the receptor point at that distance from the TPP. The top panel in Figure 6.2 shows the highest hourly SO₂

concentrations, revealing a sharp decline as the distance increases, particularly noticeable within the first 25 km from the TPP. Beyond this range, the concentrations level off but continue to decrease gradually up to 120 km. The middle and bottom panels in Figure 6.2 focus on the highest 24-hour and monthly average concentrations, respectively. Both metrics show a similar pattern of decrease, with concentrations remaining significantly below the National Ambient Air Quality Standards (NAAQS) for SO₂. Specifically, the 24-hour concentration limit is set at 80 µg/m³, and the annual (there is no standard for monthly) average at 50 µg/m³, both of which are well adhered to at all distances from the TPP.

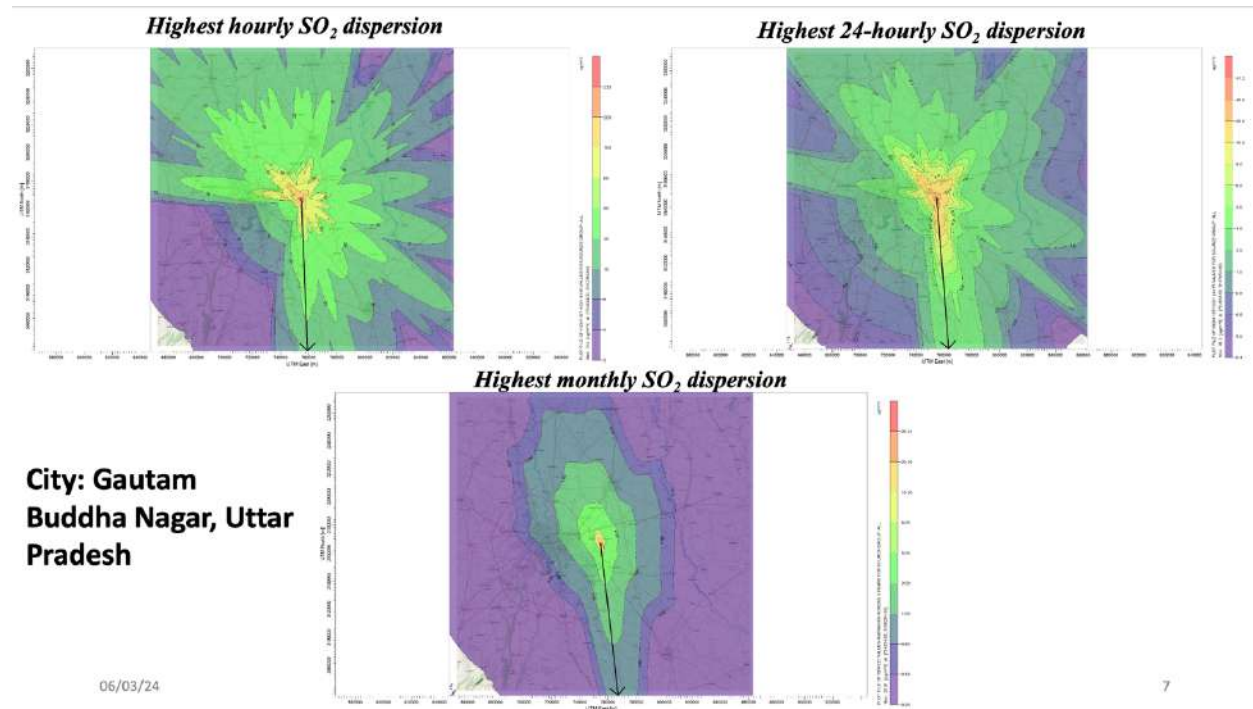
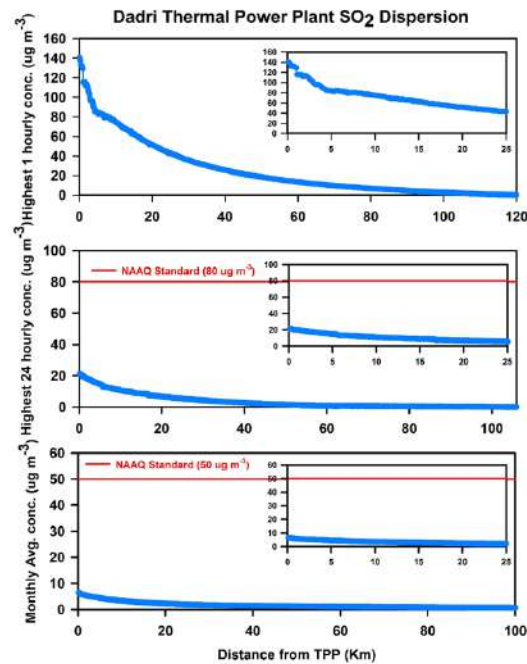


Figure 6.1: Highest hourly, 24-hourly, and monthly dispersion of SO₂ from the Dadri TPP during the simulation period from 8th November to 24th December 2023. The black arrows show the direction of maximum dispersion of SO₂ as simulated by the model.

City: Gautam
Buddha Nagar, Uttar
Pradesh

SO₂ Concentration versus Distance plot for Nov-Dec 2024

06/03/24



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Figure 6.2: Highest hourly, 24-hourly, and monthly concentration of SO₂ plotted as a function of distance from the Dadri TPP in the direction of maximum dispersion during the simulation period from 8th November to 24th December 2023.

These results underscore the effective dispersion of SO₂ emissions with distance from the source, highlighting the localized nature of the impact near the TPP and demonstrating compliance with environmental standards at greater distances. This dispersion modeling helps in assessing the environmental impact of SO₂ emissions and in planning mitigation strategies effectively.

It is important to note that air pollution dispersion models like AERMOD are designed to understand the dispersion of primary air pollutants by considering only their dry and wet deposition processes, without accounting for any chemical reactions that might occur during their atmospheric dispersion. For example, as the SO₂ plume travels downwind, it is likely to undergo oxidation through gas-phase reactions with hydroxyl radicals (OH) during the daytime or aqueous-phase heterogeneous oxidation with H₂O₂ and O₃ through its dissolution in cloud and fog water. Because dispersion models do not account for these chemical processes, the actual decrease in SO₂ concentrations with increasing distance from the TPP is likely faster than what is simulated. Chemical transport models like WRF-Chem do consider the transformation of primary air pollutants into secondary pollutants but are typically run at a coarser resolution than dispersion models. Therefore, using both dispersion models and chemical transport models together provides a better understanding of the dispersion of air pollutants like SO₂ that serve as precursors for secondary pollutants.

The results of our dispersion modelling of SO₂ emissions from the NTPC Dadri TPP in Gautam Buddha Nagar using AERMOD model helped us determine the extent of SO₂ emission influence on ambient air concentrations of SO₂ and identify suitable measurement sites for Phase III of our survey. As previously mentioned, we designed Phase III survey to measure ambient air SO₂ concentrations at two sites close to the TPP (approximately 1-10 km away), one in the upwind direction and the other in the downwind direction. Additionally, we conducted measurements at a third site located in the downwind direction, approximately 40-60 km from the TPP.

Identification of Measurement sites in each city during Phase-III

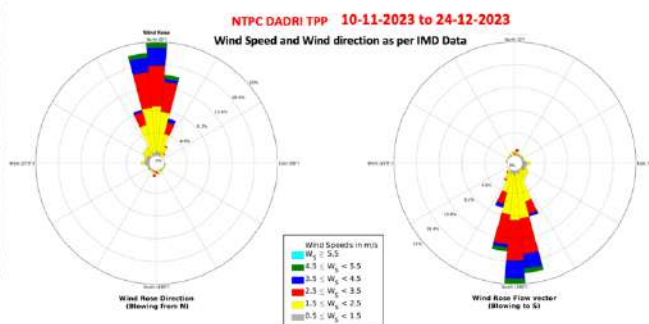
Category-3 City: Gautam Buddha Nagar, Uttar Pradesh



06/03/24

**Sampling height: 10-15m
above ground**

NTPC DADRI TPP	Gautam Buddha Nagar , Uttar Pradesh. Operated by the NTPC.
Location 1	Govt. Public School, Dehra (5 Km from NTPC DADRI TPP)
Location 2	Maharana Kumbha Inter College, Dadupur Khatana (5 Km from NTPC DADRI TPP)
Location 3	Vidya International School, Rabupura (40 Km from NTPC DADRI TPP)



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Figure 6.3: Satellite image (google earth) showing location of the measurement sites for Category-3 city GBN considered during Phase-III of the survey

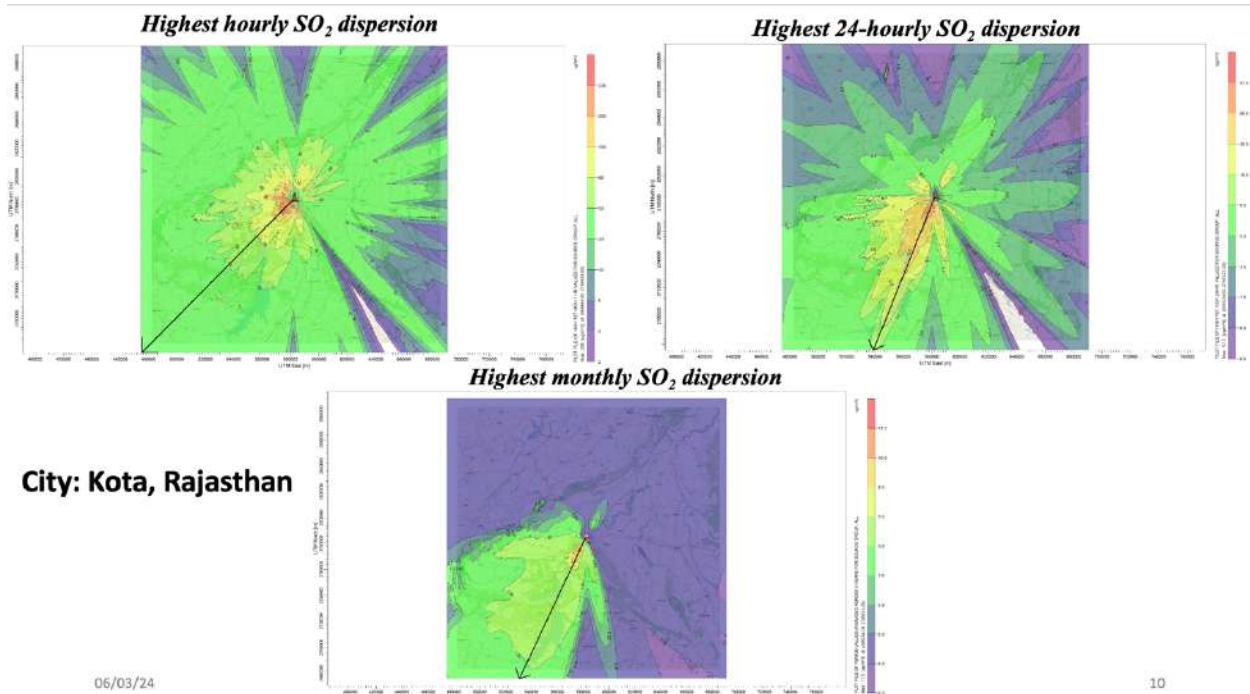


Figure 6.4: Highest hourly, 24-hourly, and monthly dispersion of SO₂ from the Kota Super TPP during the simulation period from 8th November to 24th December 2023. The black arrows show the direction of maximum dispersion of SO₂ as simulated by the model.

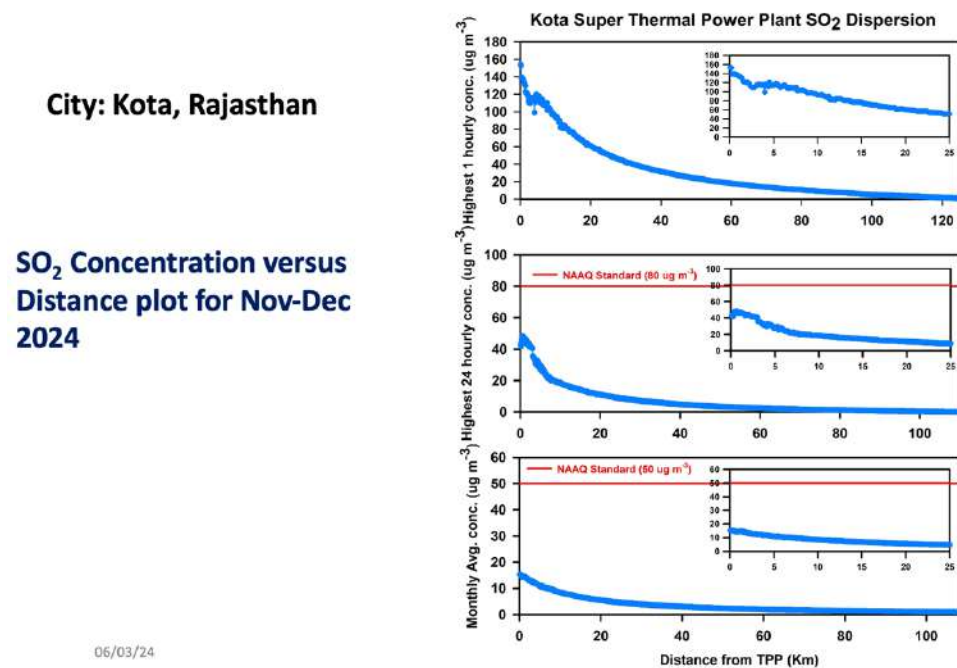
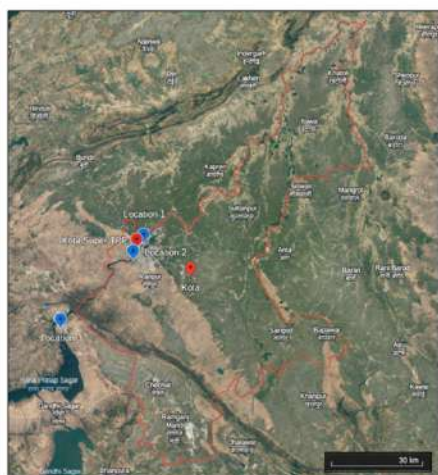


Figure 6.5: Highest hourly, 24-hourly, and monthly concentration of SO₂ plotted as a function of distance from the Kota TPP in the direction of maximum dispersion during the simulation period from 8th November to 24th December 2023.

Figure 6.5 displays the results of our dispersion modeling using AERMOD for SO₂ emissions from the Kota Super Thermal Power Plant (TPP) in Rajasthan, illustrating the relationship between SO₂ concentration and distance from the TPP for November-December 2024. The top panel in Figure 6.5 shows the highest hourly SO₂ concentrations, which decrease significantly as the distance from the TPP increases, particularly within the first 20 km. Beyond this range, the concentrations continue to decline but at a slower rate, extending up to 120 km. The middle panel illustrates the highest 24-hour SO₂ concentrations, with a sharp initial drop-off that levels out as the distance increases, staying well below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ at all distances from the TPP. The bottom panel shows the monthly average SO₂ concentrations, also demonstrating a rapid decrease within the first 20 km, remaining under the NAAQS limit of 50 µg/m³ at all distances from the TPP. These results highlight the localized impact of SO₂ emissions from the TPP, with significant concentration reductions as the distance from the emission source (or the TPP) increases, ensuring compliance with environmental standards. This analysis underscores the importance of spatial considerations in air quality management around thermal power plants.

Identification of Measurement sites in each city during Phase-III

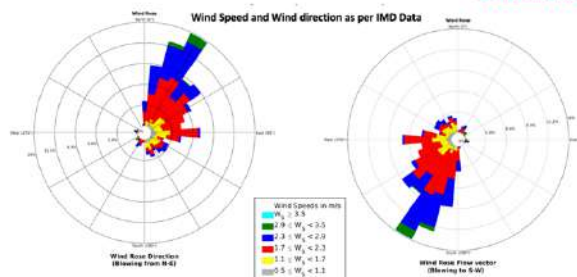
Category-2 city: Kota, Rajasthan



KOTA Super TPP	Kota, Rajasthan. Owned by Rajasthan Rajya Vidyut Utpadan Nigam.
Location 1 (Upwind)	Mahatma Gandhi Senior Secondary School 3 Km from KOTA Super TPP.
Location 2 (Downwind)	Rajasthan Technical University 4 Km from KOTA Super TPP.
Location 3 (Downwind)	Govt. ITI College, Rawatbhata 40 Km from KOTA Super TPP.

Sampling height: 10-15m above ground

10-11-2023 to 24-12-2023



06/03/24

12

Figure 6.6: Satellite image (google earth) showing location of the measurement sites for Category-2 city Kota considered during Phase-III of the survey

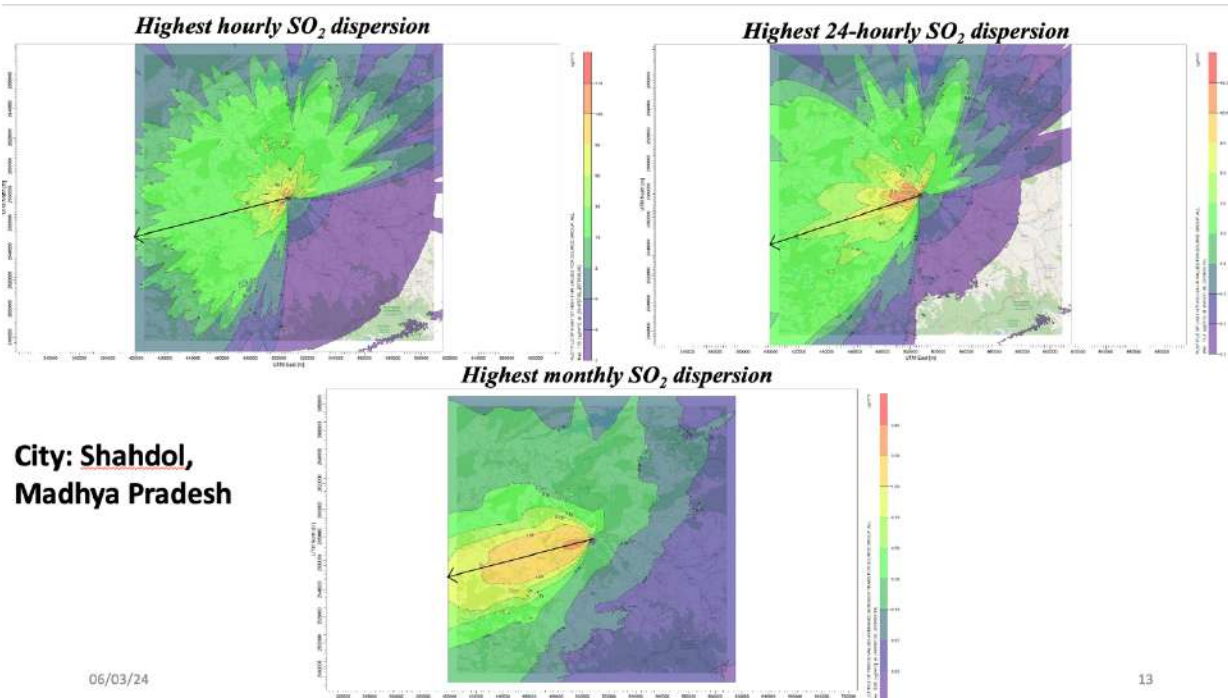


Figure 6.7: Highest hourly, 24-hourly, and monthly dispersion of SO₂ from the Shahdol TPP during the simulation period from 8th January to 21st February 2024. The black arrows show the direction of maximum dispersion of SO₂ as simulated by the model.

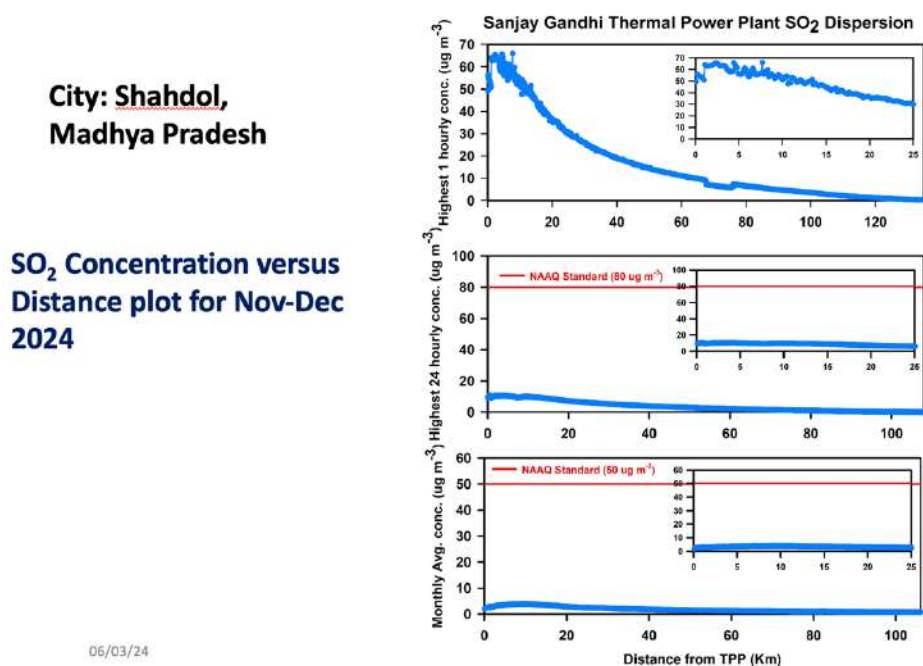


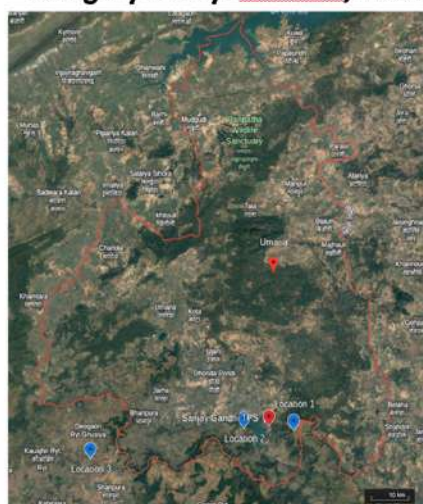
Figure 6.8: Highest hourly, 24-hourly, and monthly concentration of SO₂ plotted as a function of distance from the Shahdol TPP in the direction of maximum dispersion during the simulation period from 8th January to 21st February 2024.

Figure 6.8 presents the results of our dispersion modeling using AERMOD for SO₂ emissions from the Sanjay Gandhi Thermal Power Plant (TPP) in Shahdol, Madhya Pradesh, showing the

relationship between SO₂ concentration and distance from the TPP for November-December 2024. The top panel depicts the highest hourly SO₂ concentrations, which demonstrate a steep decline within the first 20 km from the TPP, followed by a more gradual decrease up to 120 km. The middle panel shows the highest 24-hour SO₂ concentrations, which similarly drop sharply within the initial 20 km and then level out, maintaining values well below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ at all distances from the TPP. The bottom graph illustrates the monthly average SO₂ concentrations, exhibiting a rapid reduction within the first 20 km and remaining under the NAAQS limit of 50 µg/m³ at all distances from the TPP. These results highlight the localized impact of SO₂ emissions from the TPP, with significant concentration reductions as the distance from the emission source increases, ensuring compliance with environmental standards beyond a certain range.

Identification of Measurement sites in each city during Phase-III

Category-2 City: Shahdol, Madhya Pradesh



Sampling height:
10-15m above
ground

SANJAY GANDHI TPP	Umaria, Madhya Pradesh. Operated by the MPPGCL.
Location 1	Govt. Primary School, Tummichot 5 Km from SANJAY GANDHI TPP)
Location 2	Govt. Primary School, Bandhwa Tola (5 Km from SG TPP)
Location 3	Govt. High School, Pipariya (40 Km from SG TPP)

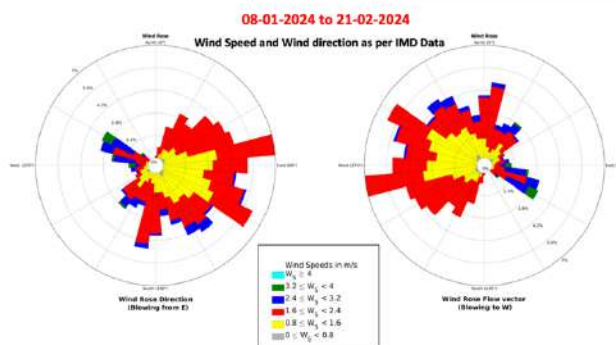


Figure 6.9: Satellite image (google earth) showing location of the measurement sites for Category-2 city Shahdol considered during Phase-III of the survey

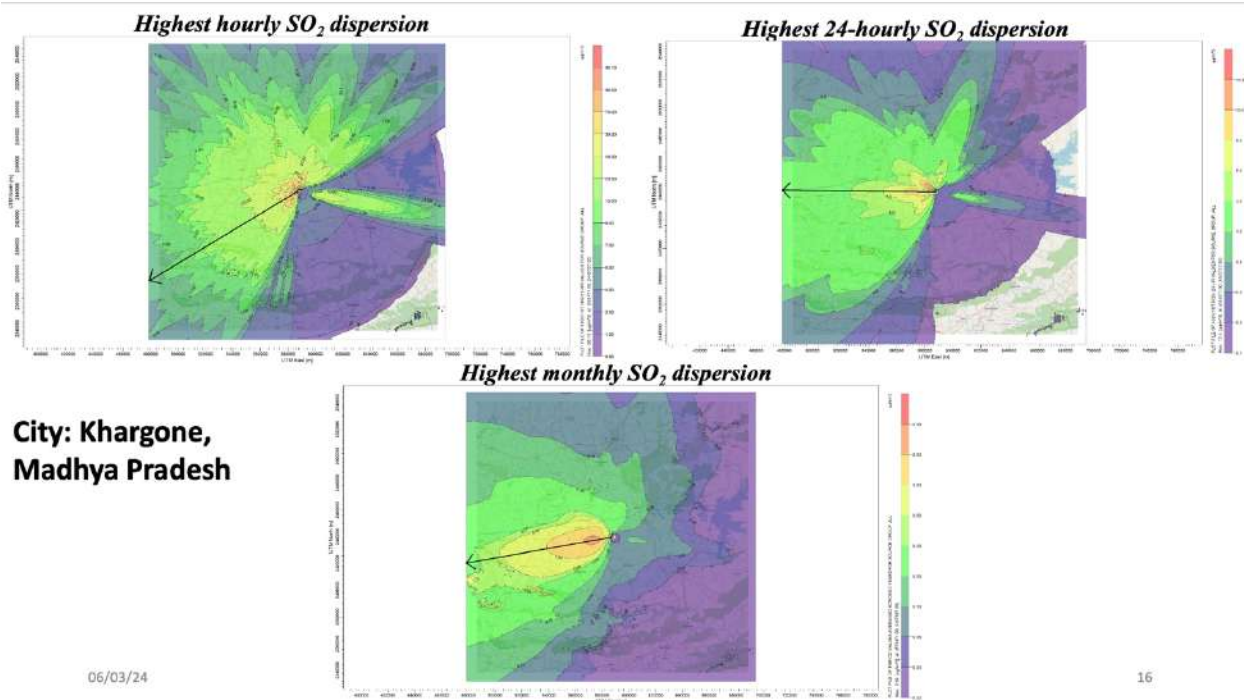


Figure 6.10: Highest hourly, 24-hourly, and monthly dispersion of SO₂ from the Khargone TPP during the simulation period from 8th January to 21st February 2024. The black arrows show the direction of maximum dispersion of SO₂ as simulated by the model.

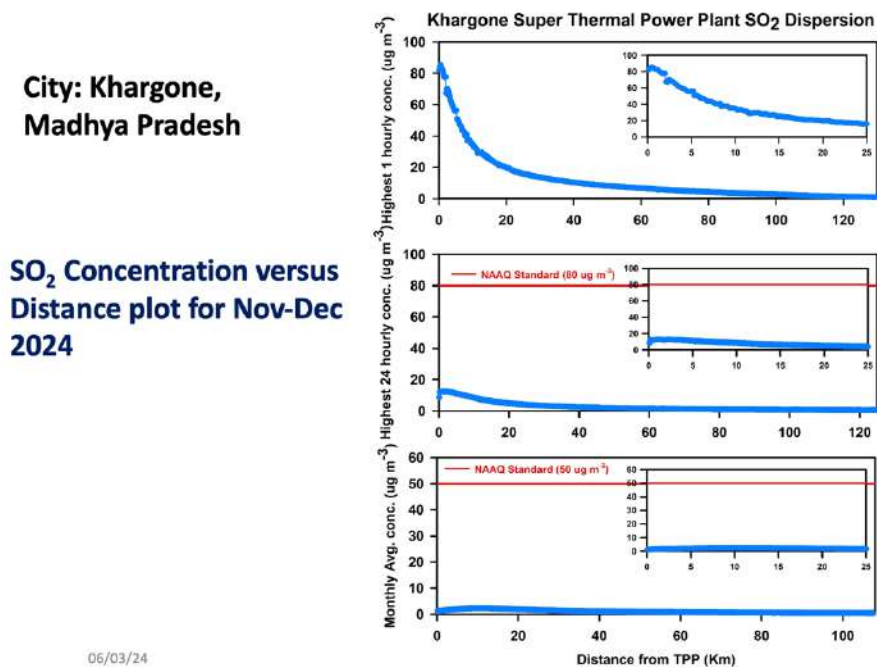
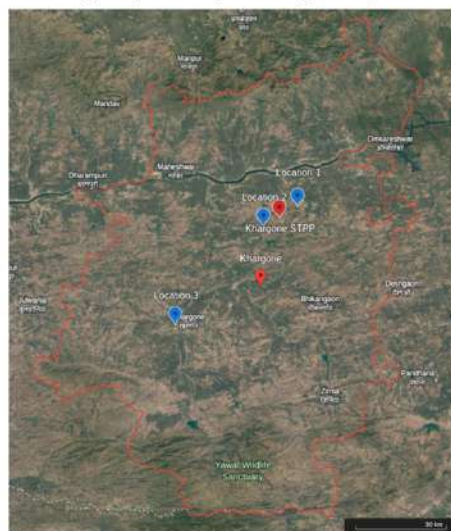


Figure 6.11: Highest hourly, 24-hourly, and monthly concentration of SO₂ plotted as a function of distance from the Khargone TPP in the direction of maximum dispersion during the simulation period from 8th January to 21st February 2024.

Figure 6.11 displays the results of our dispersion modeling using AERMOD for SO₂ emissions from the Khargone Super Thermal Power Plant (TPP) in Khargone, Madhya Pradesh, illustrating the relationship between SO₂ concentration and distance from the TPP for November-December 2024. The top panel shows the highest hourly SO₂ concentrations, which significantly decrease within the first 20 km from the TPP and continue to decline gradually up to 120 km. The middle panel depicts the highest 24-hour SO₂ concentrations, which similarly drop sharply within the initial 20 km and then level off, maintaining values well below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ at all distances from the TPP. The bottom panel presents the monthly average SO₂ concentrations, exhibiting a rapid reduction within the first 20 km and remaining under the NAAQS limit of 50 µg/m³ at all distances from the TPP. These results highlight the localized impact of SO₂ emissions from the TPP, with significant concentration reductions as the distance from the emission source increases, ensuring compliance with environmental standards. This analysis underscores the importance of considering spatial dispersion when assessing the environmental impact of thermal power plant emissions.

Identification of Measurement sites in each city during Phase-III

Category-3 City: Khargone, Madhya Pradesh



Sampling height:
10-15m above
ground

KHARGONE Super TPP	Khargone, Madhya Pradesh. Operated by the NTPC.
Location 1	Govt. Primary School, Julwanya (5 Km from Khargone TPP)
Location 2	Govt. Primary School, Bhopada (5 Km from Khargone TPP)
Location 3	Govt. Law College, Khargone (40 Km from Khargone TPP)

08-01-2024 to 21-02-2024

Wind Speed and Wind direction as per IMD Data

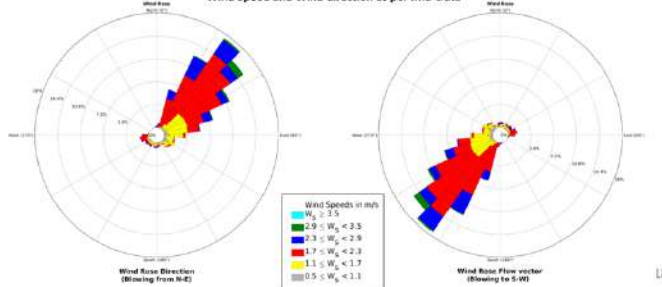


Figure 6.12: Satellite image (google earth) showing location of the measurement sites for Category-2 city Khargone considered during Phase-III of the survey

Measurement Plan for Phase-III of the Survey

We made simultaneous measurements at three pre-identified locations in each of the four cities so as to avoid any biases in our measured SO₂ concentration data due to seasonal variations in SO₂ concentrations caused by seasonal variations in temperature, wind, relative humidity, and other meteorological variables which influence the transport and removal of SO₂ and hence the lifetime of SO₂ in the atmosphere. As all cities considered in Phase III had TPPs in their vicinity,

we designed the survey to measure ambient air SO₂ concentrations at two sites close to the TPP (approximately 1-10 km away), one in the upwind direction and the other in the downwind direction. Additionally, we conducted measurements at a third site located in the downwind direction of the TPP, at a distance of about 40-60 km from the TPP. We first conducted simultaneous measurements at three sites each in Kota and Gautam Buddha Nagar from November 8th to December 24th 2023. Subsequently, we performed simultaneous measurements at three sites each in Shahdol and Khargone from January 8th to February 21st 2024. We made continuous measurements at every 10-minute intervals from three different locations in each of these cities for 45 days during the survey period. It was important to make simultaneous measurements in each of the six different measurement locations spread across the three cities in the same month or season so that our measurement data can be considered as truly representative SO₂ concentrations from each of the cities in the same season. This avoids any kind of bias in our measured SO₂ concentrations due to seasonal variability of temperature, wind, relative humidity, and other meteorological variables which influence the transport and removal of SO₂ from the atmosphere. That means, we measured at least 6,480 air samples at each location and a total of at least 19,440 samples were collected in each city. Thus, ambient SO₂ concentrations from a total of three different cities were surveyed during Phase-III of our study.

Measurement technique and equipment involved:

We used the same equipment and followed the same measurement techniques as described in Chapter 2; therefore, those details are not repeated here.

Measurement data from Phase-III of the Survey

This section presents the results of the measurements conducted in various category cities across the country during Phase III of our survey. In this phase, we first conducted simultaneous measurements at three sites each in Kota and Gautam Buddha Nagar from November 8th to December 24th, 2023. Subsequently, we performed simultaneous measurements at three sites each in Shahdol and Khargone from January 8th to February 21st, 2024. Table 6.2 summarizes the daily mean, maximum instantaneous, and minimum instantaneous values of ambient air SO₂ concentrations measured at three different locations in each of the four cities selected for Phase III of our survey during the winter season.

In the Category 2 city of Kota, the maximum instantaneous ambient air SO₂ concentration was measured to be 68.09 µg/m³, the minimum was 0.77 µg/m³, and the daily mean values ranged from 3.23 ± 0.71 µg/m³ to 11.23 ± 4.94 µg/m³. In Shahdol, another Category 2 city, the maximum ambient air SO₂ concentration was 22.91 µg/m³, the minimum was 1.06 µg/m³, and the daily mean values ranged from 4.42 ± 0.78 µg/m³ to 5.78 ± 1.13 µg/m³. In the Category 3 city of

Gautam Buddha Nagar, the maximum instantaneous SO₂ concentration was 70.14 µg/m³, the minimum was 0.54 µg/m³, and the daily mean values ranged from 6.51 ± 0.93 µg/m³ to 12.51 ± 2.82 µg/m³. It is noteworthy that the highest values in both Kota and Gautam Buddha Nagar were measured on November 13th, the day after the Diwali festival, which is characterized by the bursting of firecrackers that significantly contributed to these peak values. Excluding this anomalous high SO₂ concentration during the Diwali festival, the maximum instantaneous SO₂ concentration measured in Gautam Buddha Nagar and Kota during our survey was 36.41 µg/m³ and 48.56 µg/m³ respectively. In Khargone, another Category 3 city, the maximum ambient air SO₂ concentration was 11.73 µg/m³, the minimum was 1.14 µg/m³, and the daily mean values ranged from 4.24 ± 0.31 µg/m³ to 4.39 ± 0.43 µg/m³.

Summarizing by city categories, Category 2 cities had maximum instantaneous SO₂ concentrations of up to 68.09 µg/m³ and minimum concentrations down to 0.77 µg/m³, with daily mean values ranging from 3.23 to 11.23 µg/m³. Category 3 cities had maximum concentrations of up to 70.14 µg/m³ and minimum concentrations down to 0.54 µg/m³, with daily mean values ranging from 4.24 to 12.51 µg/m³. These results highlight the variability in ambient air SO₂ concentrations across different locations and city categories, with Category 3 cities generally showing higher SO₂ levels. Additionally, the measured SO₂ concentrations were generally higher at downwind sites compared to upwind sites, and SO₂ levels tended to decrease with increasing distance from the TPP across all cities.

As the National Ambient Air Quality Standards (NAAQS) or the maximum permissible limit of ambient air SO₂ concentrations based on 24 hours average measurements for industrial, residential, rural, and other areas as notified by the MoEF&CC, Govt. of India is 80 µg/m³, results of our survey confirm that the ambient air SO₂ concentrations in all cities are meeting the existing standards during the period of our survey.

As evident from Table 6.2, the daily mean values of ambient air SO₂ concentrations measured at various locations in all four cities during Phase III of our survey are comparable to the SO₂ data from the CPCB/SPCB/PCC measurement sites in those cities (<https://cpcb.nic.in/air-pollution/>), thereby validating the robustness of our collected data.

Next, we discuss the findings of our survey from all four cities one by one with more details. Figure 6.13 show the time series of daily mean ambient SO₂ concentrations measured from November 8 to December 24, 2023, at three sites in Gautam Buddha Nagar (GBN). One site is upwind (Location-1) and two are downwind (Location-2 and Location-3) relative to the Dadri Thermal Power Plant (TPP). At Location-1, which is 5 km upwind from the TPP, SO₂ concentrations remained relatively low, fluctuating between approximately 5 and 20 µg/m³, with standard deviation bars indicating moderate daily variability. In contrast, at the downwind sites, Location-

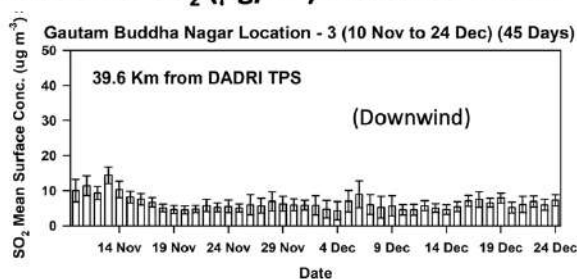
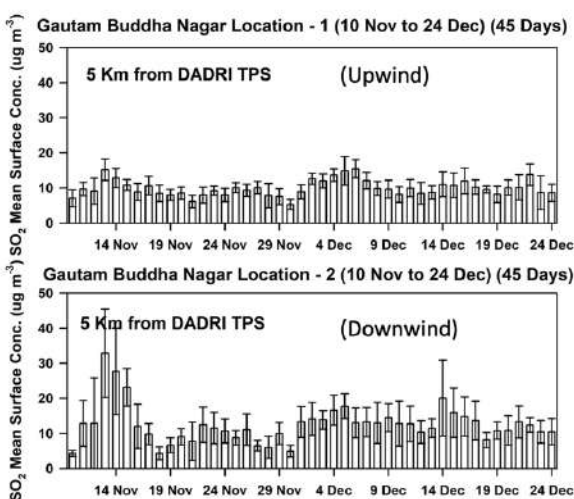
2 (5 km from the TPP) and Location-3 (40 km from the TPP), SO₂ concentrations were higher and more variable. Location-2 recorded highest daily mean values ranging from about 10 to 35 µg/m³, showing noticeable peaks around mid-November and early December.

Summary of survey results from Phase-III (Nov 2023 to Feb 2024)

	Name of City (Measurement Site, distance from TPP)	Period of Survey	This Study SO ₂ Concentration (µg m ⁻³)			CPCB/SPCB measurements (µgm ⁻³)
			Maximum (Instantaneous)	Minimum (Instantaneous)	Daily Mean ± 1σ (NAAQS = 80 µg m ⁻³)	
Kota Category-2	3 Km from Kota Super TPS (upwind)	10-11-2023 to 24-12-2023 (1.5 months)	29.21	0.89	5.13 ± 1.96	8.97 ± 2.34
	4 Km from Kota Super TPS (downwind)		68.09	1.54	11.23 ± 4.94	
	40 Km from Kota Super TPS (downwind)		27.74	0.77	3.23 ± 0.71	
GBN Category-3	5 Km from DADRI TPP (upwind)	10-11-2023 to 24-12-2023 (1.5 months)	25.14	2.46	9.82 ± 1.59	12.48 ± 1.74
	5 Km from DADRI TPP (downwind)		70.14	1.19	12.51 ± 2.82	
	40 Km from DADRI TPP (downwind)		18.61	0.54	6.51 ± 0.93	
Shahdol Category-2	5 Km from SG TPS (upwind)	08-01-2024 to 21-02-2024 (1.5 months)	13.58	1.64	5.21 ± 1.58	6.11 ± 1.85
	5 Km from SG TPS (downwind)		22.91	1.19	5.78 ± 1.13	
	40 Km from SG TPS (downwind)		12.73	1.06	4.42 ± 0.78	
Khargone Category-3	5 Km from Khargone TPP (upwind)	08-01-2024 to 21-02-2024 (1.5 months)	9.52	2.37	4.38 ± 0.38	3.37 ± 0.85
	5 Km from Khargone TPP (downwind)		11.73	1.14	4.24 ± 0.31	
	40 Km from Khargone TPP (downwind)		8.37	1.45	4.39 ± 0.43	

Table 6.2: Daily mean, maximum, and minimum values of ambient air SO₂ concentration (µg/m³) measured at two different locations of four different cities classified under three different categories from across the country during Phase-III of our survey are listed here. SO₂ concentrations data from CPCB/SPCB measurements sites from each city are also mentioned.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in GBN



National Ambient Air Quality Standards (NAAQS)					
[NAAQS Notification dated 18 th November, 2009]					
S. No.	Pollutants	Time Weighted Average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and other Areas	Ecologically Sensitive Area (notified by Central Government)	
1	Sulphur Dioxide (SO ₂), µg/m ³	Annual 24 Hours	50 80	20 80	1. Improved West and Gaeke 2. Ultraviolet Fluorescence

There has been no occurrences of ambient SO₂ concentrations exceeding the NAAQS at any of the measurement locations in GBN throughout the period of our survey (Even the instantaneous values have never exceeded the standard)

Figure 6.13: Time series of daily mean ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (8th November to 24th December 2023) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of GBN. Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

Location-3 exhibited daily mean SO₂ concentrations between roughly 5 and 20 $\mu\text{g}/\text{m}^3$, with less pronounced peaks and lower overall variability compared to Location-2. It is worth mentioning here that despite the higher SO₂ levels at the downwind sites, none of the measured daily mean concentrations at any of the locations exceeded the National Ambient Air Quality Standards (NAAQS) limit of 80 $\mu\text{g}/\text{m}^3$. This indicates that the ambient air quality in terms of SO₂ concentrations remained well within permissible levels throughout the survey period, even considering the instantaneous values reflected by the vertical standard deviation bars. This further confirms the effective management of SO₂ emissions in the vicinity of the Dadri TPP.

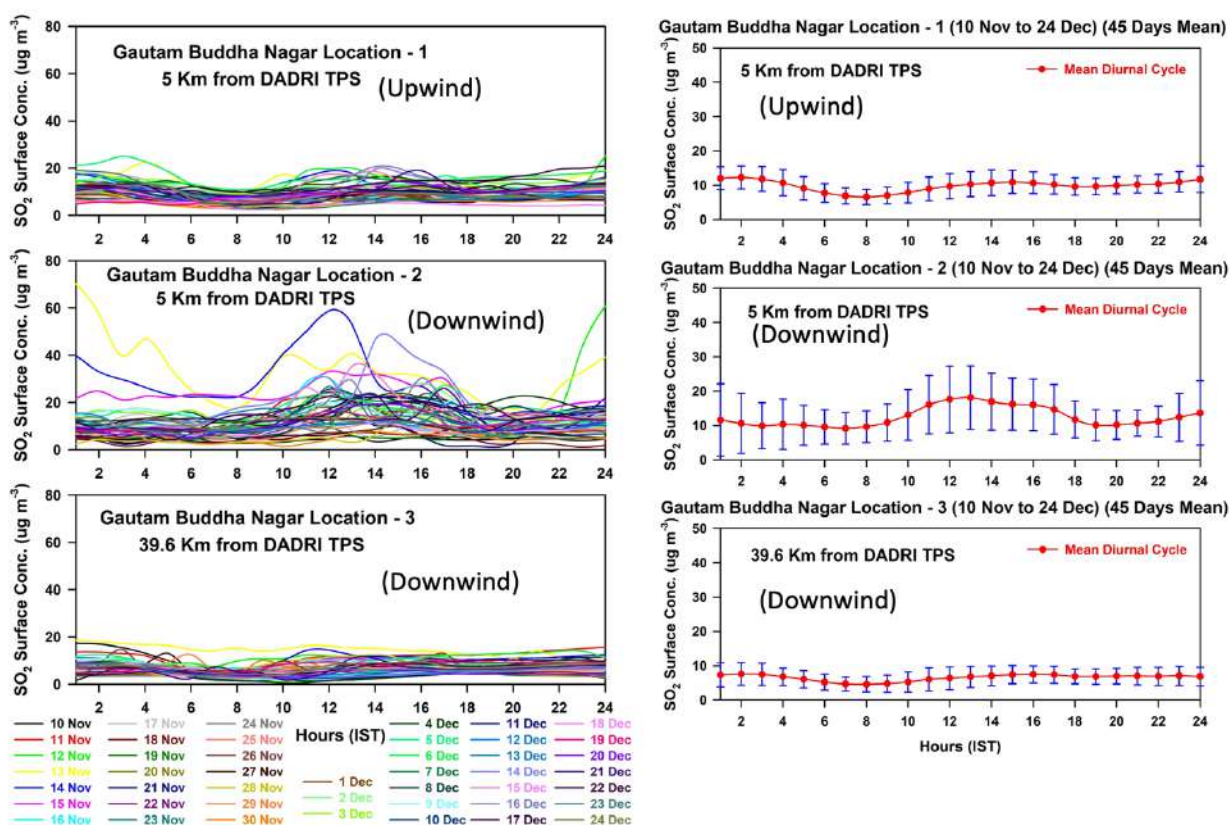
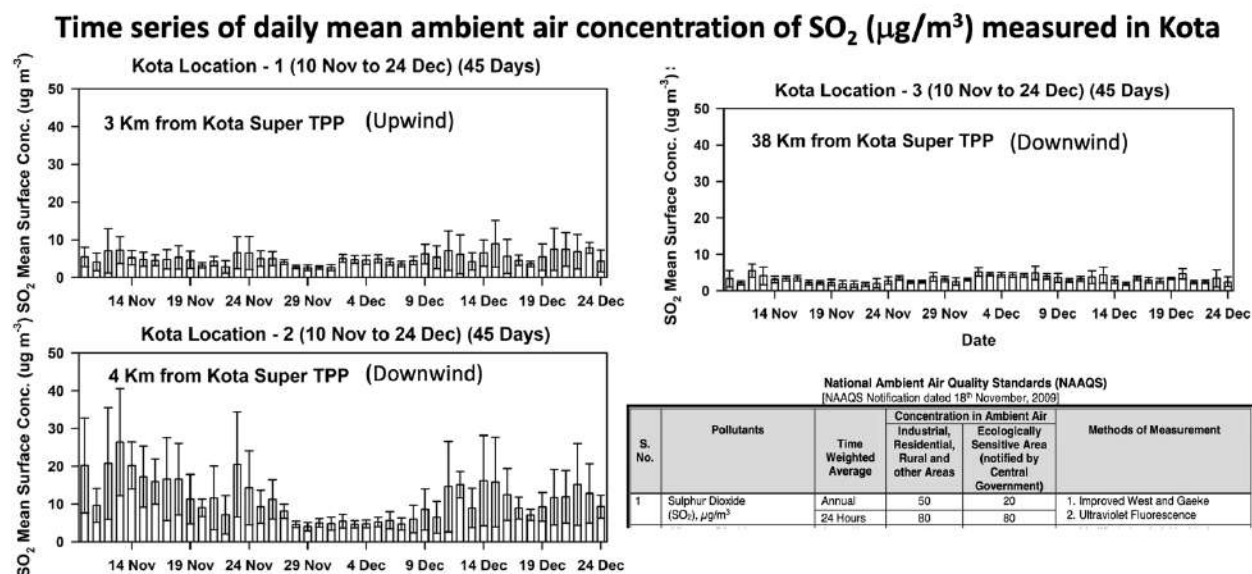


Figure 6.14: Diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (8th November to 24th December 2023) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of GBN. 45-days mean pattern of diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) derived from measurements made at all three sites of GBN are also shown. Vertical lines in all panels on the right represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Figure 6.14 shows the diurnal variation of ambient air SO₂ concentration (µg/m³) measured from November 8 to December 24, 2023, at one upwind (Location-1) and two downwind (Location-2 and Location-3) sites in Gautam Buddha Nagar (GBN). At Location 1, situated 5 km upwind from the Dadri TPP, SO₂ concentrations are relatively stable with minor fluctuations throughout the day. The levels generally remain low, with small increases observed in the early morning, midday, and late evening. These fluctuations can be attributed to local residential activities such as cooking, vehicular emissions, and industrial contributions. Additionally, emissions from diesel generators used as power backups in office complexes, educational institutes, construction activities, and housing societies may contribute to these variations. Meteorological factors and the diurnal variation of the atmospheric boundary layer, which is typically shallower during nighttime, early morning, and late evening, also trap pollutants closer to the ground. The overall low and stable SO₂ concentrations at Location 1, compared to Location 2, indicate that TPP emissions have a relatively smaller influence at this upwind site during the winter season, largely due to the prevailing wind direction. Location 2, located 5 km downwind from the Dadri TPP, exhibits a more pronounced diurnal variation in SO₂ concentrations. The levels are higher compared to the upwind site, with noticeable peaks during midday and late evening. The midday peak likely corresponds to the TPP's operational hours and increased industrial and vehicular activities, while the late evening peak may be influenced by residential activities such as cooking and emissions from diesel generators. Meteorological conditions, such as wind direction and speed, play a significant role in transporting TPP emissions and other sources to this site. The atmospheric boundary layer's variation, which is generally deeper during the daytime, allows for better dispersion of pollutants, whereas a shallower boundary layer in the evening leads to higher concentrations of air pollutants near the surface during nighttime. Observed spikes in SO₂ concentrations lasting for 2-4 hours during daytime on different days of our survey indicates that the stronger emissions from multiple local sources are overwhelming the expected dilution of the concentrations during the midday. At Location 3, about 40 km downwind from the Dadri TPP, the diurnal variation in SO₂ concentrations is less pronounced than at Location 2 and similar to Location 1. SO₂ levels at Location 3 are only slightly lower than at the upwind site Location 1 but show a smoother diurnal cycle compared to Location 2. There are minor increases throughout the day, with less distinct peaks. This pattern suggests a diluted impact of TPP emissions and other SO₂ sources due to the greater distance, coupled with contributions from local sources such as transportation, minor industrial activities, and diesel generators. Meteorological factors, including wind patterns and boundary layer dynamics, influence the dispersion and concentration of SO₂ at this site, leading to a more moderated variation.

Figure 6.14 also shows the mean diurnal variability of ambient air SO₂ concentrations at three measurement locations in Gautam Buddha Nagar during Phase III of our survey, situated at different distances and directions (upwind and downwind) relative to the Dadri TPP. At Location

1 (5 km upwind from the TPP), SO₂ concentrations remain relatively low and stable throughout the day, with slight increases in the early morning and late evening, which can be attributed to local residential activities, vehicular emissions, and the use of diesel generators. At Location 2 (5 km downwind from the TPP), we noted a more pronounced diurnal variation, with higher SO₂ levels and noticeable peaks during midday and late evening. These midday peaks are likely due to a combination of emissions from the TPP as well as various local sources such as diesel generators, industrial activities, and vehicular traffic. Despite the expectation of pollutant dilution due to a deeper atmospheric boundary layer during midday, the spikes in SO₂ concentrations suggest that emissions from these multiple local sources are overwhelming the dilution effect. Location 3 (40 km downwind from the TPP) shows a smoother diurnal cycle with less pronounced peaks, indicating a more diluted impact of the TPP emissions due to the greater distance. However, the minor increases in SO₂ levels throughout the day still reflect contributions from local sources like residential, transportation and industrial activities. Overall, the higher midday SO₂ concentrations, especially at Location 2, underscore the significant role of local emissions from the residential sector, diesel generators, industries, and vehicular traffic, in addition to TPP emissions, in influencing ambient SO₂ levels. These local sources contribute to elevated SO₂ concentrations, particularly during midday when emissions are high, indicating their strong impact on air pollution in the region despite the natural dilution processes expected at this time of day.



There has been no occurrences of ambient SO₂ concentrations exceeding the NAAQS at any of the measurement locations in Kota throughout the period of our survey (Even the instantaneous values have never exceeded the standard)

Figure 6.15: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (8th November to 24th December 2023) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of Kota. Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

Figure 6.15 presents the time series of daily mean ambient air SO₂ concentrations ($\mu\text{g}/\text{m}^3$) from November 8 to December 24, 2023, at three locations in Kota: one upwind (Location-1) and two downwind (Location-2 and Location-3) relative to the Kota Super TPP. The vertical lines on each bar represent the $\pm 1\sigma$ standard deviation around the daily mean values. At Location 1, situated 3 km upwind from the TPP, SO₂ concentrations remain consistently low throughout the measurement period, with values generally below 10 $\mu\text{g}/\text{m}^3$. The low and stable concentrations at this site indicate minimal influence from the TPP emissions due to the upwind positioning. In contrast, Location 2, located 4 km downwind from the TPP, shows higher SO₂ concentrations with significant daily variability. The levels at this site often peak between 10 and 40 $\mu\text{g}/\text{m}^3$, indicating a stronger influence from the TPP emissions and potentially other local sources. The higher variability and elevated concentrations suggest that the emissions from the TPP are more concentrated downwind, particularly impacting this location.

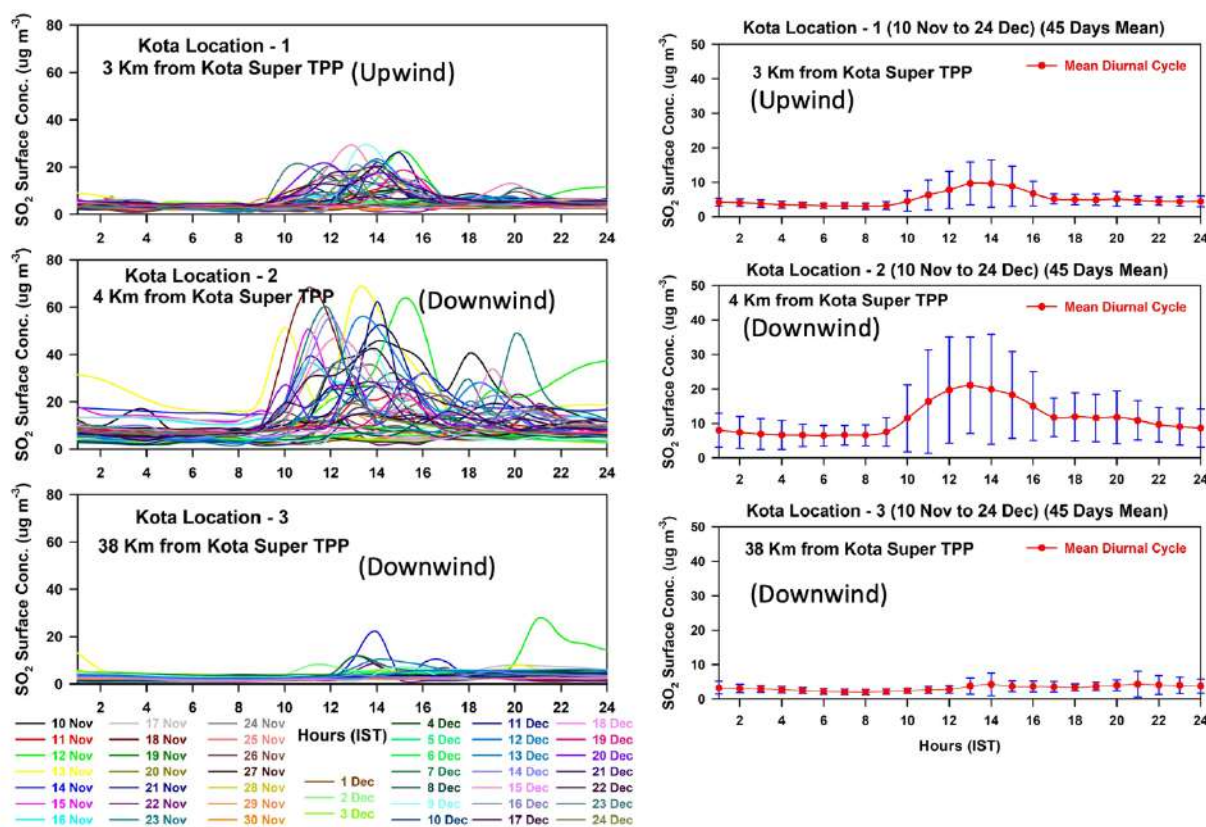


Figure 6.16: Diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (8th November to 24th December 2023) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of Kota. 45-days mean pattern of diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) derived from measurements made at all three sites of Kota are also shown. Vertical lines in all panels on the right represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

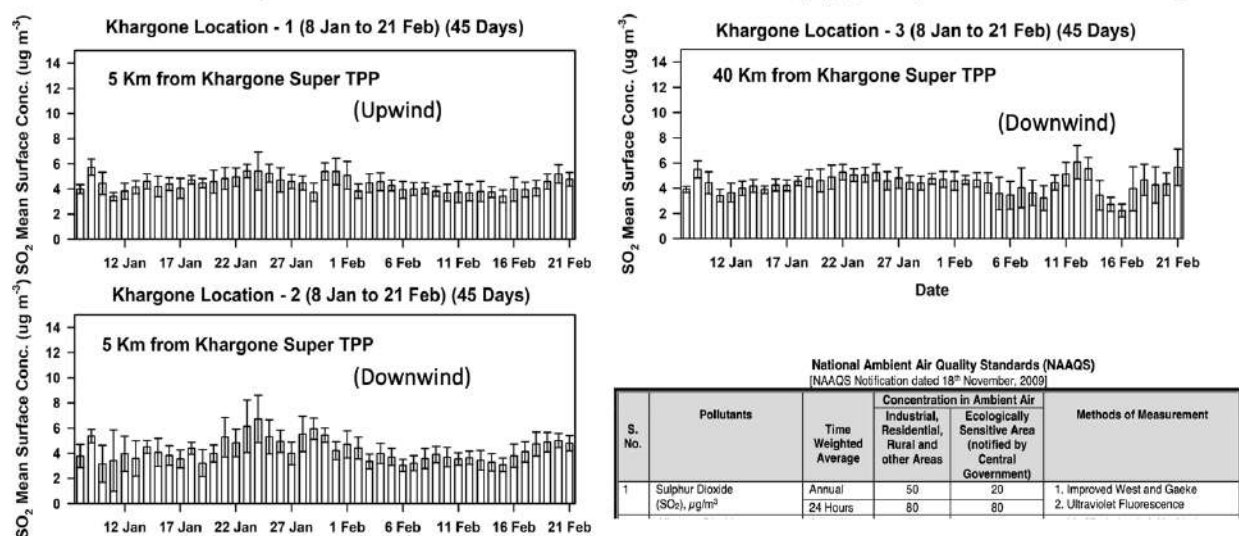
Location 3, situated about 38 km downwind from the TPP, exhibits SO₂ concentrations similar to Location 1, with generally low values and minor fluctuations throughout the period. The SO₂ levels at this site remain well below 10 µg/m³, indicating that the emissions from the TPP are sufficiently dispersed by the time they reach this distance, resulting in lower concentrations. Across all three sites, the measured SO₂ concentrations are significantly below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ for 24-hour average measurements. This compliance with the NAAQS suggests that the ambient air quality in terms of SO₂ remains within permissible levels in Kota during the survey period, despite the proximity to the TPP.

Figure 6.16 displays the diurnal variation of ambient air SO₂ concentrations (µg/m³) from November 8 to December 24, 2023, at one upwind (Location-1) and two downwind (Location-2 and Location-3) sites in Kota measured during Phase III of our survey. At Location-1, situated 3 km upwind from the Kota Super TPP, SO₂ concentrations remain consistently low throughout the day, with minor fluctuations. These levels are influenced by local emissions from residential activities, vehicular traffic, and possibly some industrial contributions including brick kilns. The spikes observed lasting 2-3 hours at different times, mostly during the daytime, could be attributed to bursts of activity from these local sources. In contrast, Location-2, 4 km downwind from the Kota Super TPP, exhibits much higher and more variable SO₂ concentrations. Notable spikes in SO₂ levels are observed, particularly during midday, likely due to a combination of emissions from the TPP, local industries, diesel generators, brick kilns, and the transportation sector. These spikes contribute significantly to the overall midday peak in SO₂ concentrations, underscoring the strong impact of local emissions. The frequent spikes lasting a few hours on individual days indicate episodic activities such as industrial operations or increased traffic, which overwhelm the expected natural dilution during midday due to a deeper atmospheric boundary layer. Location-3, 38 km downwind from the Kota Super TPP, shows lower concentrations similar to Location-1, with a more stable diurnal pattern. The lower and more stable SO₂ levels in Location 3 suggest that the emissions from the TPP are significantly dispersed by the time they reach this distance, and local sources have a lesser impact here as compared to Location-2.

The right three panels in Figure 6.16 illustrate the 45-day mean diurnal variation in SO₂ concentrations at the three locations, with vertical lines representing the $\pm 1\sigma$ standard deviation around the mean values for each hour. Location-1 shows a stable mean diurnal pattern with low SO₂ levels throughout the day. Location-2, however, displays a distinct midday peak, indicating higher emissions during this period, which may be due to increased activity from local industries, residential sector emissions including diesel generators, brick kilns, and transportation activities, along with emissions from the TPP. These midday spikes on individual days contribute significantly to the mean pattern observed, especially in Location 2 and Location 1. Whereas Location-3 shows a relatively flat diurnal cycle with minor variations, indicating effective dispersion and dilution of TPP emissions at this greater distance.

Comparing the three sites in Kota, we find that Location-2 exhibits the highest variability and concentrations, highlighting the significant impact of the TPP and other nearby local emission sources. Locations 1 and 3 have lower and more stable concentrations, with Location-1 being slightly more variable due to closer proximity to local sources as well as the TPP. Despite these variations, all measured SO₂ concentrations across the sites remain well below the NAAQS limit of 80 µg/m³, indicating that the ambient air quality in terms of SO₂ is within permissible levels throughout the survey period.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in Khargone



There has been no occurrences of ambient SO₂ concentrations exceeding the NAAQS at any of the measurement locations in Khargone throughout the period of our survey (Even the instantaneous values have never exceeded the standard)

Figure 6.17: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (8th January to 21st February 2024) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of Khargone. Vertical lines on each bar represents the ±1σ standard deviation variation around the daily mean values for each day.

Figure 6.17 presents the time series of daily mean ambient air SO₂ concentrations (µg/m³) from January 8 to February 21, 2024, at three locations in Khargone, Madhya Pradesh: one upwind (Location-1) and two downwind (Location-2 and Location-3) relative to the Khargone Super TPP. The vertical lines on each bar represent the ±1σ standard deviation around the daily mean values. At Location 1, situated 5 km upwind from the TPP, daily mean SO₂ concentrations remain consistently low, generally ranging between 2 and 6 µg/m³. The stable and low levels indicate steady but minimal influence from the TPP emissions, as this site is upwind. The day to day fluctuations are minor and likely attributable to local sources other than the TPP such as residential activities and vehicular traffic. In contrast, Location 2, located 5 km downwind from the TPP, shows higher daily mean SO₂ concentrations with more noticeable daily variability. The levels often range between 4 and 10 µg/m³, with some days maximum values reaching almost

up to $12 \mu\text{g}/\text{m}^3$. These elevated concentrations are likely due to the combined influence of emissions from the TPP and other local sources, such as other industries, diesel generators, and vehicular traffic. The greater variability in SO_2 levels at this site underscores the impact of emission sources other than the TPP. Location 3, positioned 40 km downwind from the TPP, exhibits daily mean SO_2 concentrations similar to Location 1, with values generally between 2 and $6 \mu\text{g}/\text{m}^3$. The reduced day-to-day variability in SO_2 concentrations at all measurement locations, along with the smaller differences in SO_2 levels among the three sites, suggests that SO_2 pollution in the region is more regional than local in nature. This could imply that emissions from other sources, or the dispersal pattern of emissions from the TPP, compensate for the lower concentrations expected at the upwind Location 1 and the more distant downwind Location 3 compared to the downwind Location 2, which is closer to the TPP. Consequently, we find a more uniform distribution of SO_2 concentrations across the region. Nevertheless, across all three sites, the measured SO_2 concentrations are significantly below the National Ambient Air Quality Standards (NAAQS) limit of $80 \mu\text{g}/\text{m}^3$ for 24-hour average measurements. That means the ambient air quality in terms of SO_2 remains within permissible levels in Khargone during the survey period.

Figure 6.18 shows the diurnal variation of ambient air SO_2 concentrations from January 8 to February 21, 2024, at one upwind (Location-1) and two downwind (Location-2 and Location-3) sites in Khargone. At Location-1, situated 5 km upwind from the Khargone Super TPP, SO_2 concentrations exhibit relatively low variability throughout the day, generally remaining between 4 and $8 \mu\text{g}/\text{m}^3$. These levels highlight the impact of emissions from the TPP as well as local sources such as residential activities and vehicular traffic. At Location-2, 5 km downwind from the TPP, SO_2 concentrations show higher variability and increased levels, often ranging from 5 to $10 \mu\text{g}/\text{m}^3$, with occasional peaks. This increased variability indicates a significant influence from the TPP emissions, combined with local industrial activities, residential activities, diesel generators, and vehicular traffic. Location-3, 40 km downwind from the TPP, presents SO_2 concentrations similar to Location-2, generally ranging from 5 to $7 \mu\text{g}/\text{m}^3$, reflecting a dispersed yet consistent impact of the TPP emissions and suggesting regional pollution influences.

The right three panels in Figure 6.18 illustrate the 45-day mean diurnal variation in SO_2 concentrations at the three locations, with vertical lines representing the $\pm 1\sigma$ standard deviation around the mean values for each hour. Location-1 shows a stable mean diurnal pattern with relatively low SO_2 levels throughout the day, typically between 5 and $6 \mu\text{g}/\text{m}^3$. Location-2 displays a slight dip in SO_2 concentrations in the morning hours after sunrise, likely caused by the dilution of air pollutants due to the increase in boundary layer height during this time. Similarly, Location-3, despite being 40 km from the TPP, shows SO_2 levels comparable to Location-1, suggesting that regional pollution transport mechanisms and boundary layer dynamics contribute to similar concentration levels at this distance.

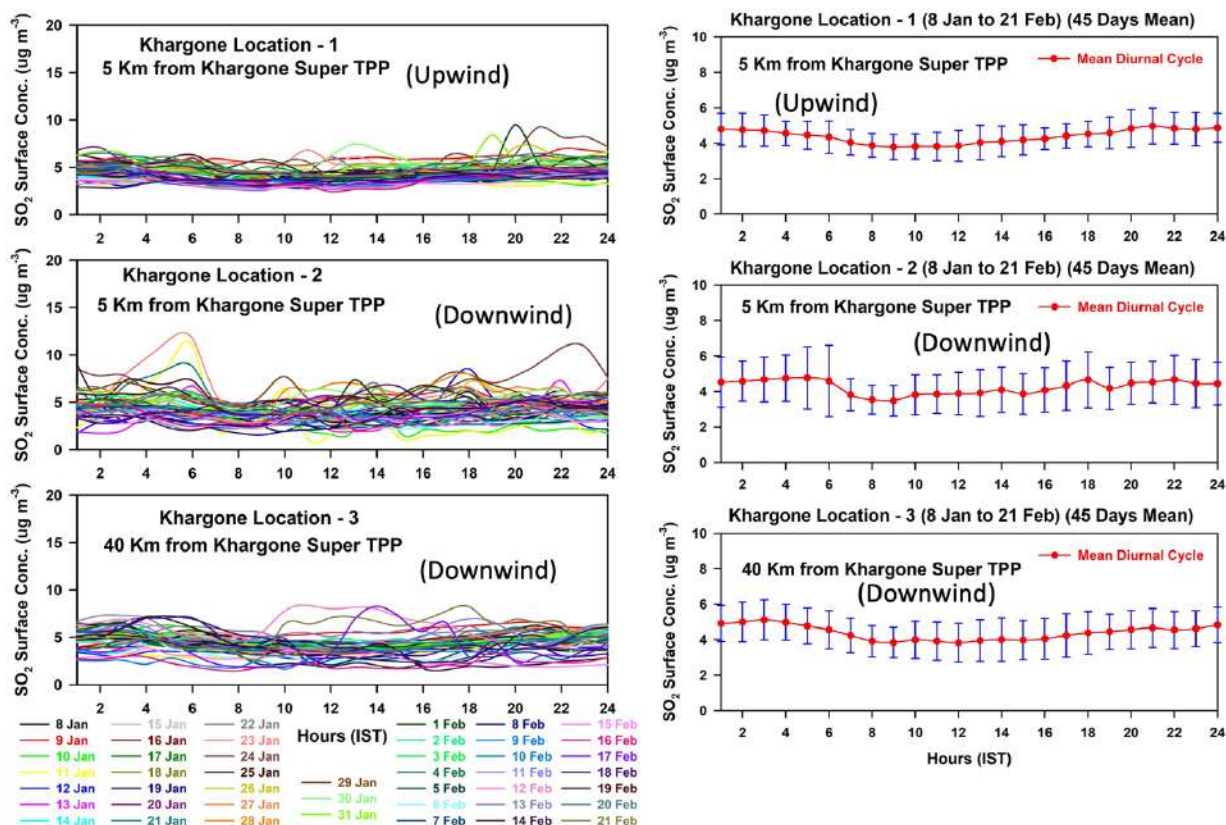


Figure 6.18: Diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) for all days (8th January to 21st February 2024) as measured in Location-1 of Khargone (upper left panel) and Location-2 (upper right panel). 45-days mean pattern of diurnal variation of ambient air SO₂ concentration ($\mu\text{g}/\text{m}^3$) derived from measurements made at all three sites of Khargone are also shown. Vertical lines in all panels on the right represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

The variations in boundary layer height play a crucial role in modulating ambient SO₂ concentrations at all three sites. During the day, a higher boundary layer allows for better dispersion of pollutants, leading to lower concentrations. Conversely, a lower boundary layer at night traps pollutants closer to the ground, resulting in higher concentrations. This pattern is evident in the relatively higher concentrations of ambient SO₂ during nighttime for all three locations. The lack of significant differences in SO₂ concentrations between the upwind and downwind sites suggests that regional sources and the overall dispersion of TPP emissions contribute to a more uniform distribution of SO₂ across the region, rather than localized variations. All measured SO₂ concentrations at the three sites are significantly below the National Ambient Air Quality Standards (NAAQS) limit of 80 $\mu\text{g}/\text{m}^3$ for 24-hour average measurements. This compliance indicates that the ambient air quality in terms of SO₂ is well within permissible levels in Khargone during the survey period.

Time series of daily mean ambient air concentration of SO₂ (µg/m³) measured in Shahdol

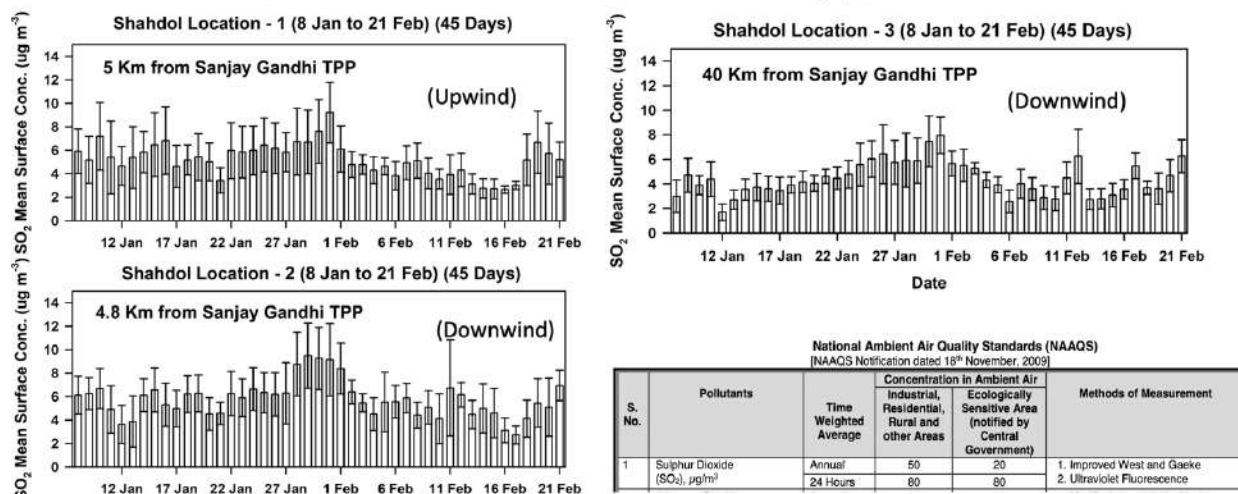


Figure 6.19: Time series of daily mean ambient air SO₂ concentration (µg/m³) for all days (8th January to 21st February 2024) as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of Shahdol. Vertical lines on each bar represents the $\pm 1\sigma$ standard deviation variation around the daily mean values for each day.

Figure 6.19 presents the time series of daily mean ambient air SO₂ concentrations (µg/m³) from January 8 to February 21, 2024, at three locations in Shahdol, Madhya Pradesh: one upwind (Location-1) and two downwind (Location-2 and Location-3) relative to the Sanjay Gandhi TPP. The vertical lines on each bar represent the $\pm 1\sigma$ standard deviation around the daily mean values. At Location-1, situated 5 km upwind from the TPP, daily mean SO₂ concentrations show moderate variability, generally ranging between 2 and 10 µg/m³. Day-to-day variations exhibit some peaks, with higher values around late January and mid-February. These fluctuations likely result from local residential activities, vehicular traffic, and occasional industrial emissions. Location-2, located 4.8 km downwind from the TPP, experiences higher variability and increased daily mean SO₂ levels, often ranging from 4 to 12 µg/m³, with several peaks reaching up to 14 µg/m³. The pronounced day-to-day variations at this site reflect the significant influence of TPP emissions, along with contributions from local industries, diesel generators, and traffic. This location records the highest SO₂ concentrations among the three sites, highlighting the strong impact of the nearby TPP emissions. Location-3, 40 km downwind from the TPP, shows significantly lower SO₂ concentrations compared to Location-2 and Location-1. The daily mean SO₂ levels generally range from 2 to 8 µg/m³, with fewer and smaller peaks. The day-to-day variations at this site are more stable, indicating a drop in SO₂ levels due to the dispersion of pollutants with increasing distance from the major source.

The measured daily mean SO₂ concentrations at all three sites are well below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ for 24-hour average measurements. This compliance with the NAAQS indicates that the ambient air quality in terms of SO₂ remains

within permissible levels in Shahdol during the survey period. Effective emission control at the TPP and relatively low contributions from other local SO₂ sources ensure that, despite some variability, the overall air quality remains safe and well-managed across the region. The lower concentrations at the far downwind Location-3 further demonstrate the dispersal effect, which reduces ambient air SO₂ levels as the distance from the TPP increases.

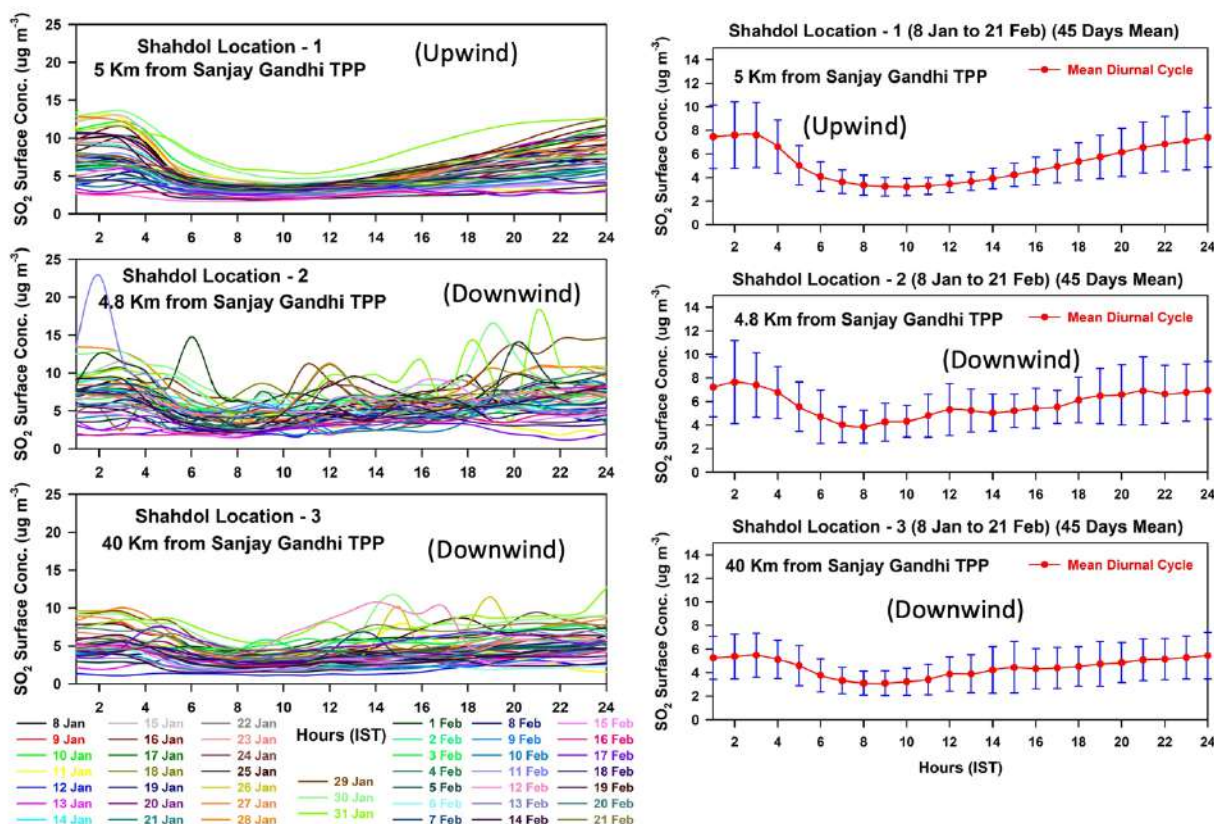


Figure 6.20: Diurnal variation of ambient air SO₂ concentration (µg/m³) for all days (8th January to 21st February 2024) as measured as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of Shahdol. 45-days mean pattern of diurnal variation of ambient air SO₂ concentration (µg/m³) derived from measurements made at all three sites of Shahdol are also shown. Vertical lines in all panels on the right represent the $\pm 1\sigma$ standard deviation variation around the monthly mean values for each hour.

Figure 6.20 displays the diurnal variation of ambient air SO₂ concentrations (µg/m³) from January 8 to February 21, 2024, at three locations in Shahdol: one upwind (Location-1) and two downwind (Location-2 and Location-3) relative to the Sanjay Gandhi TPP. At Location-1, situated 5 km upwind from the TPP, SO₂ concentrations show a notable increase during the late evening and night, peaking around 10-15 µg/m³. Throughout the day, concentrations generally stay between 4 and 10 µg/m³, indicating the influence of local sources such as residential activities and vehicular traffic. The day-to-day variations and minor fluctuations reflect routine activities and

changes in meteorological conditions, such as wind speed and direction, which can affect pollutant dispersion. Location-2, located 4.8 km downwind from the TPP, exhibits higher variability and increased SO₂ levels, with frequent peaks reaching up to 20 µg/m³. Significant diurnal fluctuations occur, particularly during the late evening and night. Random spikes in SO₂ concentrations lasting 2-3 hours on different days and at different times suggest episodic emissions. These spikes are likely caused by short-term increases in emissions from sources other than the TPP such as local industries, diesel generators, and vehicular traffic, exacerbated by meteorological conditions that trap pollutants near the ground. The vertical movement of the atmospheric boundary layer also plays a crucial role, as a lower boundary layer at night traps pollutants including SO₂ closer to the surface, resulting in higher concentrations. Location-3, 40 km downwind from the TPP, shows lower concentrations compared to Location-2, generally ranging from 2 to 15 µg/m³. Day-to-day variations at this site are more stable and exhibit lower overall concentrations, indicating the dispersal effect of pollutants with increasing distance from the major source. SO₂ levels generally peak during the late evening and night, similar to the other locations, but with lower intensity due to the distance from the TPP. The influence of the atmospheric boundary layer is also evident here, as nighttime trapping of pollutants leads to higher concentrations of SO₂.

The right three panels of Figure 6.20 illustrate the 45-day mean diurnal variation in SO₂ concentrations at the three locations, with vertical lines representing the $\pm 1\sigma$ standard deviation around the mean values for each hour. Location-1 shows a stable mean diurnal pattern, with SO₂ levels typically decreasing after sunrise and gradually increasing in the evening, ranging from 4 to 8 µg/m³. Location-2 exhibits a similar pattern but with higher concentrations, ranging from 5 to 12 µg/m³. A slight dip in the morning hours is likely due to the increased boundary layer height, which dilutes pollutants. At night, the boundary layer height decreases, trapping air pollutants and leading to higher concentrations of SO₂. Location-3, despite being 40 km from the TPP, presents a similar diurnal pattern to Location-1 but with even lower concentrations, typically ranging from 3 to 7 µg/m³. This demonstrates the dispersal of pollutants over distance and a decrease in SO₂ levels far from the TPP. All measured SO₂ concentrations at the three sites are significantly below the National Ambient Air Quality Standards (NAAQS) limit of 80 µg/m³ for 24-hour average measurements. This compliance with NAAQS indicates that ambient air quality in terms of SO₂ remains well within permissible levels in Shahdol during the survey period. The effective emission control at the TPP and relatively low contributions from other local SO₂ sources ensure that, despite some variability, overall air quality remains safe and well-managed across the region. The impact of meteorological variations and the vertical movement of the atmospheric boundary layer further emphasizes the role of pollutant dispersion in maintaining air quality standards.

Impact of FGD operation on daily mean ambient air concentration of SO₂ in category-3 cities during Phase-III of the Survey

During Phase III of the survey, we conducted measurements in two Category-3 cities, Gautam Buddha Nagar and Khargone. During this period, the flue gas desulfurization (FGD) units in some of the stacks of the TPPs in these cities were operational.

Daily mean ambient air concentration of SO₂ (µg/m³) during FGD operation in TPPs

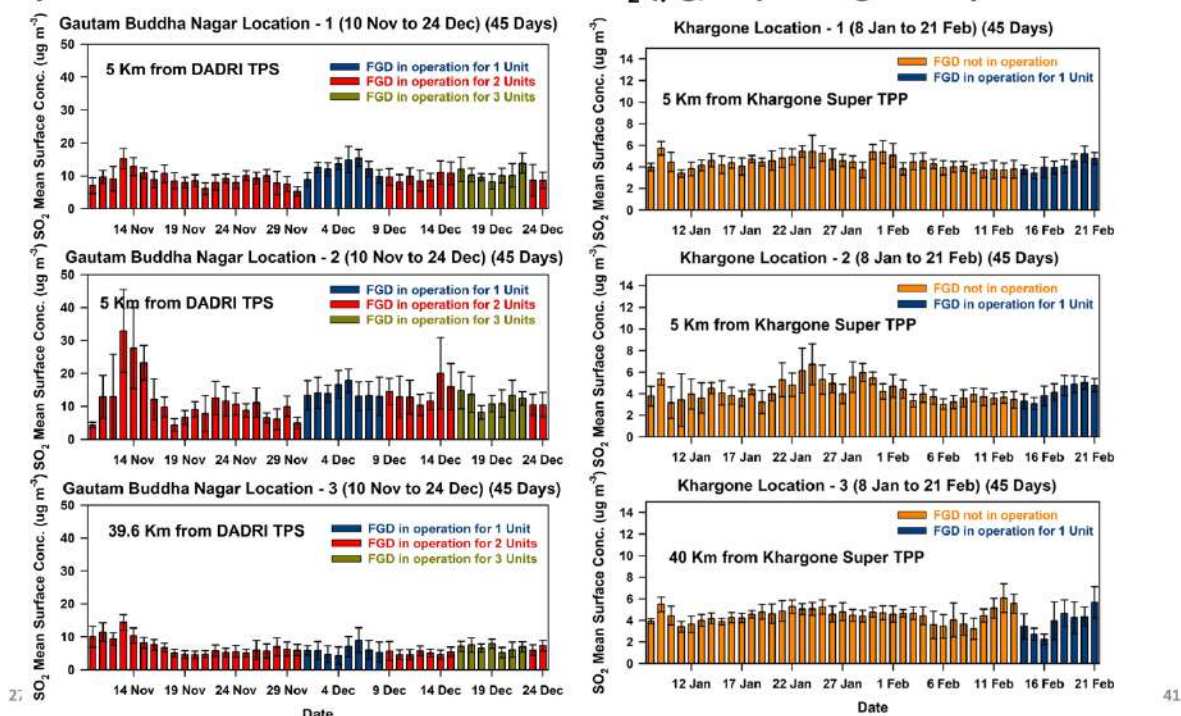


Figure 6.21: Left three panels show the time series of daily mean ambient air SO₂ concentration (µg/m³) during 8th November to 24th December 2023 as measured in one upwind (Location-1) and two downwind (Location-2 and Location-3) sites of GBN. Right three panels show the time series of daily mean ambient air SO₂ concentration measured at three sites in Khargone during 8th January to 21st February 2024.

The left three panels of Figure 6.21 show the time series of daily mean ambient air SO₂ concentrations (µg/m³) from November 8 to December 24, 2023, measured at one upwind (Location-1) and two downwind (Location-2 and Location-3) sites in Gautam Buddha Nagar (GBN). The right three panels display the time series of daily mean ambient air SO₂ concentrations at three sites in Khargone from January 8 to February 21, 2024. In GBN, the FGD was operational in at least one unit of the TPP for the entire 45 days of our survey, whereas in Khargone, the FGD was operational for only eight out of the 45 days.

As evident from the data in Figure 6.21, no notable systematic differences in ambient air SO₂ concentrations were observed with the operation of FGD units during the survey period at any of the measurement locations in both GBN and Khargone. Although there was large day-to-day variability in ambient air SO₂ concentrations at all measurement sites in both cities, this variability did not correlate with the operation of FGD units or the number of FGD units in operation at either of these TPPs, raising doubts about the effectiveness of the installed FGD systems in lowering SO₂ concentrations in the ambient air around these two TPPs.

CHAPTER-7: CONTRIBUTION OF SO₂ EMISSIONS FROM COAL-BASED TPPS TOWARDS AMBIENT ATMOSPHERIC SO₂, SULFATE AEROSOLS, PM_{2.5}, AND PM₁₀ MASS CONCENTRATIONS IN DIFFERENT CATEGORY CITIES DURING PHASE III OF SURVEY

In order to understand the contribution of SO₂ emissions from the power sector, specifically coal-based thermal power plants (TPPs), on ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in various cities selected for Phase III of the survey, we conducted a series of meticulously planned simulations using the WRF-Chem chemical transport model. These simulations aimed to delineate the contributions of various sources, particularly TPP emissions, to ambient air SO₂ and sulfate aerosols as components of PM_{2.5} and PM₁₀ mass concentrations across the surveyed cities. Additionally, we aimed to determine the contributions of major aerosol types, including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust, to the ambient air concentrations of PM_{2.5} and PM₁₀ in these cities through a comprehensive modeling approach. Specifically, we sought to quantify the impact of SO₂ emissions from TPPs on the ambient air concentrations of sulfate aerosols, PM_{2.5} and PM₁₀ mass concentrations in the cities included in the Phase III of this survey. The insights gained from this study also contribute to a better understanding of the regional and local impacts of SO₂ emissions from TPPs on air quality. This understanding can further help us assess the expected benefits of stringent emission regulations, specifically advanced SO₂ control technologies like Flue-gas desulfurization (FGD), on ambient air SO₂ and sulfate aerosols as components of PM_{2.5} and PM₁₀ mass concentrations across the surveyed cities.

Model setup and Simulation Details

The Weather Research and Forecasting model coupled with a chemistry module (WRF-Chem) is a regional system designed for both operational weather forecasting and atmospheric chemistry research (Skamarock, 2008; Powers et al., 2017). In this study, WRF-Chem version 4.2.2 was used to conduct nine sets of atmospheric chemistry simulations for each city of interest: Kota and Gautam Buddha Nagar, covering the period from November 8th to December 24th, 2023, and Shahdol and Khargone, covering the period from January 8th to February 21st, 2024. For the first set of simulations, model domains were centered at Gautam Buddha Nagar (77.61° E and 28.34° N), each covering approximately 2,250,000 square kilometres at a horizontal resolution of 10 km, with 150x150 grid cells in the outer domain and a horizontal resolution of 3 km, with 136x136 grid cells in the inner domain, following a nested WRF-Chem modeling setup. The model included 44 vertical levels on a hybrid-sigma coordinate system, extending from the surface to about 10 hPa as the model top pressure. The NCEP GDAS Final Analysis data, available at 6-hour intervals and with a resolution of 0.25°x0.25°, provided the meteorological initial and lateral boundary conditions for the model simulations covering two periods from November 8th to December

24th, 2023, and from January 8th to February 21st, 2024. Anthropogenic emissions were based on the EDGAR-v6.1 (2023) dataset. ERA5 Temperature, Water Vapor, and Wind data were used for both the WRF-Chem simulations and the Four-Dimensional Data Assimilation (FDDA) approach. Initial and lateral chemical boundary conditions for the WRF-Chem model simulations were obtained from previously available results from the Community Atmospheric Model With Chemistry (CAM-Chem) simulations.

To evaluate the sectoral contributions to ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in the selected cities of Kota, Gautam Buddha Nagar, Shahdol and Khargone during Phase II of the survey, we utilized an emission suppression method. This approach involved conducting a series of systematically designed simulations using the WRF-Chem model, where emissions from specific sectors were disabled in each simulation. We modified the emissions assuming that FGD was operational in two units of the NTPC Dadri TPP during Phase III of our survey. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

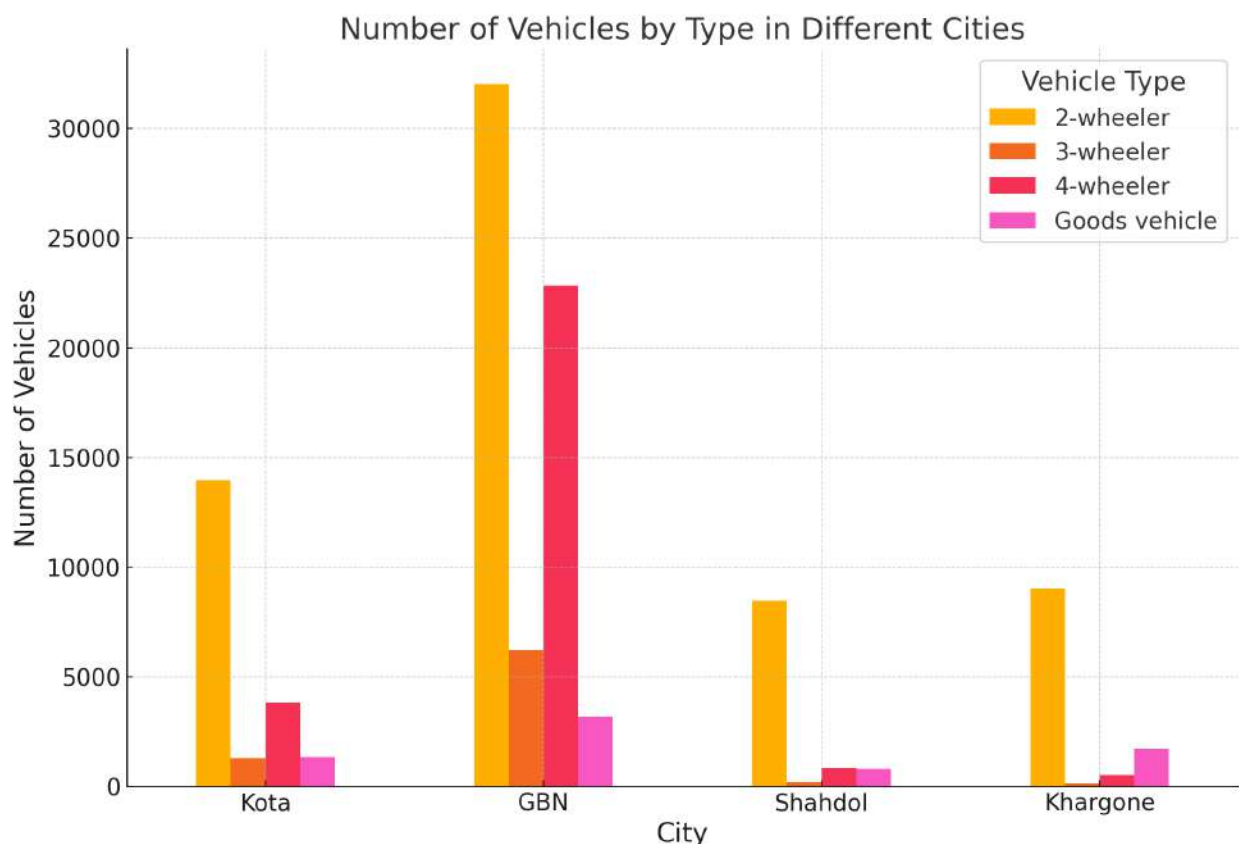


Figure 7.1: Total number of registered vehicles of different categories in the four cities selected during Phase-III of our survey as per the Road Transport Year Book 2019-20.

Figure 7.1 illustrates the number of different types of vehicles across four cities selected for Phase III of the survey: Kota, GBN (Gautam Buddha Nagar), Shahdol, and Khargone, as per the Road Transport Year Book 2019-20 (<https://morth.nic.in/road-transport-year-books>). Among these cities, GBN shows the highest numbers in all vehicle categories, with 32,034 two-wheelers, 6,212 three-wheelers, 22,826 four-wheelers, and 3,162 goods vehicles. Kota follows with significant numbers, particularly in two-wheelers (13,950) and four-wheelers (3,823). Shahdol and Khargone have considerably lower vehicle counts, with Shahdol having 8,460 two-wheelers and Khargone having 9,027 two-wheelers. Goods vehicles are relatively fewer across all cities, with GBN having the highest at 3,162. The data highlights the varying distribution and density of vehicle types in these cities, with GBN having the highest vehicle presence overall. This data has been used in preparing the emission inventory for transportation sector, which has been further utilized in this study to understand the sectoral contributions to ambient atmospheric concentrations of SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ in the selected cities.

Chemical Transport Modeling using WRF-Chem model

A series of Separate Model simulations have been performed in a systematic way to conduct source apportionment studies for each city

**Category-3 city: GBN,
Uttar Pradesh**

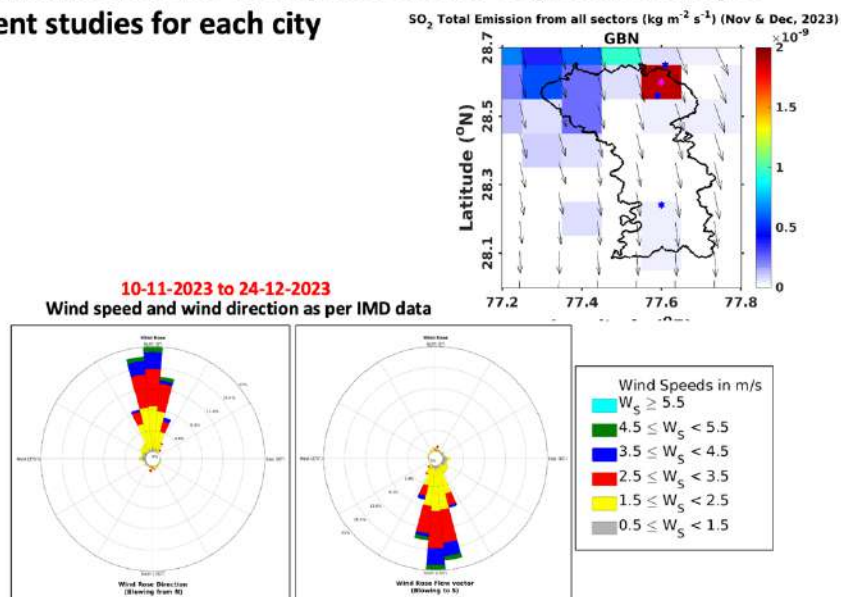
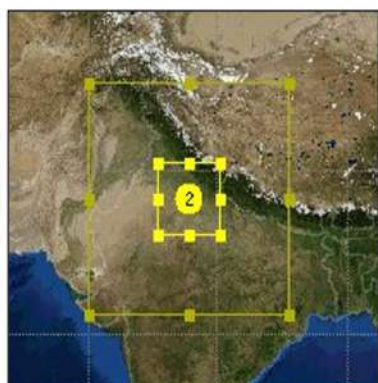


Figure 7.2: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over GBN during the simulation period from 8th November to 24th December 2023.

First, we present the results of our simulations, detailing the contributions of major emission sectors to ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ mass concentrations in the city of Gautam Buddha Nagar during Phase III of our survey.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-3
Gautam Buddha Nagar,
Uttar Pradesh

Phase III
Winter Season

GBN SO₂ ($26.08 \pm 10.38 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

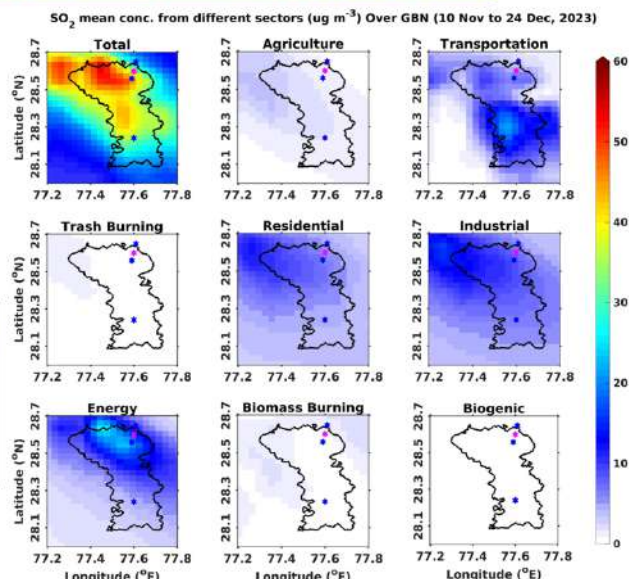
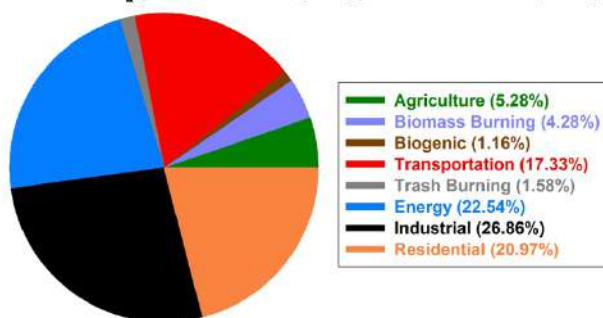


Figure 7.3: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-3
Gautam Buddha Nagar,
Uttar Pradesh

Phase III
Winter Season

GBN SO₄ ($20.37 \pm 6.35 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

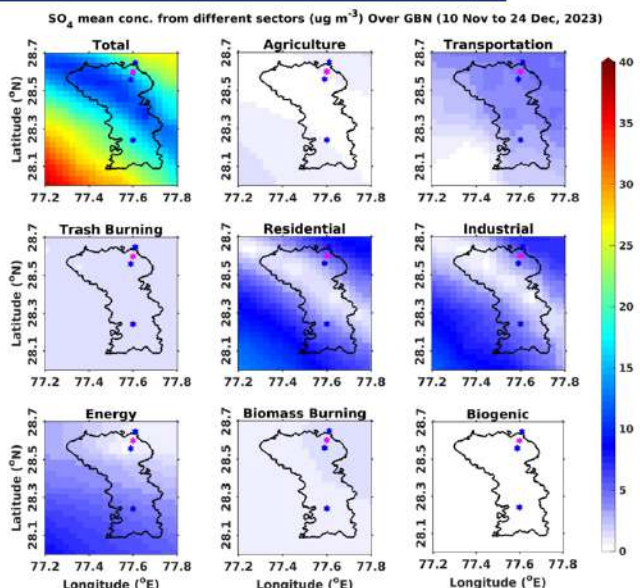
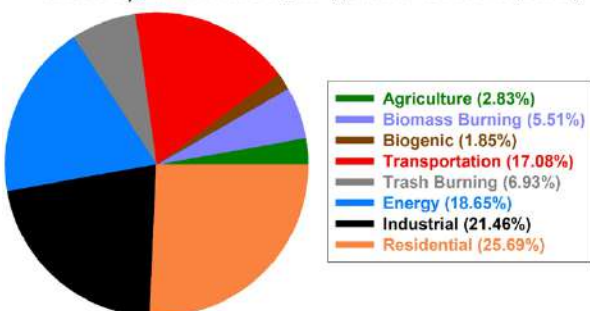


Figure 7.4: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

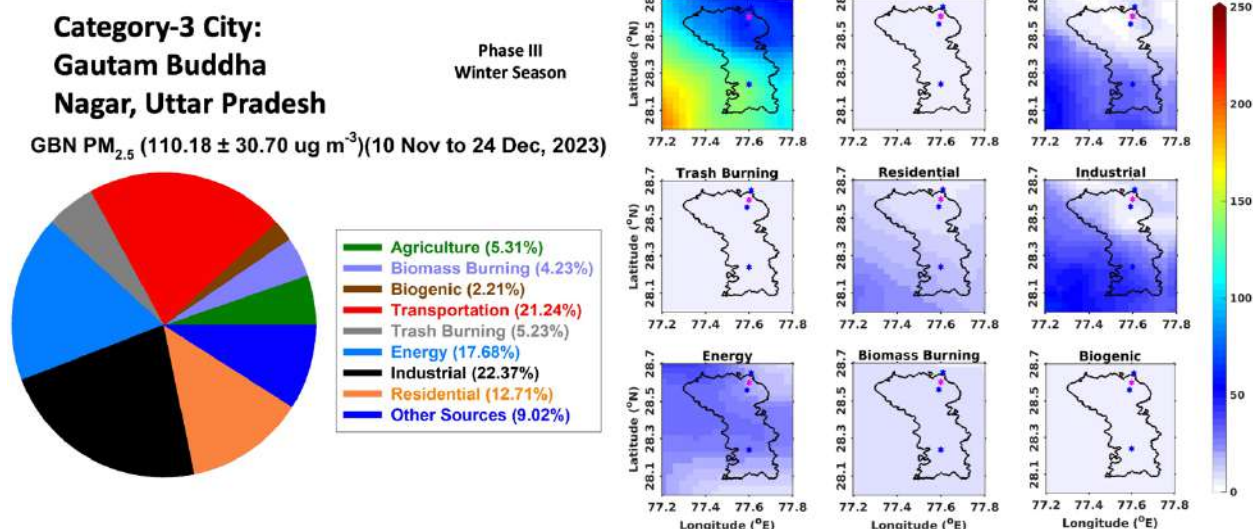


Figure 7.5: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

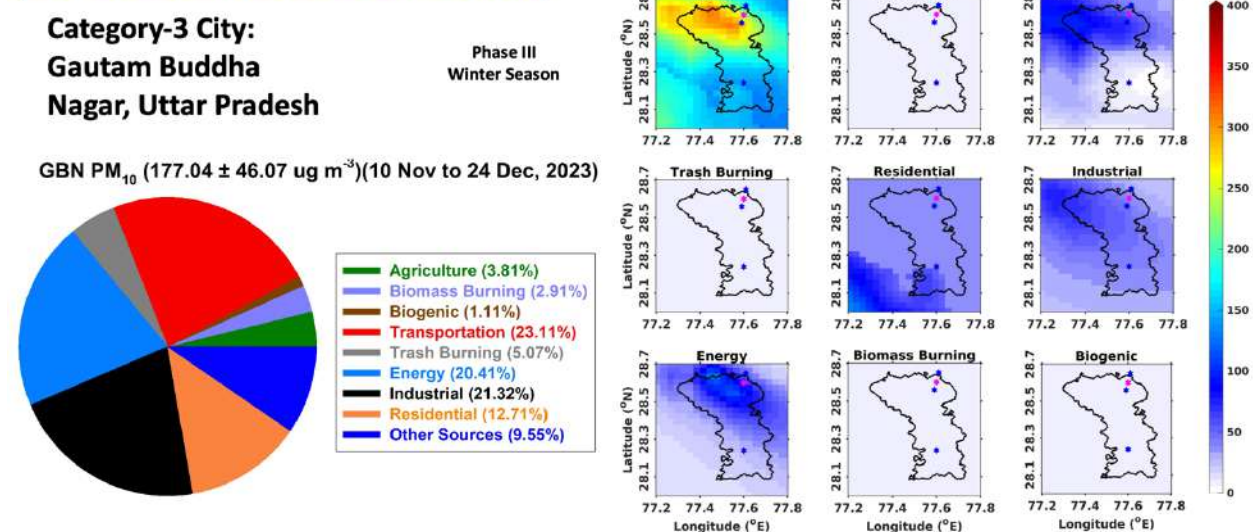


Figure 7.6: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Gautam Buddha Nagar during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-3 City:

Gautam Buddha

Nagar, Uttar Pradesh

Phase III
Winter Season

GBN PM_{2.5} ($110.18 \pm 30.70 \text{ ug m}^{-3}$) (10 Nov to 24 Dec, 2023)

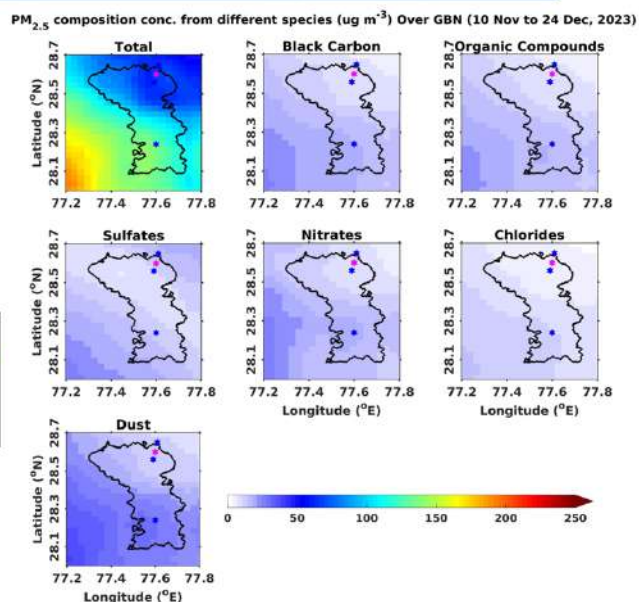
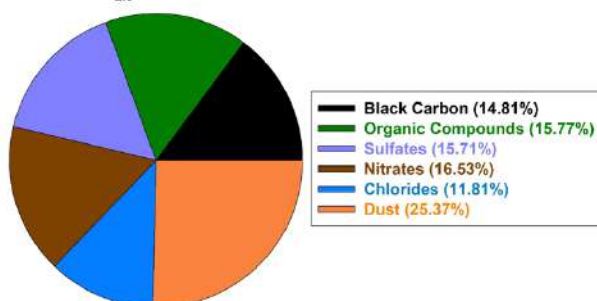


Figure 7.7: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-3 City:

Gautam Buddha

Nagar, Uttar Pradesh

Phase III
Winter Season

GBN PM₁₀ ($177.04 \pm 46.07 \text{ ug m}^{-3}$) (10 Nov to 24 Dec, 2023)

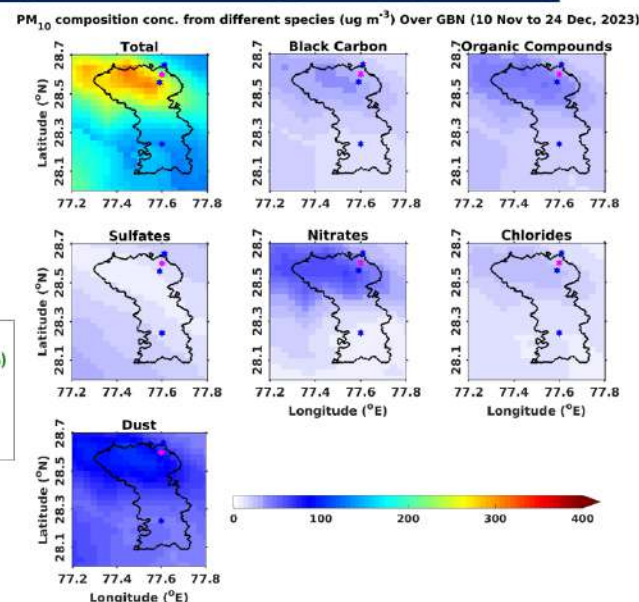
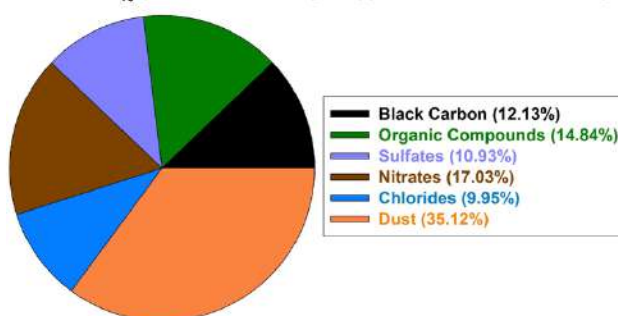


Figure 7.8: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 8th November to 24th December 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM_{2.5} and PM₁₀

**Category-3 City:
Gautam Buddha
Nagar, Uttar Pradesh**

10th Nov to 24th Dec 2023

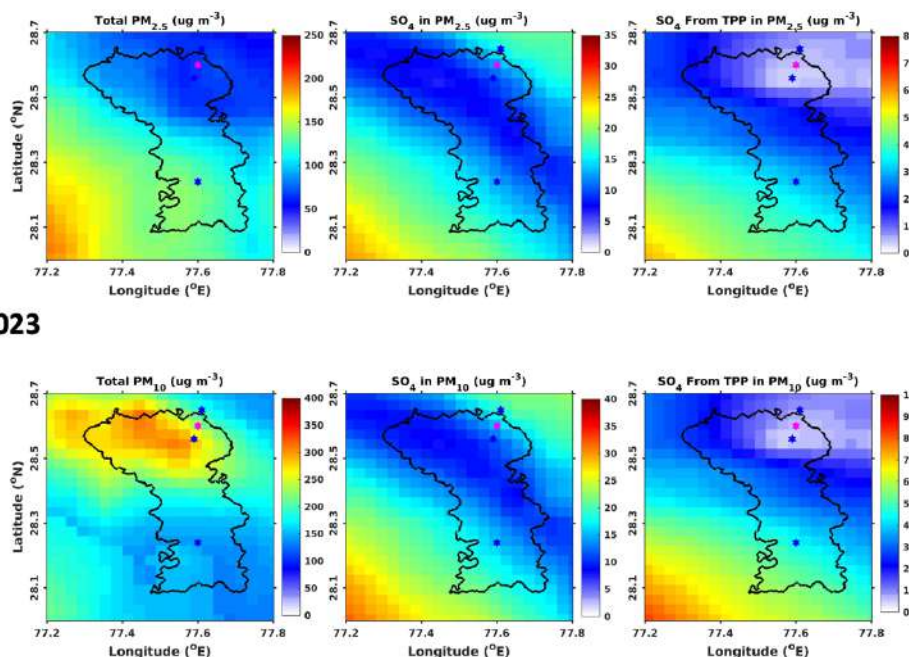


Figure 7.9: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Next we performed another series of systematically designed WRF-Chem model simulations to know the contribution different sources towards SO₂ and sulfate aerosols in Kota, which is a Category-2 city considered during the Phase-III of our survey. We also wanted to understand the contribution of Power sector towards the ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in the city of Kota during our survey. WRF-Chem version 4.2.2 has been used to perform a set of nine atmospheric chemistry simulations over Kota for November 8th to December 24th, 2023. For this study, the model domains are centered at Kota (75.84° E and 25.18° N). Each of the simulation domain covers approximately 2250000 square Km area at a horizontal resolution of 10x10 Km², with 150x150 grid cells in the outer domain and horizontal resolution of 3x3 Km², with 136x136 grid cells in the inner domain following nested WRF-Chem modeling setup and 44 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis (available at 6 hourly intervals) with a resolution of 0.25°x0.25° have been used to provide meteorological initial and lateral boundary conditions to the model simulation of November 8th to December 24th, 2023. To estimate the sectoral emission contribution towards the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Kota, we followed an emission suppression method. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

Chemical Transport Modeling for Kota, Rajasthan

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO_2 sulfate aerosols in the city and the contribution of TPPs towards $\text{PM}_{2.5}$ and PM_{10}

Category-2 city: Kota, Rajasthan

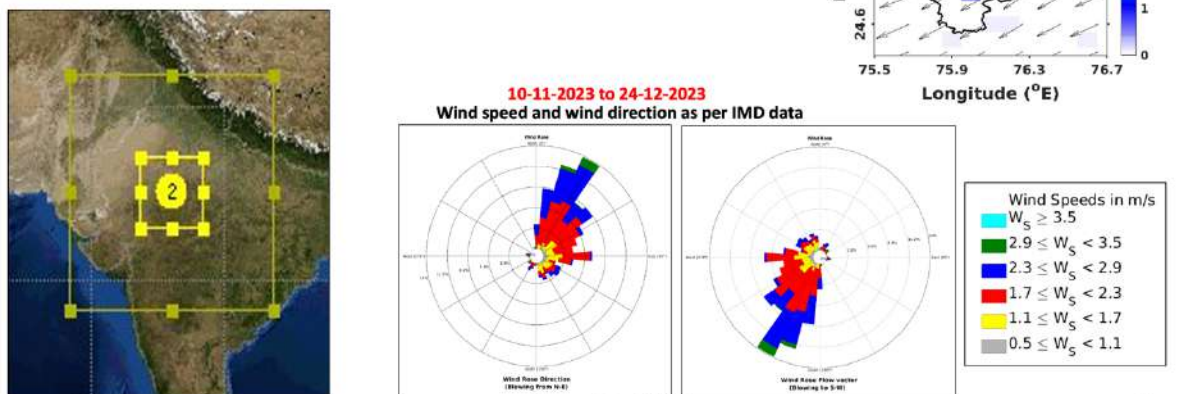


Figure 7.10: Simulation domain, gridded SO_2 emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Kota during the simulation period from 8th November to 24th December 2023.

First, we present the results of our simulations, detailing the contributions of major emission sectors to ambient atmospheric SO_2 , sulfate aerosols, $\text{PM}_{2.5}$, and PM_{10} mass concentrations in the city of Kota during Phase II of our survey.

Normalized Contribution of different emission sectors towards ambient air SO_2

Category-2 city: Kota, Rajasthan

Kota SO_2 ($13.78 \pm 10.65 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

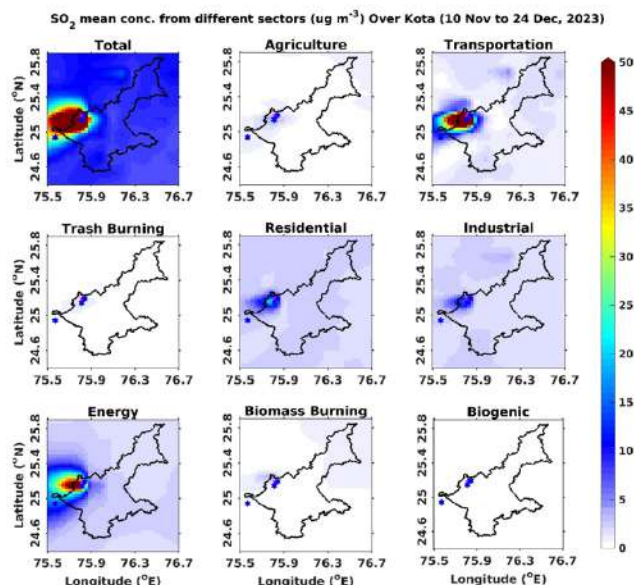
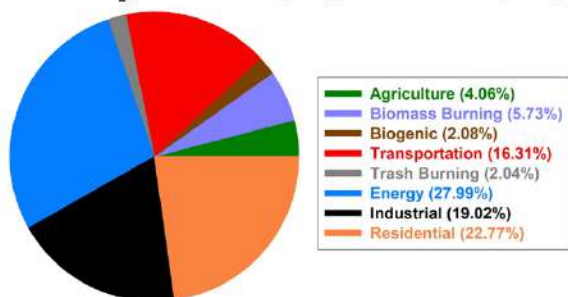


Figure 7.11: Contribution of different emission sectors towards ambient atmospheric SO_2 concentrations in Kota during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-2 city: Kota,
Rajasthan

Kota SO₄ ($10.76 \pm 2.14 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

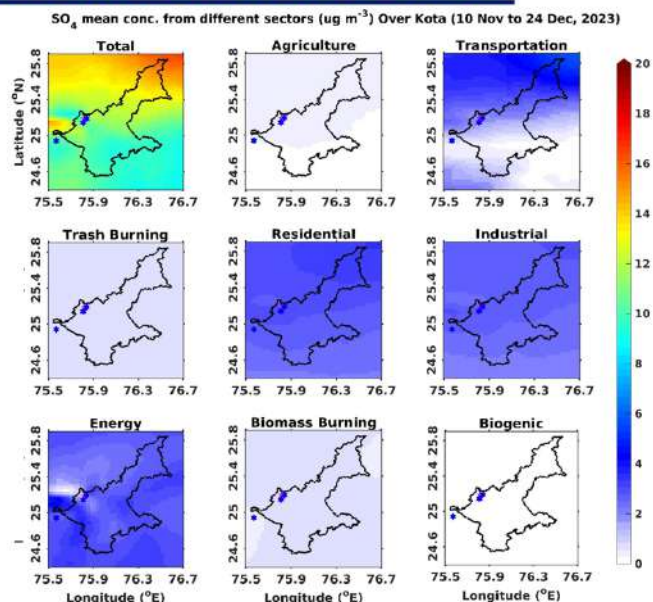
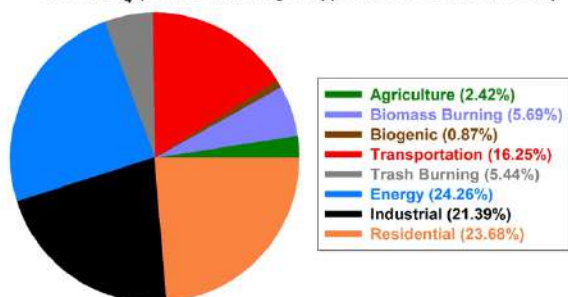


Figure 7.12: Contribution of different emission sectors towards ambient atmospheric sulfate aerosols concentrations in Kota during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

Category-2 city: Kota,
Rajasthan

Kota PM_{2.5} ($72.69 \pm 14.75 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

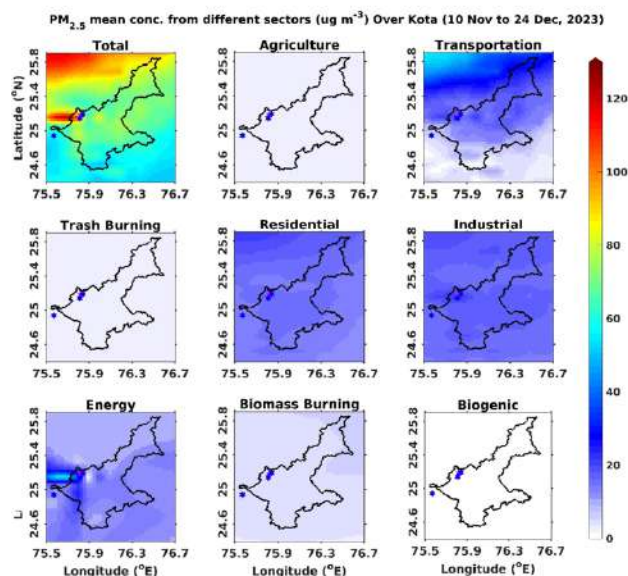
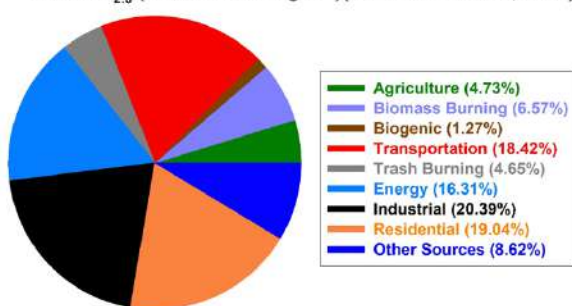


Figure 7.13: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} aerosols concentrations in Kota during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

Category-2 city: Kota,
Rajasthan

Kota PM₁₀ ($114.71 \pm 9.74 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

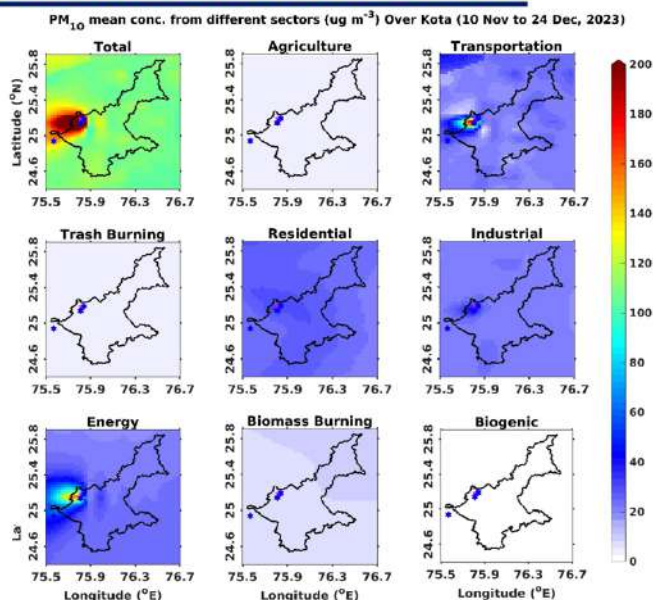
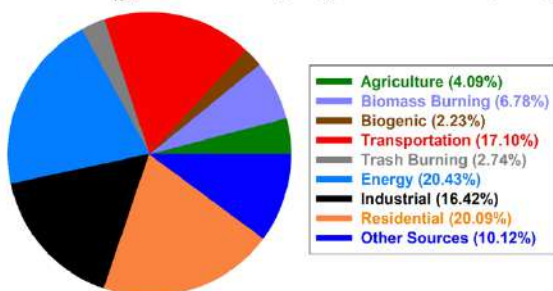


Figure 7.14: Contribution of different emission sectors towards ambient atmospheric PM₁₀ aerosols concentrations in Kota during the simulation period from 8th November to 24th December 2023.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Kota during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-2 city: Kota,
Rajasthan

Phase III
Winter Season

Kota PM_{2.5} ($72.69 \pm 14.75 \text{ ug m}^{-3}$)(10 Nov to 24 Dec, 2023)

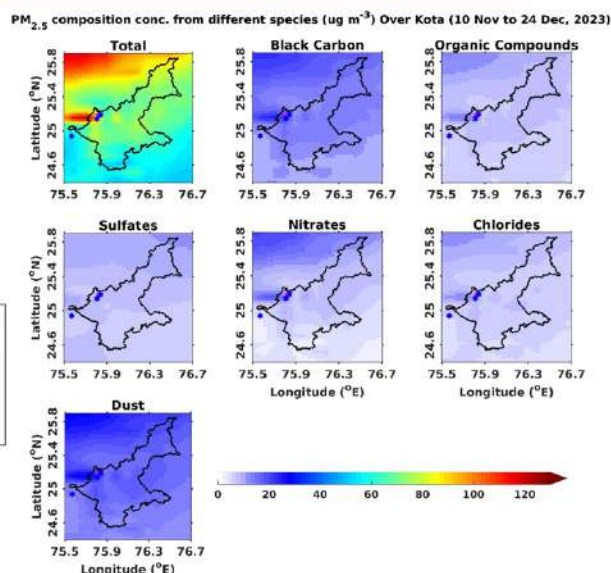
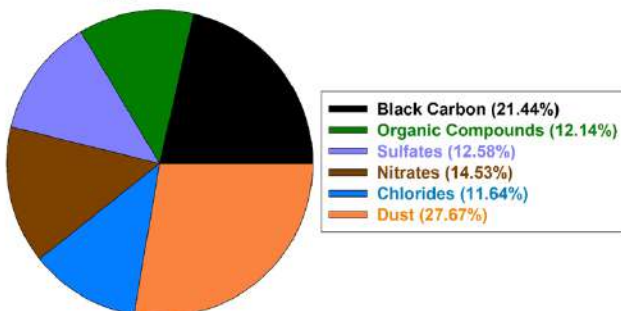


Figure 7.15: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Kota during the simulation period from 8th November to 24th December 2023.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-2 city: Kota,
Rajasthan

Phase III
Winter Season

Kota PM₁₀ ($114.71 \pm 9.74 \text{ ug m}^{-3}$) (10 Nov to 24 Dec, 2023)

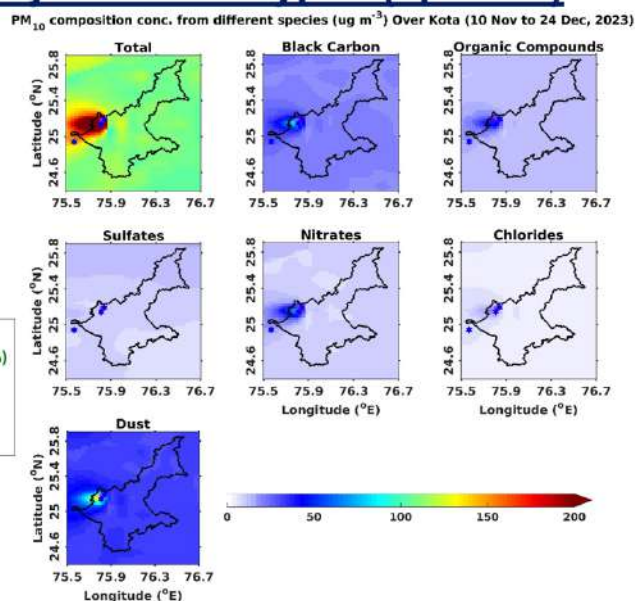
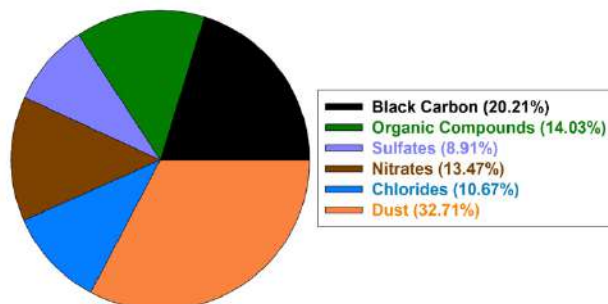


Figure 7.16: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in GBN during the simulation period from 8th November to 24th December 2023.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-2 city: Kota,
Rajasthan

10th Nov to 24th Dec 2023

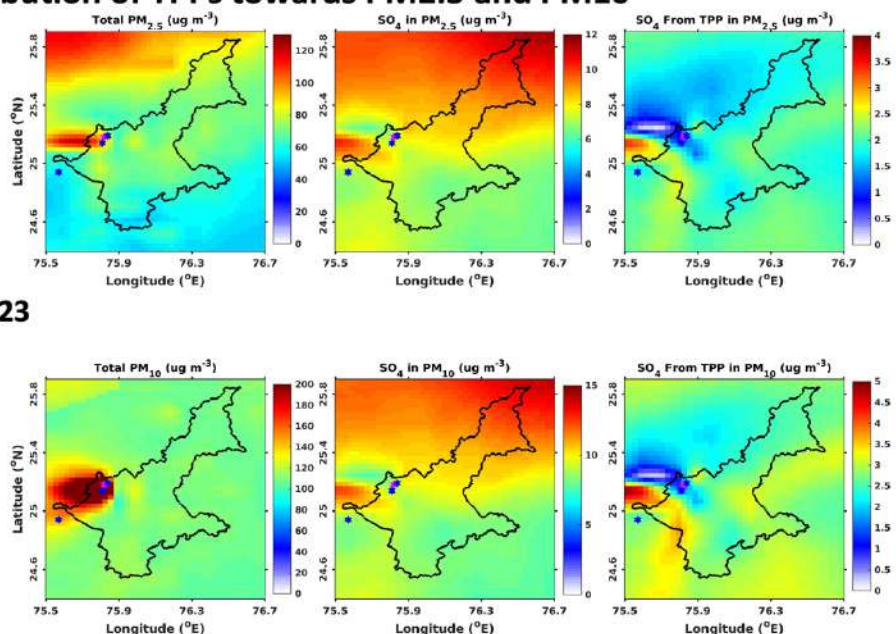


Figure 7.17: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Kota during the simulation period from 8th November to 24th December 2023.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Next we performed another series of systematically designed WRF-Chem model simulations to know the contribution different sources towards SO₂ and sulfate aerosols in Shahdol, which is a Category-2 city considered during the Phase-III of our survey. We also wanted to understand the contribution of Power sector towards the ambient atmospheric SO₂, PM_{2.5}, and PM₁₀ concentrations in the city of Shahdol during our survey. WRF-Chem version 4.2.2 has been used to perform a set of nine atmospheric chemistry simulations over Shahdol for January 8th to February 21st, 2024. For this study, the model domains have centre at Shahdol (81.07° E and 23.31° N).

Chemical Transport Modeling for Shahdol, Madhya Pradesh

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

Category-2 City: Shahdol, Madhya Pradesh

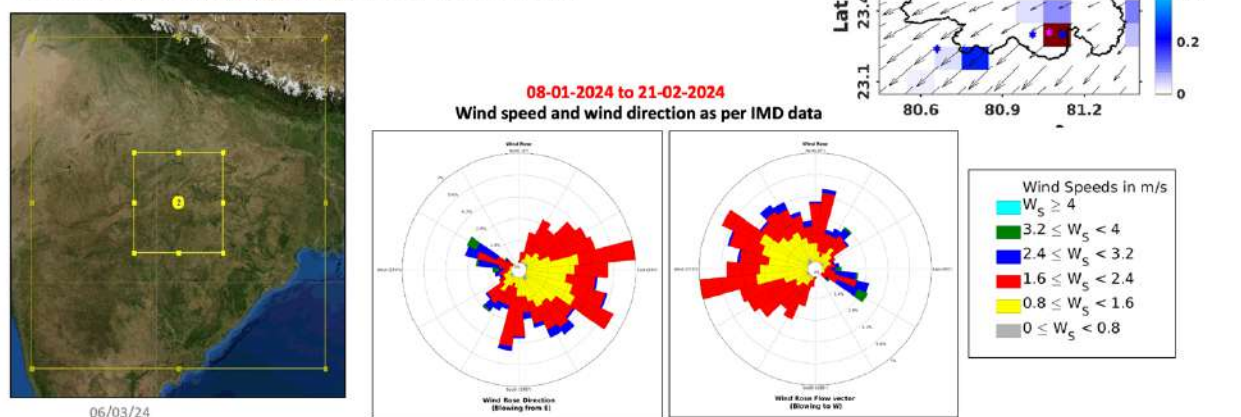


Figure 7.18: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Shahdol during the simulation period from 8th January to 21st February 2024.

Each of the simulation domain covers approximately 2250000 square Km area at a horizontal resolution of 10x10 Km², with 150x150 grid cells in the outer domain and horizontal resolution of 3x3 Km², with 136x136 grid cells in the inner domain following nested WRF-Chem modeling setup and 44 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis (available at 6 hourly intervals) with a resolution of 0.25°x0.25° have been used to provide meteorological initial and lateral

boundary conditions to the model simulation of January 8th to February 21st, 2024. To estimate the sectoral emission contribution towards the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Shahdol, we followed an emission suppression method. The details of the model configuration, the various anthropogenic, biomass burning, and biogenic emissions considered, as well as the numerical experiment design, are provided in Chapter 3 and are therefore not repeated here.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-2 City: Shahdol,
Madhya Pradesh

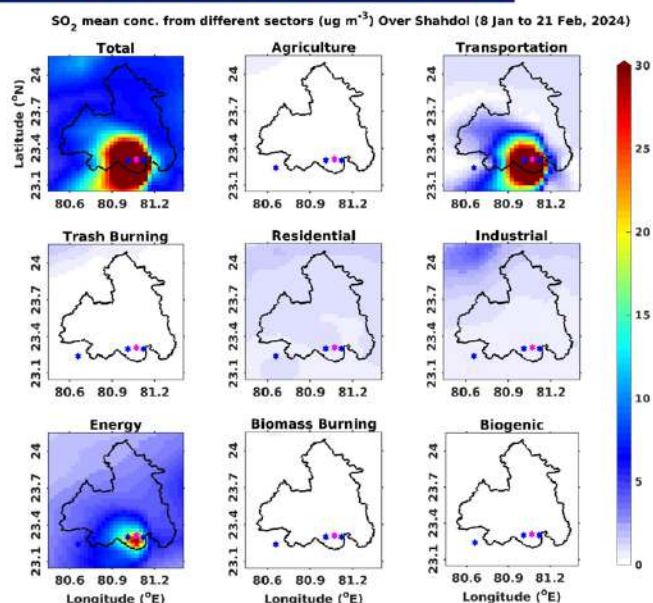
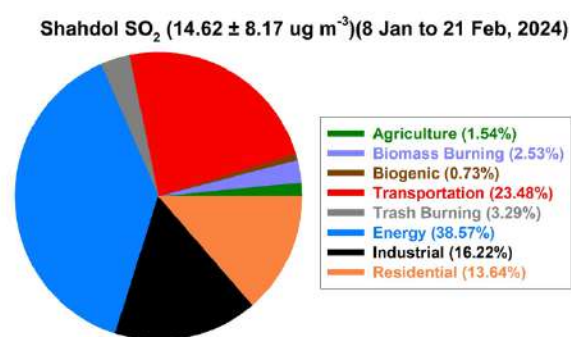


Figure 7.19: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air SO₄

Category-2 City: Shahdol,
Madhya Pradesh

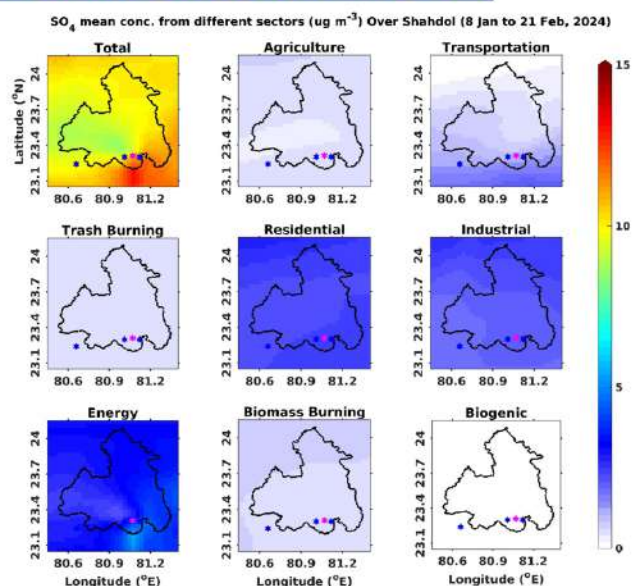
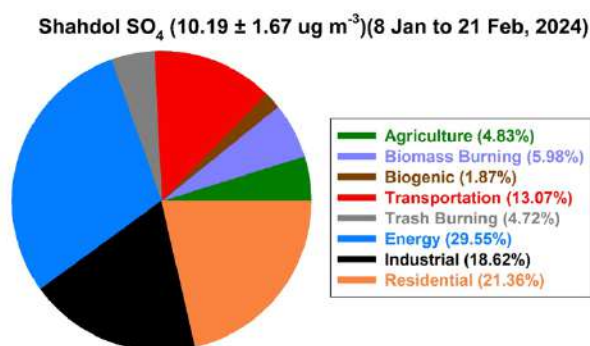


Figure 7.20: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air PM2.5

Category-2 City: Shahdol,
Madhya Pradesh

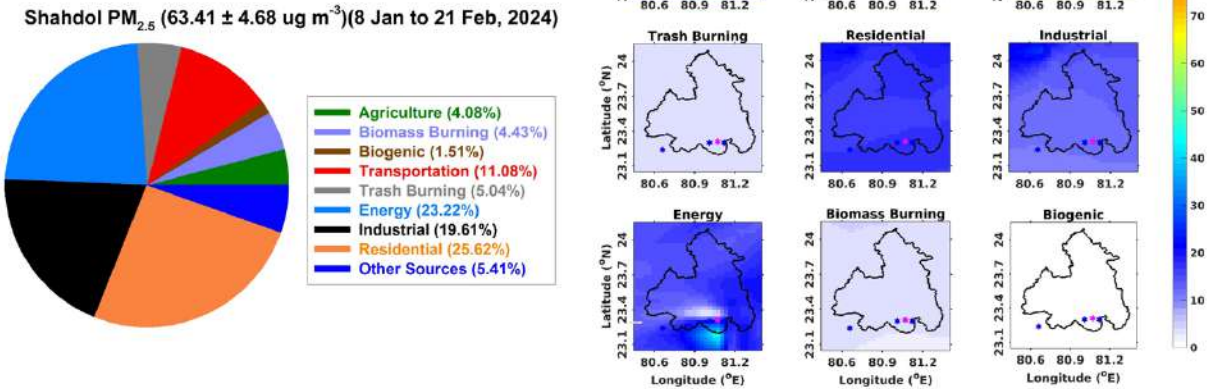


Figure 7.21: Contribution of different emission sectors towards ambient atmospheric PM2.5 concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air PM10

Category-2 City: Shahdol,
Madhya Pradesh

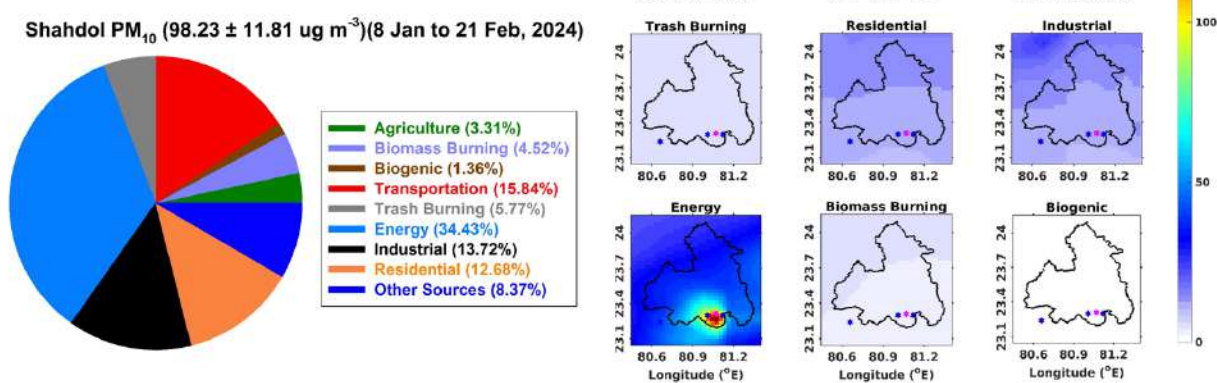


Figure 7.22: Contribution of different emission sectors towards ambient atmospheric PM10 concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Shahdol during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

Category-2 City: Shahdol,
Madhya Pradesh

Phase III
Winter Season

Shahdol PM_{2.5} ($63.41 \pm 4.68 \text{ ug m}^{-3}$) (8 Jan to 21 Feb, 2024)

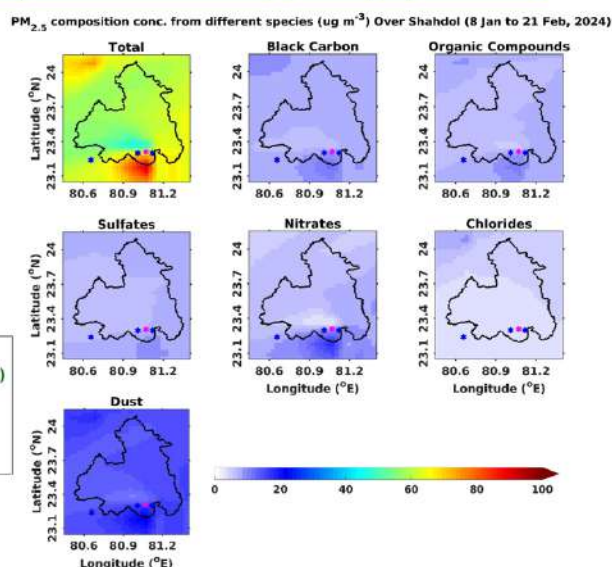
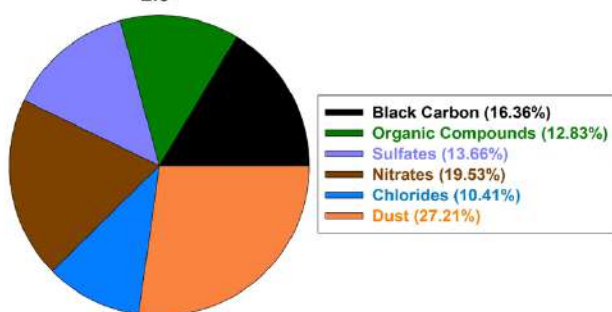


Figure 7.23: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-2 City: Shahdol,
Madhya Pradesh

Phase III
Winter Season

Shahdol PM₁₀ ($98.23 \pm 11.81 \text{ ug m}^{-3}$) (8 Jan to 21 Feb, 2024)

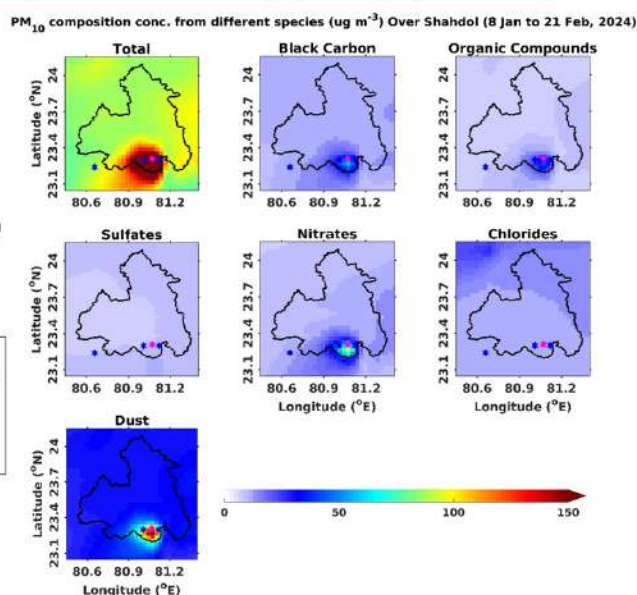
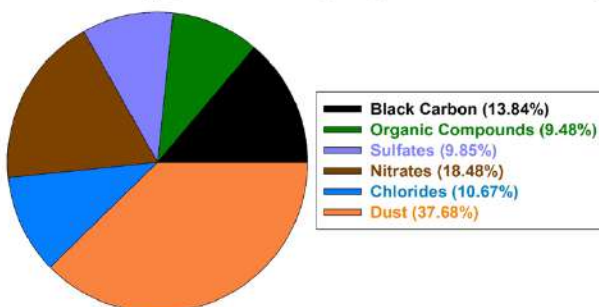


Figure 7.24: Contribution of major aerosol types (species) towards ambient atmospheric PM10 concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

By determining the total amount of sulfate aerosols in ambient air PM2.5 and PM10 concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM2.5 and PM10 that originated from SO₂ emissions from TPPs in the cities included in this survey.

Contribution of TPPs towards PM2.5 and PM10

**Category-2 City: Shahdol,
Madhya Pradesh**

8th Jan to 21st Feb 2024

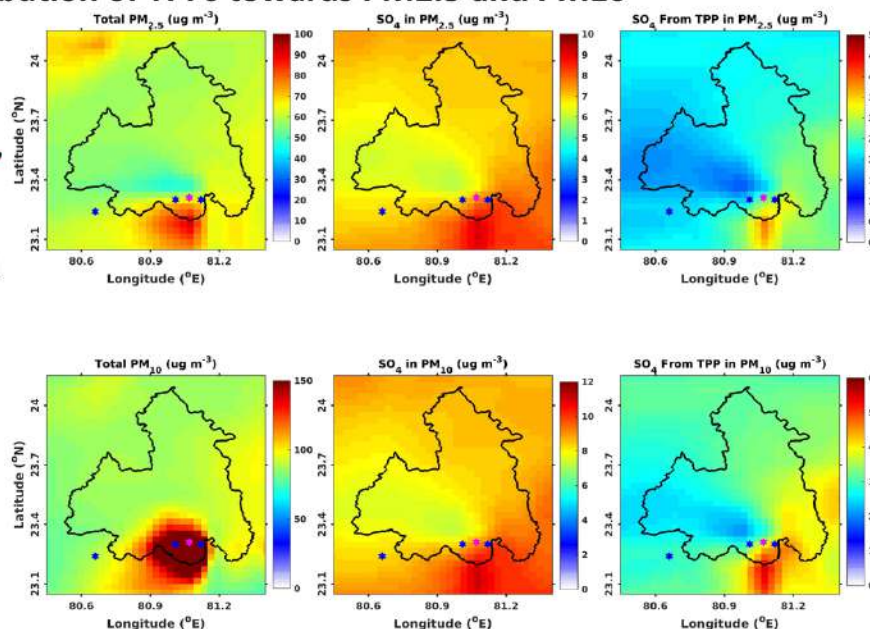


Figure 7.25: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM2.5 and PM10 concentrations in Shahdol during the simulation period from 8th January to 21st February 2024.

Next we performed another series of systematically designed WRF-Chem model simulations to know the contribution different sources towards SO₂ and sulfate aerosols in Khargone, which is a Category-3 city considered during the Phase-III of our survey. We also wanted to understand the contribution of Power sector towards the ambient atmospheric SO₂, PM2.5, and PM10 concentrations in the city of Khargone during our survey. WRF-Chem version 4.2.2 has been used to perform a set of nine atmospheric chemistry simulations over Khargone for January 8th to February 21st, 2024. For this study, the model domains are centered at Khargone (75.84° E and 22.06° N). Each of the simulation domain covers approximately 2250000 square Km area at a horizontal resolution of 10x10 Km², with 150x150 grid cells in the outer domain and horizontal resolution of 3x3 Km², with 136x136 grid cells in the inner domain following nested WRF-Chem modeling setup and 44 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. NCEP GDAS Final Analysis (available at 6 hourly intervals) with a resolution of 0.25°x0.25° have been used to provide meteorological initial

and lateral boundary conditions to the model simulation of January 8th to February 21st, 2024. To estimate the sectoral emission contribution towards the ambient atmospheric SO₂, sulfate aerosols, PM_{2.5}, and PM₁₀ concentrations in Khargone, we followed an emission suppression method. We modified the emissions assuming that FGD was operational in one of the two units of the Khargone TPP during Phase III of our survey.

Chemical Transport Modeling for Khargone, Madhya Pradesh

A series of model simulations have been performed in a systematic manner to know the contribution different sources towards SO₂ sulfate aerosols in the city and the contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City: Khargone, Madhya Pradesh

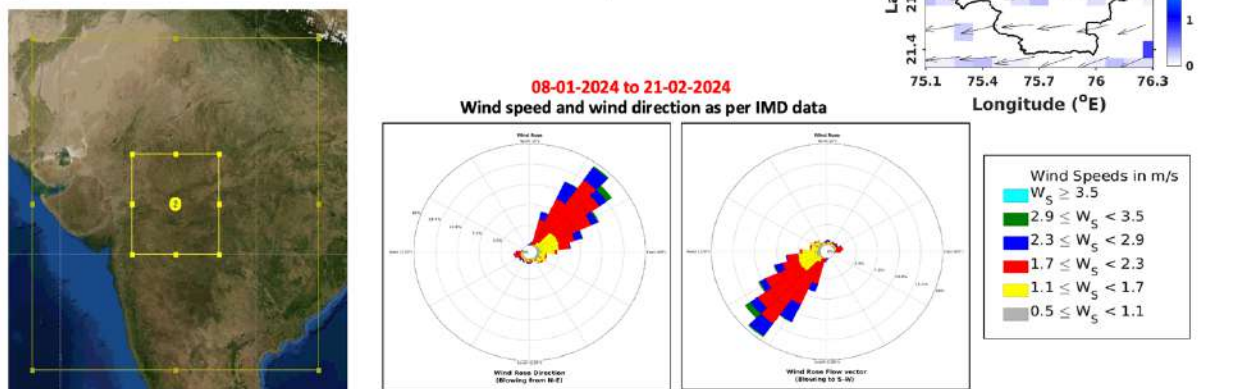


Figure 7.26: Simulation domain, gridded SO₂ emissions used as input in the model simulation and the monthly mean near surface wind speed and wind directions over Khargone during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air SO₂

Category-3 City: Khargone, Madhya Pradesh

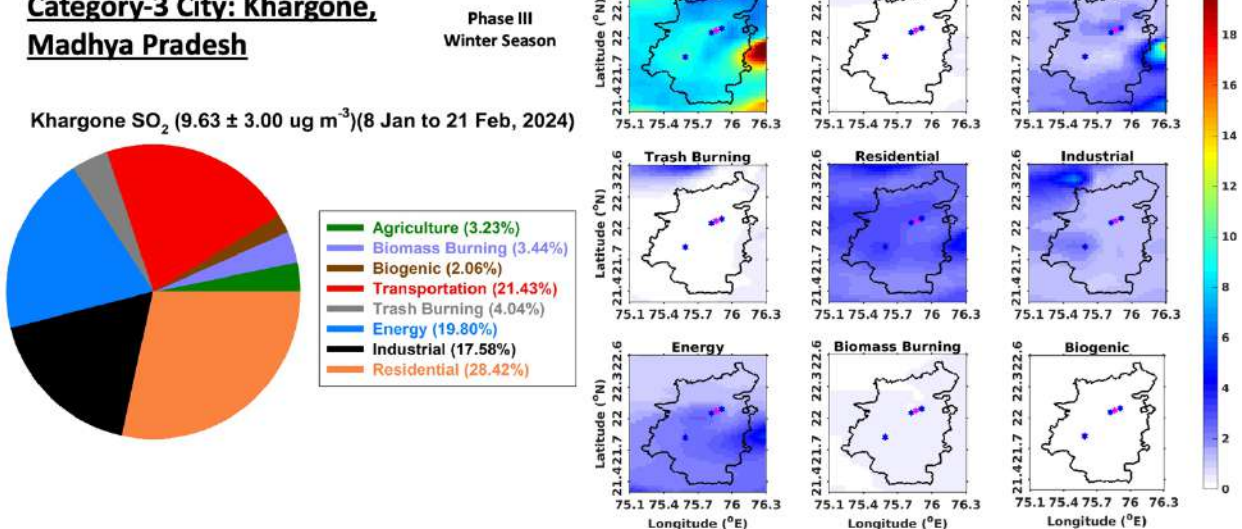


Figure 7.27: Contribution of different emission sectors towards ambient atmospheric SO₂ concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air SO₄

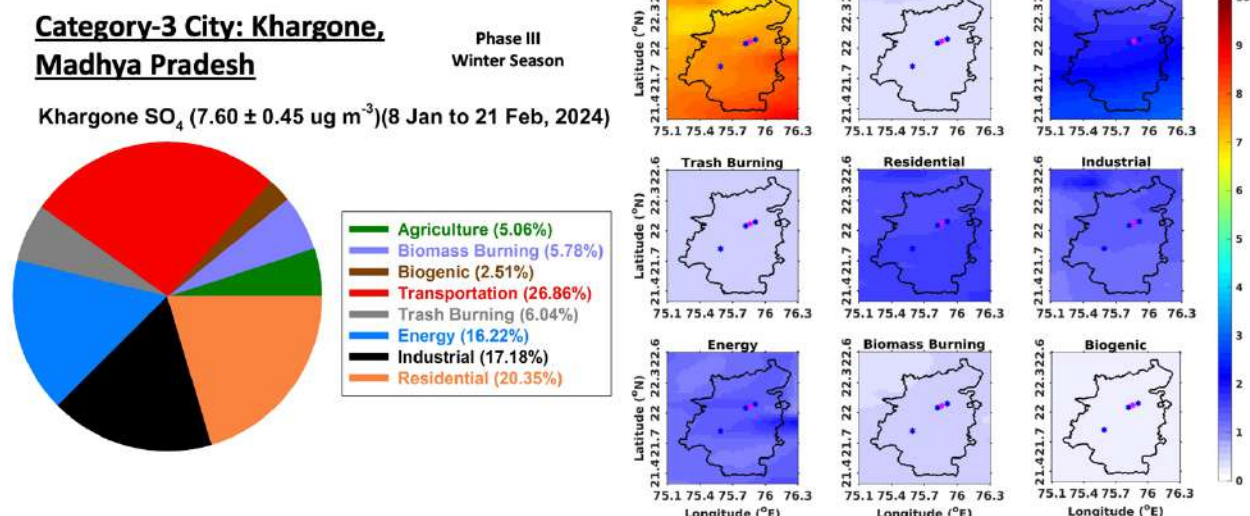


Figure 7.28: Contribution of different emission sectors towards ambient atmospheric sulfate aerosol concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air PM_{2.5}

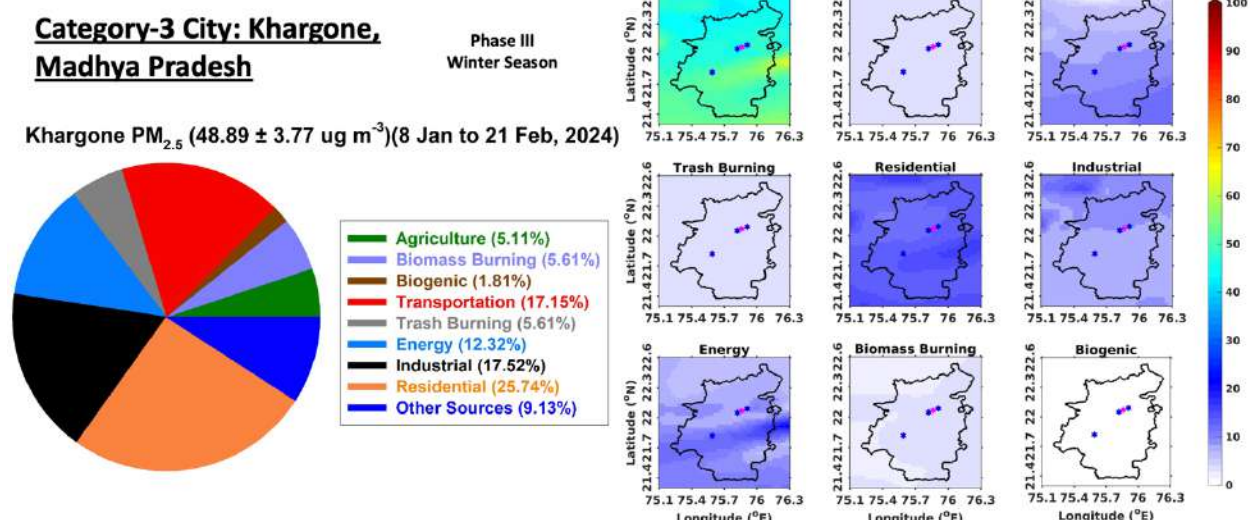


Figure 7.29: Contribution of different emission sectors towards ambient atmospheric PM_{2.5} concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of different emission sectors towards ambient air PM₁₀

**Category-3 City: Khargone,
Madhya Pradesh**

Phase III
Winter Season

Khargone PM₁₀ ($82.03 \pm 5.11 \text{ ug m}^{-3}$) (8 Jan to 21 Feb, 2024)

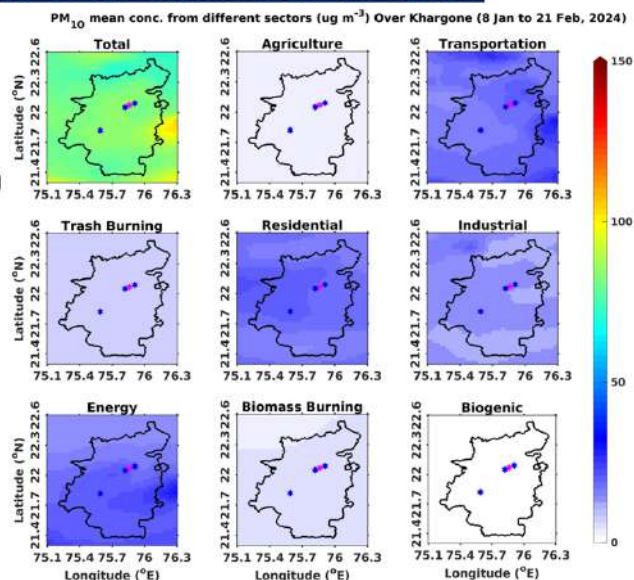
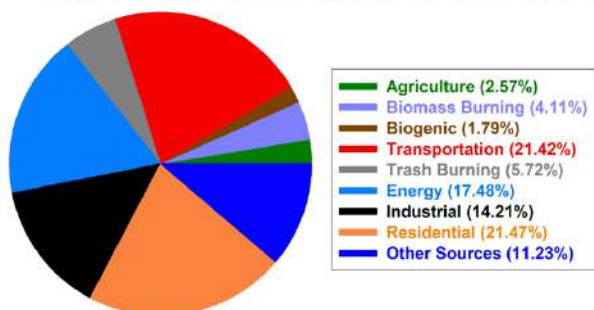


Figure 7.30: Contribution of different emission sectors towards ambient atmospheric PM₁₀ concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Next, we present the results of our simulations, which provide information on the contributions of major aerosol types—including black carbon (BC), organic compounds, sulfates, nitrates, chlorides, and dust—to the ambient air concentrations of PM_{2.5} and PM₁₀ in the city of Khargone during the survey period.

Normalized Contribution of major aerosol types (species) towards ambient air PM_{2.5}

**Category-3 City: Khargone,
Madhya Pradesh**

Phase III
Winter Season

Khargone PM_{2.5} ($48.89 \pm 3.77 \text{ ug m}^{-3}$) (8 Jan to 21 Feb, 2024)

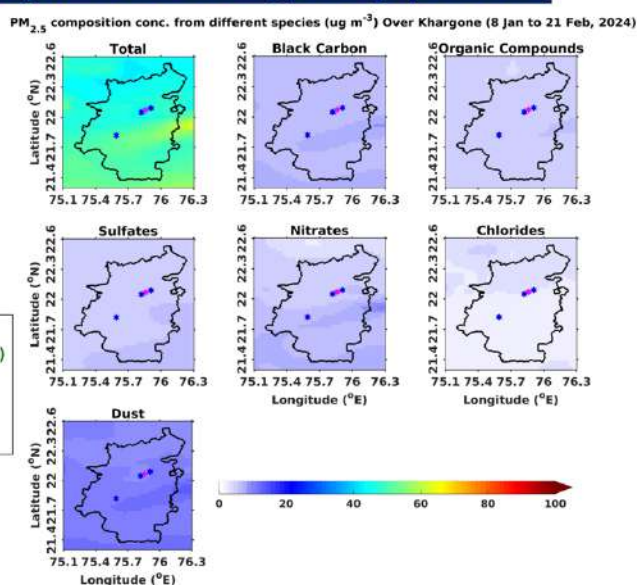
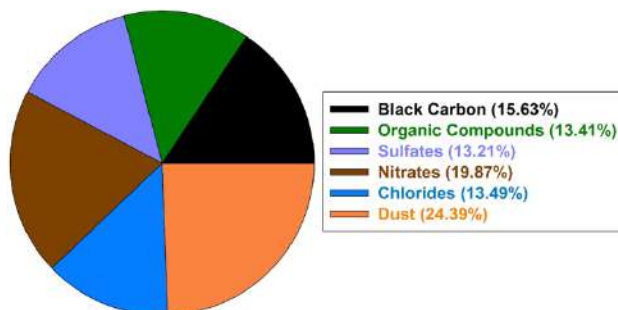


Figure 7.31: Contribution of major aerosol types (species) towards ambient atmospheric PM_{2.5} concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Normalized Contribution of major aerosol types (species) towards ambient air PM₁₀

Category-3 City: Khargone,
Madhya Pradesh

Phase III
Winter Season

Khargone PM₁₀ (82.03 ± 5.11 µg m⁻³) (8 Jan to 21 Feb, 2024)

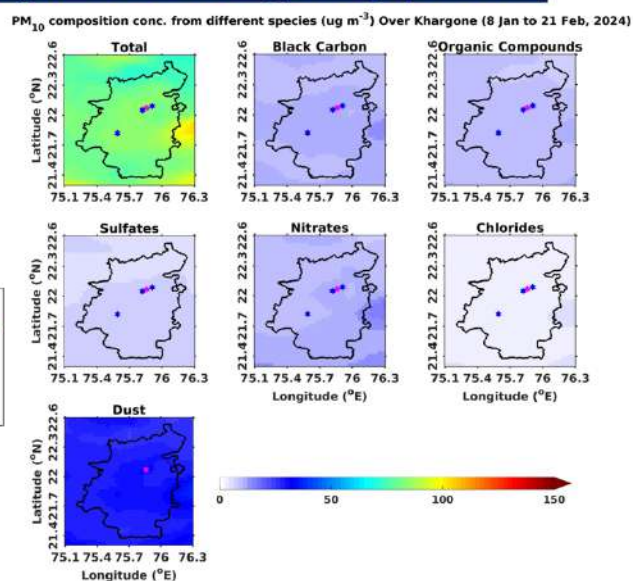
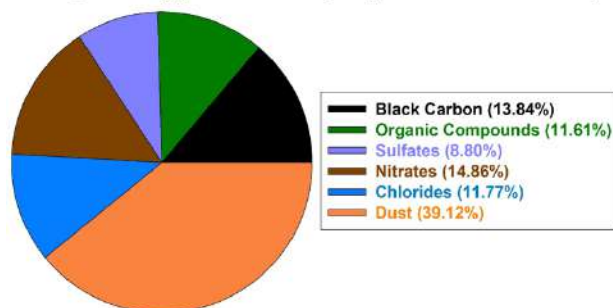


Figure 7.32: Contribution of major aerosol types (species) towards ambient atmospheric PM₁₀ concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

Contribution of TPPs towards PM_{2.5} and PM₁₀

Category-3 City:
Khargone,
Madhya Pradesh

8th Jan to 21st Feb 2024

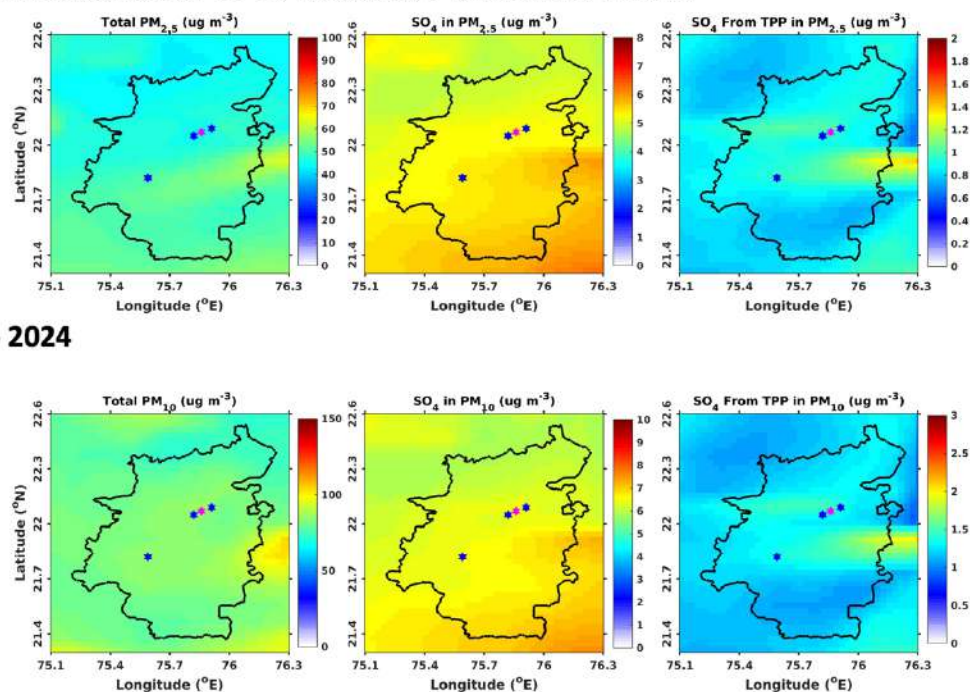


Figure 7.33: Contribution of SO₂ emissions from power sector towards sulfate aerosols as part of ambient atmospheric PM_{2.5} and PM₁₀ concentrations in Khargone during the simulation period from 8th January to 21st February 2024.

By determining the total amount of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ concentrations and the contribution of energy sector emissions, specifically SO₂ emissions from thermal power plants (TPPs), we estimated the portion of sulfate aerosols in ambient air PM_{2.5} and PM₁₀ that originated from SO₂ emissions from TPPs in the cities included in this survey.

Summary of results from Phase-III (Nov 2023 to Feb 2024)

Name of City (Measurement Site, distance from TPP)		Period of Survey	Total SO ₂ (µg m ⁻³) (NAAQS = 80 µg m ⁻³)	SO ₂ from Power Sector (µg m ⁻³)
Kota Category-2	3 Km from Kota Super TPS (upwind)	10-11-2023 to 24-12-2023 (1.5 months)	5.13 ± 1.96	1.73 ± 0.43
	4 Km from Kota Super TPS (downwind)		11.23 ± 4.94	2.44 ± 0.31
	40 Km from Kota Super TPS (downwind)		3.23 ± 0.71	1.39 ± 0.27
GBN Category-3	5 Km from DADRI TPP (upwind)	10-11-2023 to 24-12-2023 (1.5 months)	9.82 ± 1.59	3.34 ± 1.17
	5 Km from DADRI TPP (downwind)		12.51 ± 2.82	5.63 ± 0.73
	40 Km from DADRI TPP (downwind)		6.51 ± 0.93	1.24 ± 0.83
Shahdol Category-2	5 Km from SG TPS (upwind)	08-01-2024 to 21-02-2024 (1.5 months)	5.21 ± 1.58	1.06 ± 0.09
	5 Km from SG TPS (downwind)		5.78 ± 1.13	1.04 ± 0.11
	40 Km from SG TPS (downwind)		4.42 ± 0.78	1.89 ± 0.28
Khargone Category-3	5 Km from Khargone TPP (upwind)	08-01-2024 to 21-02-2024 (1.5 months)	4.38 ± 0.38	0.92 ± 0.17
	5 Km from Khargone TPP (downwind)		4.24 ± 0.31	1.19 ± 0.28
	40 Km from Khargone TPP (downwind)		4.39 ± 0.43	1.05 ± 0.19

Table 7.1: Normalized contribution of Power sector towards ambient atmospheric SO₂ concentrations at specific measurement locations in various cities during the period of our survey from 8th November 2023 to 21st February 2024.

Based on the results from a series of meticulously planned simulations using the WRF-Chem chemical transport model, the contribution of SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric SO₂ concentrations during Phase III of our survey (the winter season) exhibits significant variability across different cities. In Category-2 cities like Kota, the average contribution of TPPs to SO₂ levels was 27.99%. In Shahdol, another Category-2 city, the average contribution of TPPs to SO₂ concentrations was notably higher at 38.57%. Meanwhile, Category-3 cities such as Gautam Buddha Nagar showed a lower average contribution from TPPs, at 22.54%, and in Khargone, the TPPs contributed an average of 19.80% to SO₂ levels. Summarizing by city category, Category-2 cities experienced a higher average contribution of TPPs to SO₂ levels, with averages of 27.99% in Kota and 38.57% in Shahdol. In

contrast, Category-3 cities showed lower average contributions from TPPs, with 22.54% in Gautam Buddha Nagar and 19.80% in Khargone. This data highlights the variability in the influence of TPPs on local air quality, with contributions generally higher in Category-2 cities compared to Category-3 cities. This data underscores the varying impact of coal-based thermal power plants on ambient SO₂ levels during the winter season, with significant differences observed between city categories.

After discussing the average contribution of TPPs to ambient atmospheric SO₂ concentrations in each city and city category, we examine the normalized contribution of the power sector, specifically coal-based thermal power plants (TPPs), to ambient atmospheric SO₂ concentrations at specific measurement locations across different cities during the Phase II of our survey. According to the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. As evident from the data presented in Table 5.3, our survey results confirm that ambient air SO₂ concentrations at all measurement locations across the six cities met the existing standards during the survey period. The data presented in Table 7.1 summarizes the approximate contribution of the power sector, specifically coal based thermal power plants (TPP), to ambient atmospheric SO₂ concentrations at various measurement locations across different cities during Phase III our survey period. For each city, measurements were taken at three locations: one upwind and two downwind from the respective thermal power plants (TPPs). In Kota (Category-2), the upwind and downwind locations showed different levels of TPP contributions. At 3 km upwind, the TPPs contributed 34% (1.73 ± 0.43 µg/m³), while at 4 km and 40 km downwind, the contributions were 22% (2.44 ± 0.31 µg/m³) and 42% (1.39 ± 0.27 µg/m³), respectively. In Gautam Buddha Nagar (Category-3), the upwind location (5 km) had a TPP contribution of 34% (3.34 ± 1.17 µg/m³), while the downwind locations (5 km and 40 km) had contributions of 45% (5.63 ± 0.73 µg/m³) and 19% (1.24 ± 0.83 µg/m³), respectively. In Shahdol (Category-2), the upwind and downwind locations at 5 km showed contributions of 20% (1.06 ± 0.09 µg/m³) and 18% (1.04 ± 0.11 µg/m³), while at 40 km downwind, the contribution was 42% (1.89 ± 0.28 µg/m³). In Khargone (Category-3), the upwind location (5 km) had a contribution of 21% (0.92 ± 0.17 µg/m³), while the downwind locations (5 km and 40 km) had contributions of 28% (1.19 ± 0.28 µg/m³) and 24% (1.05 ± 0.19 µg/m³), respectively. These findings, derived from a combination of actual measurements and modeling studies, highlight the varying impact of TPP emissions on ambient air SO₂ concentrations in different locations and underscore the significant contribution of the power sector to ambient SO₂ levels across the surveyed cities. As per the National Ambient Air Quality Standards (NAAQS) set by the MoEF&CC, Government of India, the maximum permissible limit for ambient air SO₂ concentrations based on 24-hour average measurements for industrial, residential, rural, and other areas is 80 µg/m³. Our survey results confirm that the ambient air SO₂ concentrations at all measurement locations across four cities met the existing standards

during the survey period. Overall, our measurement data and analysis of modeling results indicate that the proximity to thermal power plants significantly affects SO₂ concentrations, with closer locations showing higher contributions from the power sector.

Summary of results from Phase-III (Nov 2023 to Feb 2024)

City	Total PM _{2.5} ($\mu\text{g m}^{-3}$)	Total PM ₁₀ ($\mu\text{g m}^{-3}$)	Sulfate aerosols in PM _{2.5} (%)	Sulfate aerosols in PM _{2.5} ($\mu\text{g m}^{-3}$)	Sulfate aerosols in PM ₁₀ (%)	Sulfate aerosols in PM ₁₀ ($\mu\text{g m}^{-3}$)	Contribution of SO ₂ emissions from TPP towards Sulfate aerosols (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} ($\mu\text{g m}^{-3}$)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ ($\mu\text{g m}^{-3}$)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM _{2.5} (%)	Sulfate aerosols originating from SO ₂ emissions from TPP in PM ₁₀ (%)
Gautam Buddha Nagar	110.18 $\pm$ 23.47	177.04 $\pm$ 42.82	15.71	17.31 $\pm$ 3.32	10.93	19.35 $\pm$ 2.31	18.65	3.23 $\pm$ 0.91	3.80 $\pm$ 1.67	2.93 $\pm$ 0.98	2.15 $\pm$ 0.52
Kota	72.69 $\pm$ 14.75	114.71 $\pm$ 9.74	14.43	10.49 $\pm$ 2.13	11.39	13.07 $\pm$ 1.11	24.26	2.54 $\pm$ 0.52	3.17 $\pm$ 0.03	3.50 $\pm$ 0.71	2.76 $\pm$ 0.02
Khargone	48.89 $\pm$ 4.27	82.03 $\pm$ 5.43	13.21	6.46 $\pm$ 0.75	8.80	7.22 $\pm$ 0.63	16.22	1.05 $\pm$ 0.15	1.23 $\pm$ 0.37	2.14 $\pm$ 0.38	1.51 $\pm$ 0.27
Shahdol	63.41 $\pm$ 4.68	98.23 $\pm$ 11.81	17.62	11.17 $\pm$ 0.82	12.41	12.19 $\pm$ 1.47	29.55	3.30 $\pm$ 0.24	3.60 $\pm$ 0.05	5.21 $\pm$ 0.38	3.67 $\pm$ 0.05

Table 7.2: Contribution of Power sector towards ambient atmospheric sulfate aerosols, PM_{2.5} and PM₁₀ concentrations in various category cities during the period of our survey from 8th November 2023 to 21st February 2024.

Table 7.2 summarizes the contribution of sulfate aerosols (SO₄) in PM_{2.5} and PM₁₀, as well as the specific contribution of sulfate aerosols originating from SO₂ emissions from the power sector (coal based TPPs) to ambient atmospheric PM_{2.5} and PM₁₀ concentrations across various cities during the Phase III of our survey period from 8th November 2023 to 21st February 2024. In Category-3 cities, such as Gautam Buddha Nagar, sulfate aerosols contributed 15.71% (17.31 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 10.93% (19.35 $\mu\text{g}/\text{m}^3$) to PM₁₀. Similarly, in Khargone, sulfate aerosols contributed 13.21% (6.46 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 8.80% (7.22 $\mu\text{g}/\text{m}^3$) to PM₁₀. For Category-2 cities, the contributions in Kota were 14.43% (10.49 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 11.39% (13.07 $\mu\text{g}/\text{m}^3$) to PM₁₀, while in Shahdol, they were 17.62% (11.17 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 12.41% (12.19 $\mu\text{g}/\text{m}^3$) to PM₁₀. On average, Category-3 cities exhibited sulfate aerosol contributions of 14.46% (11.89 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 9.87% (13.29 $\mu\text{g}/\text{m}^3$) to PM₁₀, whereas Category-2 cities showed higher contributions at 16.03% (10.83 $\mu\text{g}/\text{m}^3$) to PM_{2.5} and 11.90% (12.63 $\mu\text{g}/\text{m}^3$) to PM₁₀. These results highlight that while sulfate aerosol concentrations are significant in both categories, Category-2 cities tend to have higher percentages and absolute concentrations compared to Category-3 cities.

During the Phase III, the contribution of SO₂ emissions from the energy sector, specifically coal-based thermal power plants (TPPs), to the total ambient air SO₄ (sulfate aerosol) concentration varied significantly across different cities and city categories. In Category-2 cities, such as Kota and Shahdol, the contributions were substantial. In Kota, SO₂ emissions from TPPs contributed 24.26% (2.61 $\mu\text{g}/\text{m}^3$) to the total ambient air SO₄ concentration. Similarly, in Shahdol, the

contribution was even higher at 29.55% ($3.01 \mu\text{g}/\text{m}^3$). Category-3 cities also exhibited significant contributions from TPPs. In Gautam Buddha Nagar, the SO_2 emissions from TPPs contributed 18.65% ($3.80 \mu\text{g}/\text{m}^3$) to the total ambient air SO_4 concentration. In Khargone, the contribution was 16.22% ($1.23 \mu\text{g}/\text{m}^3$). When averaging the contributions across the cities within each category, we observe the following: For Category-2 cities, the average contribution of SO_2 emissions from TPPs towards the total ambient air SO_4 concentration was 26.91% ($2.81 \mu\text{g}/\text{m}^3$). For Category-3 cities, the average contribution was 17.44% ($2.52 \mu\text{g}/\text{m}^3$). These findings indicate that cities with coal-based thermal power plants, both with and without FGD systems, experience considerable contributions of SO_2 emissions from the energy sector to the total ambient air SO_4 concentrations. Notably, the highest sulfate aerosol contributions in absolute terms were observed in the Category-3 city of Gautam Buddha Nagar, with concentrations reaching $3.80 \mu\text{g}/\text{m}^3$. This is likely due to the overall higher concentrations of total sulfate aerosol, $\text{PM}_{2.5}$, and PM_{10} in Gautam Buddha Nagar compared to other cities in Phase III of our survey, as well as the assumption that the FGD was operational in only two units of the NTPC Dadri TPP during this period.

The specific contribution of sulfate aerosols originating from SO_2 emissions from coal-based thermal power plants (TPPs) to ambient atmospheric $\text{PM}_{2.5}$ and PM_{10} concentrations also varied across different cities and city categories. In Gautam Buddha Nagar, the contribution was 2.93% ($3.23 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 2.15% ($3.80 \mu\text{g}/\text{m}^3$) in PM_{10} . In Khargone, the contributions were 2.14% ($1.05 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 1.51% ($1.23 \mu\text{g}/\text{m}^3$) in PM_{10} . For Category-2 cities, Kota saw contributions of 3.50% ($2.54 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 2.76% ($3.17 \mu\text{g}/\text{m}^3$) in PM_{10} , while Shahdol had higher contributions of 5.21% ($3.30 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 3.67% ($3.60 \mu\text{g}/\text{m}^3$) in PM_{10} . On average, the contribution of SO_2 emissions from TPPs to sulfate aerosols in Category-3 cities was 2.54% ($2.14 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 1.83% ($2.52 \mu\text{g}/\text{m}^3$) in PM_{10} . In comparison, Category-2 cities had higher contributions, with averages of 4.36% ($2.92 \mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$ and 3.22% ($3.39 \mu\text{g}/\text{m}^3$) in PM_{10} . These figures indicate that SO_2 emissions from TPPs contribute a measurable, albeit relatively small, portion of sulfate aerosols in $\text{PM}_{2.5}$ and PM_{10} .

Overall, the contribution of SO_2 emissions from the power sector, which convert to sulfate aerosols, ranged from 2.14% to 5.21% in $\text{PM}_{2.5}$ and from 1.51% to 3.67% in PM_{10} across the cities during Phase-III of the survey. This indicates variability in the impact of power sector emissions on sulfate aerosol concentrations. While SO_2 emissions from TPPs do contribute to sulfate aerosol mass concentrations in $\text{PM}_{2.5}$ and PM_{10} , their overall contribution remains a small fraction (less than 6%) of the total $\text{PM}_{2.5}$ and PM_{10} mass concentrations across various city categories, especially during the winter season, indicating that other sources are more significant contributors to ambient air PM levels.

CHAPTER-8: SUMMARY OF RESULTS FROM THREE PHASES SURVEY ON AMBIENT ATMOSPHERIC SO₂ CONCENTRATIONS IN DIFFERENT CATEGORY OF CITIES

This chapter summarizes the results of our measurement-based survey on ambient air SO₂ concentrations across different city categories during three distinct survey periods: Phase I (pre-monsoon season, February to May 2023), Phase II (summer monsoon season, July to August 2023), and Phase III (winter season, November 2023 to February 2024). The survey was conducted in 10 cities, categorized as follows: Category 1 - Cities with no coal-based TPP; Category 2 - Cities with a coal-based TPP without FGD installed, located within 10 km from the city boundary; and Category 3 - Cities with a coal-based TPP with FGD installed, also located within 10 km from the city boundary. In Category 1, the survey was conducted in three cities: New Delhi and Hyderabad during Phase I (pre-monsoon season), and Lucknow during Phase II (summer monsoon season). For Category 2, the survey included four cities: Kolkata and Nagpur during Phase I (pre-monsoon season), Kota during both Phase II (summer monsoon season) and Phase III (winter season), and Shahdol during Phase III (winter season). In Category 3, the survey was conducted in three cities: Ghaziabad and Gautam Buddha Nagar during Phase I (pre-monsoon season), Gautam Buddha Nagar again during Phase II (summer monsoon season) and Phase III (winter season), and Khargone during Phase III (winter season). Thus the surveys spanned three distinct periods, including pre-monsoon, summer monsoon, and winter seasons, providing a comprehensive assessment of ambient air SO₂ concentrations across different environmental conditions and city categories.

8.1 Ambient Air SO₂ Concentration In Different Category Cities

In this section we summarize the results of our measurement-based survey on ambient air SO₂ concentrations across different category cities during all three phases. In Category 1 cities, New Delhi recorded the highest maximum instantaneous SO₂ concentration of 29.37 µg/m³ during Phase I (pre-monsoon season), while the lowest minimum instantaneous value was 0.83 µg/m³, also in New Delhi during the same phase. The daily mean SO₂ concentrations in Category 1 cities ranged from 2.48 to 9.26 µg/m³. For Category 2 cities, Kota exhibited the highest maximum instantaneous SO₂ concentration of 68.09 µg/m³ during Phase III (winter season), and the lowest minimum value was 0.75 µg/m³, recorded in Kota during Phase II (summer monsoon season). The daily mean values for SO₂ in Category 2 cities varied from 3.12 to 11.23 µg/m³. In Category 3 cities, Gautam Buddha Nagar had the highest maximum instantaneous SO₂ concentration of 70.14 µg/m³ during Phase III (winter season), while the lowest minimum value was 0.54 µg/m³, also observed in Gautam Buddha Nagar during Phase III. It is noteworthy that the highest values in Gautam Buddha Nagar were measured on November 13th, the day after the Diwali festival, which is characterized by the bursting of firecrackers that could have contributed to these peak

values. The daily mean SO₂ concentrations in Category 3 cities ranged from 4.24 to 12.51 µg/m³. Importantly, ambient SO₂ levels across all city categories and phases remained well within the National Ambient Air Quality Standards (NAAQS) of 80 µg/m³, which is the maximum permissible limit for 24-hour average measurements as notified by the MoEF&CC, Government of India. Even the instantaneous maximum values never exceeded this daily mean standard limit.

Generally, downwind sites exhibited higher SO₂ concentrations compared to upwind sites, and SO₂ levels tended to decrease with increasing distance from the TPP across all cities. These results highlight the variability in ambient air SO₂ concentrations across different locations and city categories, with Category 2 and Category 3 cities generally showing higher SO₂ levels. The findings of our survey clearly indicate that proximity to thermal power plants significantly affects ambient air SO₂ concentrations, with locations closer to TPPs showing higher values.

Our survey also revealed some important common features in the diurnal patterns of ambient air SO₂ concentrations across cities. We observed significant diurnal variations and intra-day fluctuations, with multiple peaks at various times of the day, including evening and nighttime, in all city categories and throughout the survey phases. These spikes, lasting 2-4 hours, are likely caused by local sources within approximately 60 km of the measurement sites, such as transportation, residential activities, and industrial emissions. The role of TPPs in these spikes can be ruled out because (i) TPP units typically operate continuously and are not switched on and off intermittently, and (ii) such intermittent spikes were observed even in Category-1 cities with no TPPs within 10 km of their boundaries. A significant influence of boundary layer dynamics on ambient air SO₂ concentrations was noted in all cities throughout the survey phases.

Overall, our survey underscored the significant impact of proximity to thermal power plants, various other local sources, wind speed, predominant wind direction, and boundary layer dynamics on ambient air SO₂ concentrations across different city categories.

Importantly, our survey data showed no notable systematic differences in ambient air SO₂ concentrations between the Category 2 and Category 3 cities. Additionally, we did not observe any significant changes in SO₂ levels with the operation of FGD units at the measurement locations in the Category 3 cities, namely GBN and Khargone, despite large day-to-day variability. However, this variability did not correlate with either the operation or the number of FGD units in operation at these TPPs.

The analysis of ambient air SO₂ concentrations across multiple cities, supported by dispersion modelling results from the AERMOD model, demonstrates a clear pattern of decreasing SO₂ levels with increasing distance from thermal power plants (TPPs). Our findings indicate that the highest hourly, 24-hourly, and monthly SO₂ concentrations drop significantly within the first 20 to 25 km

from the TPPs. Beyond this range, concentrations level off but continue to decrease gradually up to 120 km. This trend is consistent across Category-2 and Category-3 cities, including GBN, Kota, Shahdol, and Khargone. These observations align with numerous previous studies using dispersion and chemical transport models, which show that SO₂ emissions beyond 120 km from a fixed-point source like a TPP generally become part of the regional background concentration and decrease by over two orders of magnitude compared to the highest levels near the source, under moderate wind speed conditions of up to 5 m/s (or 18 km/h) (Fioletov et al. 2015).

8.2 Contribution of Energy Sector (Coal based Thermal Power Plants) Emissions Towards Ambient Air SO₂ Concentration In Different Category Cities

Results from a series of meticulously planned simulations using the WRF-Chem chemical transport model reveal that the contribution of SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric SO₂ concentrations during all phases of our survey exhibited significant spatial and seasonal variability across different cities. Our analysis shows that the energy sector's contribution to total ambient air SO₂ concentrations varies markedly across different city categories during the various phases of the study.

In Category-1 cities, which have no coal-based TPPs, the energy sector's contribution to ambient SO₂ concentrations was relatively low. New Delhi showed a contribution of 16.53% (1.36 µg/m³) during Phase-I (pre-monsoon season). In Hyderabad, the contribution was 11.57% (0.41 µg/m³) in the same phase. During Phase-II (monsoon season), Lucknow recorded contributions of 11.44% (0.66 µg/m³). These results indicate that in Category-1 cities, other sources contributing to the regional pollution play a more significant role in ambient SO₂ levels compared to emissions from the energy sector.

For Category-2 cities, which have coal-based TPPs without Flue Gas Desulfurization (FGD) installed and located within 10 km from the city boundary, the energy sector's contribution to ambient SO₂ concentrations were generally significant. Kolkata showed contributions of 28.66% (1.55 µg/m³), and Nagpur showed 32.27% (1.56 µg/m³) during Phase-I (pre-monsoon season). In Phase-II (monsoon season), energy sector's contribution to ambient SO₂ concentrations in Kota was 28.9% (1.11 µg/m³). During Phase III (winter season), Kota had a 27.99% contribution (1.82 µg/m³) from the energy sector to ambient SO₂ concentrations, while Shahdol showed a 38.57% contribution (1.99 µg/m³). These results underscore the significant impact of coal-based TPP emissions in Category-2 cities.

In Category-3 cities, which have coal-based TPPs with FGD installed and located within 10 km from the city boundary, the energy sector's contributions were also notable. Ghaziabad showed contributions of 17.37% (1.43 µg/m³) during Phase-I (pre-monsoon season). GBN had

contributions of 19.82% ($1.80 \mu\text{g}/\text{m}^3$) from the energy sector to ambient SO_2 concentrations in Phase-I (pre-monsoon season), 21.97% ($1.33 \mu\text{g}/\text{m}^3$) in Phase-II (monsoon season), and 22.54% ($2.17 \mu\text{g}/\text{m}^3$) in Phase-III (winter season). Khargone had contributions of 19.8% ($0.86 \mu\text{g}/\text{m}^3$) from the energy sector to ambient SO_2 concentrations during Phase-III (winter season). These results indicate some seasonal variation, with the highest contributions generally observed in the winter season and the lowest during the pre-monsoon season.

Overall, our study shows that the energy sector's contribution to ambient air SO_2 concentrations ranged from 11.44% ($0.66 \mu\text{g}/\text{m}^3$) to 38.57% ($1.99 \mu\text{g}/\text{m}^3$) across all cities and phases of the survey. The highest contributions were observed in Category-2 and Category-3 cities, underscoring the significant impact of coal-based TPP emissions on ambient air SO_2 in these cities. While SO_2 emissions from TPPs are among the major contributors to ambient air SO_2 concentrations in several cities, especially in Category-2 and Category-3, other sources such as industrial, residential, and transportation sectors also significantly contribute to ambient air SO_2 levels in all cities. Therefore, stringent emission control measures must be implemented across all sectors contributing to SO_2 emissions to effectively reduce the total ambient air SO_2 concentrations and improve regional air quality.

8.3 Contribution of total Sulfate aerosols (SO_4) originating from all SO_2 sources Towards $\text{PM}_{2.5}$ and PM_{10} Mass Concentrations In Different Category Cities

Our study demonstrates that the contribution of total sulfate aerosols originating from all SO_2 sources towards $\text{PM}_{2.5}$ and PM_{10} mass concentrations varies significantly across different categories of cities and seasons. By averaging the data from different cities and seasons within each category, we gain a clearer understanding of these contributions.

In Category-1 cities, which have no coal-based thermal power plants (TPPs), sulfate aerosol contributions were relatively low. In Delhi, sulfate aerosols contributed 15.15% ($12.09 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 9.82% ($13.51 \mu\text{g}/\text{m}^3$) to PM_{10} during Phase-I (pre-monsoon season). In Hyderabad, the contributions were 13.85% ($6.26 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 8.22% ($7.00 \mu\text{g}/\text{m}^3$) to PM_{10} during the same phase. In Lucknow, the sulfate contributions were 11.62% ($4.02 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 8.55% ($4.49 \mu\text{g}/\text{m}^3$) to PM_{10} during Phase-II (monsoon season). Averaging these values, Category-1 cities had an average sulfate contribution of approximately 13.54% ($7.46 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 8.86% ($8.33 \mu\text{g}/\text{m}^3$) to PM_{10} .

In Category-2 cities, which are near coal-based TPPs without flue-gas desulfurization (FGD) systems, sulfate aerosol contributions were higher. In Kolkata, the contributions were 22.32% ($7.04 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 14.87% ($7.86 \mu\text{g}/\text{m}^3$) to PM_{10} during Phase-I (pre-monsoon season). For Nagpur, the contributions were 14.16% ($8.85 \mu\text{g}/\text{m}^3$) to $\text{PM}_{2.5}$ and 11.83% ($9.90 \mu\text{g}/\text{m}^3$) to

PM10 during the same period. In Kota, sulfate contributions were 11.73% (5.71 $\mu\text{g}/\text{m}^3$) to PM2.5 and 9.71% (6.38 $\mu\text{g}/\text{m}^3$) to PM10 during Phase-II (monsoon season), which increased to 14.43% (10.49 $\mu\text{g}/\text{m}^3$) to PM2.5 and 11.39% (13.07 $\mu\text{g}/\text{m}^3$) to PM10 during Phase-III (winter season). In Shahdol, the contributions were 17.62% (11.17 $\mu\text{g}/\text{m}^3$) to PM2.5 and 12.41% (12.19 $\mu\text{g}/\text{m}^3$) to PM10 during Phase-III. Averaging these values, Category-2 cities had average sulfate contributions of approximately 16.45% (8.05 $\mu\text{g}/\text{m}^3$) to PM2.5 and 12.04% (9.88 $\mu\text{g}/\text{m}^3$) to PM10.

In Category-3 cities, which are near coal-based TPPs with FGD systems, sulfate aerosol contributions were the highest. In Gautam Buddha Nagar, the contributions were 15.56% (12.12 $\mu\text{g}/\text{m}^3$) to PM2.5 and 10.32% (13.55 $\mu\text{g}/\text{m}^3$) to PM10 during Phase-I (pre-monsoon season). During Phase-II (monsoon season), the contributions in Gautam Buddha Nagar were 13.65% (6.42 $\mu\text{g}/\text{m}^3$) to PM2.5 and 10.09% (7.18 $\mu\text{g}/\text{m}^3$) to PM10. In Phase-III (winter season), the contributions in Gautam Buddha Nagar were 15.71% (17.31 $\mu\text{g}/\text{m}^3$) to PM2.5 and 10.93% (19.35 $\mu\text{g}/\text{m}^3$) to PM10. In Khargone, the contributions were 13.21% (6.46 $\mu\text{g}/\text{m}^3$) to PM2.5 and 8.80% (7.22 $\mu\text{g}/\text{m}^3$) to PM10 during Phase-III. Averaging these values, Category-3 cities had average sulfate contributions of approximately 14.53% (10.58 $\mu\text{g}/\text{m}^3$) to PM2.5 and 10.04% (11.83 $\mu\text{g}/\text{m}^3$) to PM10.

Overall, Category-2 and Category-3 cities experienced significantly higher contributions of sulfate aerosols to PM2.5 and PM10 compared to Category-1 cities. Category-1 cities, which have no coal-based thermal power plants (TPPs), showed the lowest average sulfate aerosol contributions, at approximately 13.54% (7.46 $\mu\text{g}/\text{m}^3$) to PM2.5 and 8.86% (8.33 $\mu\text{g}/\text{m}^3$) to PM10. In contrast, Category-2 cities, located near TPPs without flue-gas desulfurization (FGD) systems, exhibited higher average sulfate aerosol contributions of 16.45% (8.05 $\mu\text{g}/\text{m}^3$) to PM2.5 and 12.04% (9.88 $\mu\text{g}/\text{m}^3$) to PM10. Category-3 cities, which are near TPPs with FGD systems, had intermediate average contributions in relative percentage terms, with 14.53% to PM2.5 and 10.04% to PM10. However, in absolute concentration terms, Category-3 cities showed the highest concentrations of sulfate aerosols, with 10.58 $\mu\text{g}/\text{m}^3$ in PM2.5 and 11.83 $\mu\text{g}/\text{m}^3$ in PM10, likely due to their higher absolute PM2.5 and PM10 concentrations compared to Category-2 and Category-1 cities.

This comparison clearly highlights that cities closer to coal-based TPPs, regardless of the presence of FGD systems, experience significantly higher sulfate aerosol contributions. Specifically, Category-2 cities had an average of 16.45% (8.05 $\mu\text{g}/\text{m}^3$) sulfate contribution to PM2.5 and 12.04% (9.88 $\mu\text{g}/\text{m}^3$) to PM10, while Category-3 cities had slightly lower averages of 14.53% (10.58 $\mu\text{g}/\text{m}^3$) to PM2.5 and 10.04% (11.83 $\mu\text{g}/\text{m}^3$) to PM10. In stark contrast, Category-1 cities had much lower averages of 13.54% (7.46 $\mu\text{g}/\text{m}^3$) to PM2.5 and 8.86% (8.33 $\mu\text{g}/\text{m}^3$) to PM10.

Our study also reveals notable seasonal variations in sulfate aerosol contributions to both PM_{2.5} and PM₁₀ during Phase-I (pre-monsoon season), Phase-II (monsoon season), and Phase-III (winter season). For instance, in Kota, the sulfate aerosol contributions to PM_{2.5} rose from 11.73% (5.71 µg/m³) in the monsoon season to 14.43% (10.49 µg/m³) in the winter season, and for PM₁₀, from 9.71% (6.38 µg/m³) to 11.39% (13.07 µg/m³) in the same periods. Similarly, in Gautam Buddha Nagar, contributions to PM_{2.5} varied from 15.56% (12.12 µg/m³) during the pre-monsoon season to 13.65% (6.42 µg/m³) during the monsoon season, and further to 15.71% (17.31 µg/m³) during the winter season. For PM₁₀ in Gautam Buddha Nagar, the contributions were 10.32% (13.55 µg/m³) during the pre-monsoon season, 10.09% (7.18 µg/m³) during the monsoon season, and 10.93% (19.35 µg/m³) during the winter season. These variations indicate a higher impact of sulfate aerosols during colder months, likely due to increased emissions and atmospheric stability changes. The higher levels of sulfate aerosols in winter months can be attributed to several factors including higher emissions from heating sources and reduced dispersion due to atmospheric stability, which allows pollutants to accumulate. These findings underscore the need for targeted air quality management strategies that consider both the proximity to TPPs and seasonal variations to effectively control sulfate aerosol pollution.

8.4 Contribution of Energy Sector (Coal based Thermal Power Plants) Emissions Towards Ambient Air SO₄ (Sulfate aerosol) Concentration In Different Category Cities

Results from a series of meticulously planned simulations using the WRF-Chem chemical transport model were analysed to understand the contribution of SO₂ emissions from the power sector, specifically from coal-based thermal power plants (TPPs), to ambient atmospheric sulfate aerosol (SO₄) concentrations in different category cities considered in this survey. Our analysis shows that the energy sector's contribution to the total ambient air sulfate aerosol concentrations varies significantly across different city categories during various study phases.

In Category-1 cities, which have no coal-based TPPs, the contributions of SO₂ emissions from TPPs to ambient sulfate aerosols were consistently lower. In Delhi, during Phase I (pre-monsoon season), the contribution from TPP SO₂ emissions was 15.85% (2.25 µg/m³). Hyderabad, also in Phase I, showed a much lower contribution of 6.96% (0.51 µg/m³). In Phase II (monsoon season), Lucknow exhibited a contribution of 10.49% (0.50 µg/m³). Averaging these contributions across the phases, Category-1 cities had an average contribution of 11.77% (1.09 µg/m³) from SO₂ emissions from TPPs to ambient sulfate aerosols.

Category-2 cities, which are near TPPs without flue-gas desulfurization (FGD) systems, exhibited the highest contributions of SO₂ emissions from TPPs to ambient sulfate aerosols. In Phase I (pre-monsoon season), Nagpur showed a contribution of 22.32% (2.33 µg/m³), and Kolkata exhibited a contribution of 24.53% (2.03 µg/m³). In Phase II (monsoon season), Kota showed a contribution

of 24.08% (1.62 $\mu\text{g}/\text{m}^3$). During Phase III (winter season), Kota's contribution was 24.26% (2.61 $\mu\text{g}/\text{m}^3$), while Shahdol had the highest contribution among all cities at 29.55% (3.01 $\mu\text{g}/\text{m}^3$). On average, Category-2 cities had an energy sector contribution of 24.55% (2.32 $\mu\text{g}/\text{m}^3$) to ambient sulfate aerosols.

Category-3 cities, which are near TPPs with FGD systems, also showed significant contributions of SO_2 emissions from TPPs to ambient sulfate aerosols. During Phase I (pre-monsoon season), Gautam Buddha Nagar had a contribution of 17.89% (2.55 $\mu\text{g}/\text{m}^3$), while Ghaziabad showed a contribution of 15.02% (1.83 $\mu\text{g}/\text{m}^3$). In Phase II (monsoon season), Gautam Buddha Nagar had a contribution of 16.54% (1.25 $\mu\text{g}/\text{m}^3$). During Phase III (winter season), Gautam Buddha Nagar's contribution was 18.65% (3.80 $\mu\text{g}/\text{m}^3$), and Khargone exhibited a contribution of 16.22% (1.23 $\mu\text{g}/\text{m}^3$). Averaging these contributions, Category-3 cities had an energy sector contribution of 16.86% (2.33 $\mu\text{g}/\text{m}^3$) to ambient sulfate aerosols.

Overall, the contribution of SO_2 emissions from coal-based TPPs to ambient sulfate aerosols was highest in Category-2 cities, with an average contribution of 24.55% (2.32 $\mu\text{g}/\text{m}^3$), followed by Category-3 cities with 16.86% (2.33 $\mu\text{g}/\text{m}^3$), and lowest in Category-1 cities at 11.77% (1.09 $\mu\text{g}/\text{m}^3$). These results indicate that coal-based TPP emissions significantly impact sulfate aerosol levels, particularly in cities near TPPs without FGD systems. Notably, the highest contribution of SO_2 emissions from TPPs to ambient sulfate aerosols in absolute terms were observed in the Category-3 city of Gautam Buddha Nagar, with concentrations reaching 3.80 $\mu\text{g}/\text{m}^3$. This is likely due to the overall higher concentrations of total sulfate aerosol, $\text{PM}_{2.5}$, and PM_{10} in Gautam Buddha Nagar compared to other cities in Phase III of our survey, as well as the assumption that the FGD was operational in only two units of the NTPC Dadri TPP during this period.

Across all cities and phases, the contribution of TPP SO_2 emissions to ambient sulfate aerosols ranged from approximately 6.96% (0.51 $\mu\text{g}/\text{m}^3$) to 29.55% (3.01 $\mu\text{g}/\text{m}^3$). Thus, our study shows that even if we completely eliminated SO_2 emissions from TPPs using FGDs, it would reduce ambient air sulfate aerosol concentrations across all surveyed cities and seasons by 6.96% (0.51 $\mu\text{g}/\text{m}^3$) to 29.55% (3.01 $\mu\text{g}/\text{m}^3$). Additionally, installing FGD systems with an 80% SO_2 removal efficiency in all coal-based TPPs across India would result in a reduction in sulfate aerosol concentrations across all surveyed cities and seasons by 5.67% (0.41 $\mu\text{g}/\text{m}^3$) to 23.64% (2.41 $\mu\text{g}/\text{m}^3$).

This indicates that while SO_2 emissions from TPPs are significant contributors to ambient sulfate aerosols, especially in Category-2 and Category-3 cities, other sources such as industrial activities, residential emissions, and the transportation sector also play crucial roles. Therefore, stringent emission control measures must be implemented across all sectors contributing to SO_2 emissions to effectively reduce total ambient air sulfate aerosol concentrations and improve overall air

quality. By addressing SO₂ emissions comprehensively, not just from TPPs but also from other significant sources, we can achieve more substantial reductions in sulfate aerosol levels and enhance air quality across all surveyed cities.

8.5 Contribution of Sulfate Aerosols (SO₄) Formed Due to SO₂ Emissions From TPPs Towards PM_{2.5} and PM₁₀ Mass Concentrations In Different Category Cities

Our study demonstrates that the contribution of sulfate aerosols (SO₄) formed due to SO₂ emissions from coal-based thermal power plants (TPPs) to ambient air PM_{2.5} and PM₁₀ mass concentrations varies significantly across different categories of cities and seasons.

Category-1 cities, which have no coal-based TPPs, showed the lowest contributions of sulfate aerosols (SO₄) formed due to SO₂ emissions from coal-based TPPs to ambient air PM_{2.5} and PM₁₀ mass concentrations. In Hyderabad during Phase I (pre-monsoon season), the contribution was 0.96% to PM_{2.5} (0.44 µg/m³) and 0.57% to PM₁₀ (0.49 µg/m³). In Lucknow during Phase II (monsoon season), the contributions were 1.22% to PM_{2.5} (0.42 µg/m³) and 0.90% to PM₁₀ (0.47 µg/m³). In Delhi, despite being a Category-1 city, the contributions were significantly higher due to regional transport of SO₂ or sulfate aerosols from nearby TPPs, with Phase I contributions of 2.41% to PM_{2.5} (1.92 µg/m³) and 1.64% to PM₁₀ (2.25 µg/m³). On average, Category-1 cities had contributions of approximately 1.79% to PM_{2.5} (0.93 µg/m³) and 1.04% to PM₁₀ (1.07 µg/m³) from sulfate aerosols (SO₄) formed due to SO₂ emissions from TPPs.

Category-2 cities, which are near TPPs without flue-gas desulfurization (FGD) systems, showed more substantial contributions of sulfate aerosols (SO₄) formed due to SO₂ emissions from coal-based TPPs to ambient air PM_{2.5} and PM₁₀ mass concentrations. In Kolkata during Phase I (pre-monsoon season), the contributions were 5.48% to PM_{2.5} (1.73 µg/m³) and 3.65% to PM₁₀ (1.93 µg/m³). In Nagpur, the contributions were 3.16% to PM_{2.5} (1.98 µg/m³) and 2.64% to PM₁₀ (2.21 µg/m³) during the same phase. In Kota during Phase II (monsoon season), the contributions were 2.82% to PM_{2.5} (1.38 µg/m³) and 2.34% to PM₁₀ (1.54 µg/m³), increasing to 3.50% to PM_{2.5} (2.54 µg/m³) and 2.76% to PM₁₀ (3.17 µg/m³) in Phase III (winter season). Shahdol in Phase III showed the highest contribution with 5.21% to PM_{2.5} (3.30 µg/m³) and 3.67% to PM₁₀ (3.60 µg/m³). On average, Category-2 cities had contributions of approximately 3.83% to PM_{2.5} (2.19 µg/m³) and 2.87% to PM₁₀ (2.49 µg/m³) from sulfate aerosols (SO₄) formed due to SO₂ emissions from TPPs.

Category-3 cities, which are near TPPs with FGD systems, had significant contributions as well of sulfate aerosols (SO₄) formed due to SO₂ emissions from coal-based TPPs to ambient air PM_{2.5} and PM₁₀ mass concentrations. In Gautam Buddha Nagar during Phase I (pre-monsoon season), the contributions were 2.78% to PM_{2.5} (2.17 µg/m³) and 1.94% to PM₁₀ (2.55 µg/m³). In Phase II (monsoon season), the contributions were 2.26% to PM_{2.5} (1.06 µg/m³) and 1.76% to PM₁₀

(1.25 $\mu\text{g}/\text{m}^3$). During Phase III (winter season), the contributions were 2.93% to PM_{2.5} (3.23 $\mu\text{g}/\text{m}^3$) and 2.15% to PM₁₀ (3.80 $\mu\text{g}/\text{m}^3$). In Ghaziabad during Phase I, the contributions were 2.15% to PM_{2.5} (1.55 $\mu\text{g}/\text{m}^3$) and 1.49% to PM₁₀ (1.83 $\mu\text{g}/\text{m}^3$). In Khargone during Phase III, the contributions were 2.14% to PM_{2.5} (1.05 $\mu\text{g}/\text{m}^3$) and 1.51% to PM₁₀ (1.23 $\mu\text{g}/\text{m}^3$). On average, Category-3 cities had contributions of approximately 2.45% to PM_{2.5} (1.61 $\mu\text{g}/\text{m}^3$) and 1.97% to PM₁₀ (2.13 $\mu\text{g}/\text{m}^3$) from sulfate aerosols (SO_4) formed due to SO_2 emissions from TPPs.

Overall, the contribution of SO_2 emissions from coal-based TPPs to ambient sulfate aerosols in PM_{2.5} and PM₁₀ mass concentrations was highest in Category-2 cities, with an average contribution of 3.83% to PM_{2.5} (2.19 $\mu\text{g}/\text{m}^3$) and 2.87% to PM₁₀ (2.49 $\mu\text{g}/\text{m}^3$). Category-3 cities showed intermediate contributions, averaging 2.45% to PM_{2.5} (1.61 $\mu\text{g}/\text{m}^3$) and 1.97% to PM₁₀ (2.13 $\mu\text{g}/\text{m}^3$), while Category-1 cities had the lowest contributions, averaging 1.79% to PM_{2.5} (0.93 $\mu\text{g}/\text{m}^3$) and 1.04% to PM₁₀ (1.07 $\mu\text{g}/\text{m}^3$).

The range of contribution of sulfate aerosols (SO_4) formed due to SO_2 emissions from coal-based TPPs to ambient air PM_{2.5} and PM₁₀ mass concentrations across all cities and phases varied from 0.96% (0.44 $\mu\text{g}/\text{m}^3$) to 5.21% (3.30 $\mu\text{g}/\text{m}^3$) for PM_{2.5} and from 0.57% (0.49 $\mu\text{g}/\text{m}^3$) to 3.67% (3.60 $\mu\text{g}/\text{m}^3$) for PM₁₀. Thus, our study indicates that completely eliminating SO_2 emissions from TPPs would result in a maximum reduction in PM_{2.5} concentrations of up to 5.21% (3.30 $\mu\text{g}/\text{m}^3$) and PM₁₀ concentrations of up to 3.67% (3.60 $\mu\text{g}/\text{m}^3$) across all surveyed cities and seasons. Furthermore, installing FGD systems with an 87.5% SO_2 removal efficiency in all coal-based TPPs across India would lead to a maximum reduction in PM_{2.5} concentrations of up to 4.56% (2.89 $\mu\text{g}/\text{m}^3$) and PM₁₀ concentrations of up to 3.21% (3.15 $\mu\text{g}/\text{m}^3$) across all surveyed cities and seasons. This reveals that SO_2 emissions from TPPs contribute relatively little to ambient air PM_{2.5} and PM₁₀ mass concentrations in the cities and seasons surveyed in this study. Consequently, there would be only a marginal improvement (maximum of 5%) in particulate matter air quality even after eliminating all SO_2 emissions from TPPs. It should be noted that SO_2 , a colourless gas, does not directly reduce visibility but contributes to haze formation after being converted into sulfate particles. Therefore, eliminating SO_2 emissions from TPPs is likely to result in a modest improvement in visibility and a reduction in haze formation.

The combustion of coal in coal-fired thermal power plants, in addition to being a major source of carbon dioxide (CO_2) emissions, also results in the direct emission of primary particulate matter (PM) such as fly ash, black carbon (BC), and various heavy metals. Additionally, it emits several particulate matter precursors, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), from the stacks (chimneys) of the TPPs into the atmosphere. Together, these emissions contribute significantly to ambient air PM_{2.5} and PM₁₀ mass concentrations. However, eliminating only SO_2 emissions from TPPs using flue-gas desulfurization (FGD) technology, which can reduce SO_2 emissions by anywhere between 50% to 99%, is unlikely to result in a significant overall improvement in PM_{2.5} and PM₁₀ mass concentrations in the different category cities surveyed in this study. Our study shows that SO_2

emissions from TPPs, which convert to sulfate aerosols, are a minor contributor (maximum up to ~5%) to particulate matter levels in the various category cities considered in this survey. Thus, comprehensive emission control measures targeting all major pollutants and particulate matter precursors emitted from various sources, including TPPs, are necessary to achieve meaningful improvements in air quality.

CHAPTER-9: DISCUSSION ON THE CHANCES OF ACID RAIN AND NEED FOR QUANTIFYING THE LIFECYCLE COST AND BENEFITS OF FGD IMPLEMENTATION IN TPPS ACROSS INDIA

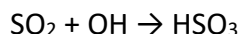
This chapter discusses the lifecycle of SO₂ in the atmosphere and the potential for acid rain in India. It argues for the urgent need to conduct a comprehensive life-cycle assessments of FGD technologies, including carbon capture systems, in the Indian context. The discussion emphasizes the crucial need for studying the lifecycle costs and benefits of FGD implementation in coal-based TPPs in India to truly understand their environmental impact and to ensure that our clean air goals do not conflict with our climate change mitigation targets. Additionally, the chapter also addresses the financial costs of FGD implementation in TPPs across India.

9.1 Lifecycle of SO₂ In The Atmosphere And Chances of Acid Rain In India

Once emitted into the atmosphere, SO₂ undergoes oxidation processes that converts it into sulfuric acid (H₂SO₄) or sulfate aerosols (SO₄²⁻). The oxidation of SO₂ occurs through both homogeneous (gas phase) and heterogeneous (aqueous phase) pathways. In the gas phase, SO₂ is oxidized primarily through reactions with hydroxyl radicals (OH) and other oxidants.

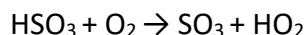
Homogeneous (Gas Phase) Oxidation: The key steps in the homogeneous oxidation pathway are as follows:

1. Reaction with Hydroxyl Radicals (OH):



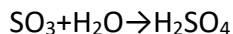
Here, sulfur dioxide (SO₂) reacts with the hydroxyl radical (OH) to form the HSO₃ radical.

2. Further Oxidation:



The HSO₃ radical further reacts with molecular oxygen (O₂) to form sulfur trioxide (SO₃) and the hydroperoxyl radical (HO₂).

3. Formation of Sulfuric Acid:

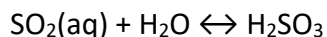
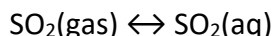


Next, Sulfur trioxide (SO₃) reacts rapidly with water vapor (H₂O) to form sulfuric acid (H₂SO₄).

These reactions primarily occur in the presence of sunlight, which is necessary for the formation of OH radicals through photolytic reactions. As H₂SO₄ is highly water soluble, gaseous H₂SO₄ rapidly dissolves into the aqueous phase of aerosol particles and cloud droplets.

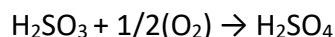
Heterogeneous (Aqueous Phase) Oxidation: In the aqueous phase, SO₂ dissolves in cloud droplets, rain, fog, or other water-containing particles and undergoes oxidation through several pathways. The key steps in the heterogeneous oxidation pathway are as follows:

1. Dissolution in Water:



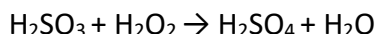
Sulfur dioxide (SO₂) gas dissolves in water to form sulfurous acid (H₂SO₃).

2. Oxidation by Dissolved Oxygen:



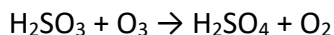
Sulfurous acid (H₂SO₃) is oxidized by dissolved molecular oxygen (O₂) to form sulfuric acid (H₂SO₄).

3. Oxidation by Hydrogen Peroxide (H₂O₂):



Hydrogen peroxide (H₂O₂) is a very efficient oxidizing agent that can oxidize sulfurous acid (H₂SO₃) to sulfuric acid (H₂SO₄).

4. Oxidation by Ozone (O₃):



Ozone (O₃) can also oxidize sulfurous acid (H₂SO₃) to sulfuric acid (H₂SO₄).

The efficiency of these oxidation processes is influenced by various factors, including pH, temperature, and the presence of catalysts such as transition metal ions (TMIs) like Fe(III) and Mn(II). It is noteworthy that the heterogeneous aqueous-phase oxidation of SO₂ is more significant than its gas-phase oxidation with OH. In fact, the reaction of SO₂ with H₂O₂ is its most important oxidation pathway. This heterogeneous oxidation occurs through the dissolution of SO₂ in water from clouds and fog, followed by reactions with other dissolved species, and can take place both day and night. The oxidation via the dissolved H₂O₂ pathway is significantly enhanced when ammonia (NH₃), the main alkaline gas in the atmosphere, dissolves in the reacting droplets and neutralizes the acidity. In environments with abundant ambient ammonia, such as across India, SO₂ is rapidly removed by cloud and fog droplets, ultimately forming ammonium sulfate [(NH₄)₂SO₄] aerosols. SO₂ is a colourless gas that does not directly reduce visibility but contributes to haze formation after being converted into sulfate particles.

SO₂ is also known to adhere to and then react on dust particles. For some mineral compositions, SO₂ uptake on dust particles is sensitive to relative humidity, the mineral composition of the particle, and the availability of H₂O₂, the relevant oxidant.

Atmospheric dust containing carbonate minerals, such as calcium carbonate (CaCO_3), magnesium carbonate (MgCO_3), and sodium carbonate (Na_2CO_3), plays a crucial role in neutralizing sulfuric acid (H_2SO_4) dissolved in fog, clouds, and raindrops. These minerals act as bases when they dissolve in water, forming inorganic salts like calcium sulfate (CaSO_4), magnesium sulfate (MgSO_4), and sodium sulfate (Na_2SO_4). Initially, these salts remain in the atmosphere as particulate matter (aerosols) and are eventually deposited on surfaces through dry deposition or washed out by precipitation. These neutralization reactions occur both in the gas phase and within cloud or raindrop water, reducing the concentration of free H_2SO_4 in the atmosphere and decreasing the acidity of rainwater.

Once SO_2 is oxidized to H_2SO_4 on particle surfaces, glyoxal, one of the most prevalent organic compounds in the atmosphere, adheres to these surfaces and reacts to form oligomers and organosulfate compounds. These processes are enhanced under high humidity conditions.

SO_2 , being heavier than dry air, is also removed from the atmosphere through dry deposition, especially on wet surfaces. Precipitation scavenging (wet deposition) offers another method for removing atmospheric SO_2 . Modeling studies indicate that slightly more than half of global atmospheric SO_2 is removed through gas- and aqueous-phase oxidation, while the remainder is scavenged through wet and dry deposition processes.

The lifetime of SO_2 in the atmosphere varies depending on several factors, including weather conditions, geographic location, and the presence of other chemicals. Typically, SO_2 has a lifetime ranging from a few hours to about two weeks in the troposphere before converting into sulfate aerosol particles (*von Glasow et al.* 2009). The atmospheric lifetime of SO_2 is typically a couple of days, but under certain conditions, such as low humidity or high wind speed, it can travel long distances (a few hundred km) and persist for longer periods. SO_2 is typically removed from the atmosphere through oxidation, forming sulfate aerosols (SO_4). This process can occur within a few hours to a few days, depending on the availability of oxidizing agents such as hydroxyl radicals (OH) and hydrogen peroxide (H_2O_2). As rainfall efficiently removes SO_2 from the atmosphere through wet deposition, regions with frequent rain can see the atmospheric lifetime of SO_2 reduced to less than a day due to this washout effect. In urban and industrial areas with higher concentrations of air pollutants, the presence of other chemicals and particulates also influence the rate at which SO_2 is removed from the atmosphere. In a recent study, Chen et al. (2024) estimated the mean chemical lifetime of SO_2 over the Indian region, finding it to range from 16 to 34 hours, with shorter values during the summer and longer values during the winter months. Overall, the atmospheric lifetime of SO_2 is typically short, ranging from a few hours to a few days, due to its rapid conversion to sulfate aerosols and removal through dry and wet deposition.

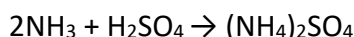
Chances of Acid Rain In India:

The natural pH of rainwater is slightly acidic, typically around 5.6, due to the presence of carbon dioxide (CO₂) in the atmosphere. When CO₂ dissolves in rainwater, it forms carbonic acid (H₂CO₃), a weak acid that slightly lowers the pH. This natural acidity is a normal part of the Earth's water cycle and is not harmful to the environment. However, this pH can be modified by the presence of acids (such as H₂SO₄, HNO₃, and RCOOH) and bases (such as NH₃ and CaCO₃) in the atmosphere. When all these influences are considered, the pH of natural rain typically ranges from 5 to 7. The term "acid rain" refers to precipitation with a pH below 5. Such low pH values generally occur only when the atmosphere contains large amounts of acidic substances from anthropogenic emissions and air pollution.

Overall, the acidity of precipitation is regulated by neutralization reactions with alkaline species, such as soil dust rich in carbonates, and dissolved gases like ammonia (NH₃) emitted from agricultural activities, including fertilizer use and livestock.

The neutralization of precipitation acidity by ammonia (NH₃) is a critical process in maintaining the pH balance of rainwater, especially in regions with significant agricultural activities. Ammonia is predominantly released into the atmosphere from sources such as fertilizer application, animal waste from livestock, and natural soil emissions. When NH₃ is present in the atmosphere, it can readily dissolve in cloud water and react with acidic compounds like sulfuric acid (H₂SO₄) and nitric acid (HNO₃). These acids are commonly produced from the oxidation of sulfur dioxide (SO₂) and nitrogen oxides (NO_x) emitted from industrial processes, vehicle exhaust, and other anthropogenic sources.

The reaction between NH₃ and these acids results in the formation of neutral salts, such as ammonium sulfate ((NH₄)₂SO₄) and ammonium nitrate (NH₄NO₃). These salts effectively neutralize the acidic content of precipitation. For instance, when ammonia reacts with sulfuric acid, the following reaction occurs:



This process substantially lowers the acidity of raindrops, bringing their pH closer to neutral. The neutralization by NH₃ is especially effective in agricultural areas where ammonia emissions are high due to extensive fertilizer use and livestock operations. This neutralization mechanism naturally helps to mitigate the environmental impacts of acid rain. By neutralizing acidic components in precipitation, ammonia plays a crucial role in protecting various ecosystems and infrastructure from acidification.

Van Damme et al. (2018) analysed ten years of daily IASI satellite observations to create a high-resolution map of atmospheric ammonia across the globe. Their goal was to identify, categorize, and quantify the world's ammonia emission hotspots. They reported that the Indo-Gangetic Plain

(IGP) is a major source of NH_3 , with the highest concentration of NH_3 column burden in the world found in this region.

Besides NH_3 , dust containing carbonate minerals such as calcium carbonate (CaCO_3), magnesium carbonate (MgCO_3), and sodium carbonate (Na_2CO_3) can significantly reduce the likelihood of acid rain. These carbonate minerals can neutralize sulfuric acid (H_2SO_4) dissolved in rainwater through various chemical processes. Here, we discuss the neutralization of sulfuric acid by calcium carbonate. Calcium carbonate (CaCO_3) is a basic (alkaline) compound that can neutralize acids through the following chemical reaction:



In this reaction, calcium carbonate (CaCO_3) reacts with sulfuric acid (H_2SO_4) to form calcium sulfate (CaSO_4), carbon dioxide (CO_2), and water (H_2O). This neutralization process reduces the acidity of rainwater. The resulting calcium sulfate (CaSO_4) can either remain as particulate matter or get washed out by precipitation. This reaction can occur both in the gas phase and in cloud or raindrop water, reducing the concentration of free H_2SO_4 in the atmosphere and thereby decreasing the acidity of rain. Dust particles containing CaCO_3 can also settle on surfaces and directly neutralize acidic compounds present on those surfaces, preventing them from being washed into waterways. During rainfall, CaCO_3 particles can be incorporated into raindrops. As rainwater containing H_2SO_4 comes into contact with these particles, the neutralization reaction occurs within the raindrop, leading to neutral pH precipitation. Thus the presence of CaCO_3 -rich dust inhibits the formation of acid rain by neutralizing acidic species in the atmosphere before they can dissolve in rainwater. This process effectively reduces the potential for acid rain formation. Even if H_2SO_4 has already dissolved in rainwater, the presence of CaCO_3 can buffer the pH of the water, preventing it from becoming acidic. This buffering capacity is crucial in regions with high levels of atmospheric dust containing CaCO_3 . Thus, the abundance of dust containing calcium carbonate (CaCO_3) plays a crucial role in mitigating the formation and impact of acid rain. By neutralizing sulfuric acid (H_2SO_4) in the atmosphere and rainwater, CaCO_3 reduces the acidity of precipitation and protects ecosystems. This natural buffering process is very effective in regions with high dust levels, contributing to a more balanced and neutral environment.

Due to the high soil dust content rich in carbonate minerals like calcium carbonate (CaCO_3) and the abundance of ammonia (NH_3) in the ambient air across India, both of which are alkaline, acid rain is not a serious issue in most parts of the country, except for southern peninsular India where the concentrations of alkaline substances like ammonia and carbonate-rich dust in the air are relatively low. However, frequent dilution caused by the sea breeze naturally keeps ambient SO_2 levels lower in coastal areas of peninsular India. Additionally, the inherent alkalinity of seawater droplets, due to the presence of bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}), effectively neutralizes sulfuric acid (H_2SO_4) in the atmosphere over coastal areas (Hedin and Likens, 1996; Kulshrestha et al., 2005; Shukla et al., 2010; Lee and Chen, 2011; Sharma et al., 2023).

9.2 Need For Quantifying The Lifecycle Cost And Benefits of FGD Implementation in TPPs in India

While there is no doubt that FGD implementation will significantly reduce SO₂ emissions from TPPs, there are, to the best of our knowledge, no credible studies that have quantified the overall life-cycle cost and benefits of FGD implementation in coal-based TPPs, especially in the Indian context. Based on the most prevalent FGD technologies available today, it is certain that CO₂ emissions will increase and there will be additional water consumption with FGD implementation in these TPPs. Primary reason for this increase in CO₂ emissions with the implementation of FGD in a coal based TPPs is that for every molecule of SO₂ captured by the FGD, a molecule of CO₂ will be released into the atmosphere for all kinds of FGD technologies. Other reasons for extra emission of CO₂ with the implementation of FGD are due to activities linked with the functioning of these FGD units. Additionally, it is well known that sulfate aerosols are highly efficient at blocking solar radiation from reaching the Earth's surface, partially offsetting the global warming caused by greenhouse gases like CO₂. However, there are no credible studies on the impacts of a sudden reduction in SO₂ emissions combined with simultaneous increases in CO₂ emissions on India's regional climate, including the Indian monsoon system, extreme weather events such as floods and droughts, and surface ozone levels. Therefore, it is crucial to quantify the long-term environmental and climate change impacts of FGD implementation in India to ensure that our clean air goals do not conflict with our climate change mitigation targets. Additionally, the increased warming due to reduced SO₂ emissions and increased CO₂ emissions is likely to exacerbate the adverse impacts of heat stress on human health, which also needs to be quantified.

Quantifying the overall life-cycle costs and benefits of FGD implementation in coal-based TPPs across India comprehensively is beyond the scope of our present study. Nevertheless, we present a discussion based on simple calculations that quantify the immediate reduction in SO₂ emissions and the likely increase in CO₂ emissions with the implementation of FGD in coal-based TPPs across India (excluding long-term impacts).

Figure 9.1 presents a comparison of total annual SO₂ emissions from India according to three different emission inventories: SMOG-India-v2 (2019) (Venkatraman et al., 2020), EDGAR-v5 (2015), and EDGAR-v6.1 (2018) (Crippa et al., 2022). The top panel shows that the total annual SO₂ emissions from India are 7.85 MT/year for SMOG-India-v2, 9.96 MT/year for EDGAR-v5, and 10.60 MT/year for EDGAR-v6.1. The bottom three panels detail the contributions of various emission sectors to the total annual SO₂ emissions for each inventory. In terms of the energy sector (primarily coal-based TPPs), SMOG-India-v2 reports 4.31 MT/year, which is 54.9% of the total emissions. EDGAR-v5 lists 5.85 MT/year from the energy sector, contributing 58.7% of the

total, while EDGAR-v6.1 indicates 6.51 MT/year from the energy sector, accounting for 61.4% of the total emissions. For the industrial sector, SMOG-v2 records 3.24 MT/year, which is 41.3% of the total SO₂ emissions. EDGAR-v5 reports 3.13 MT/year from the industrial sector, contributing 31.4% of the total, and EDGAR-v6.1 shows 3.18 MT/year from the industrial sector, making up 30% of the total emissions. In summary, the energy sector's contribution to total SO₂ emissions ranges from 54.9% to 61.4%, with absolute emissions between 4.31 MT/year and 6.51 MT/year across the inventories. The industrial sector contributes between 30% and 41.3%, with absolute emissions ranging from 3.13 MT/year to 3.24 MT/year.

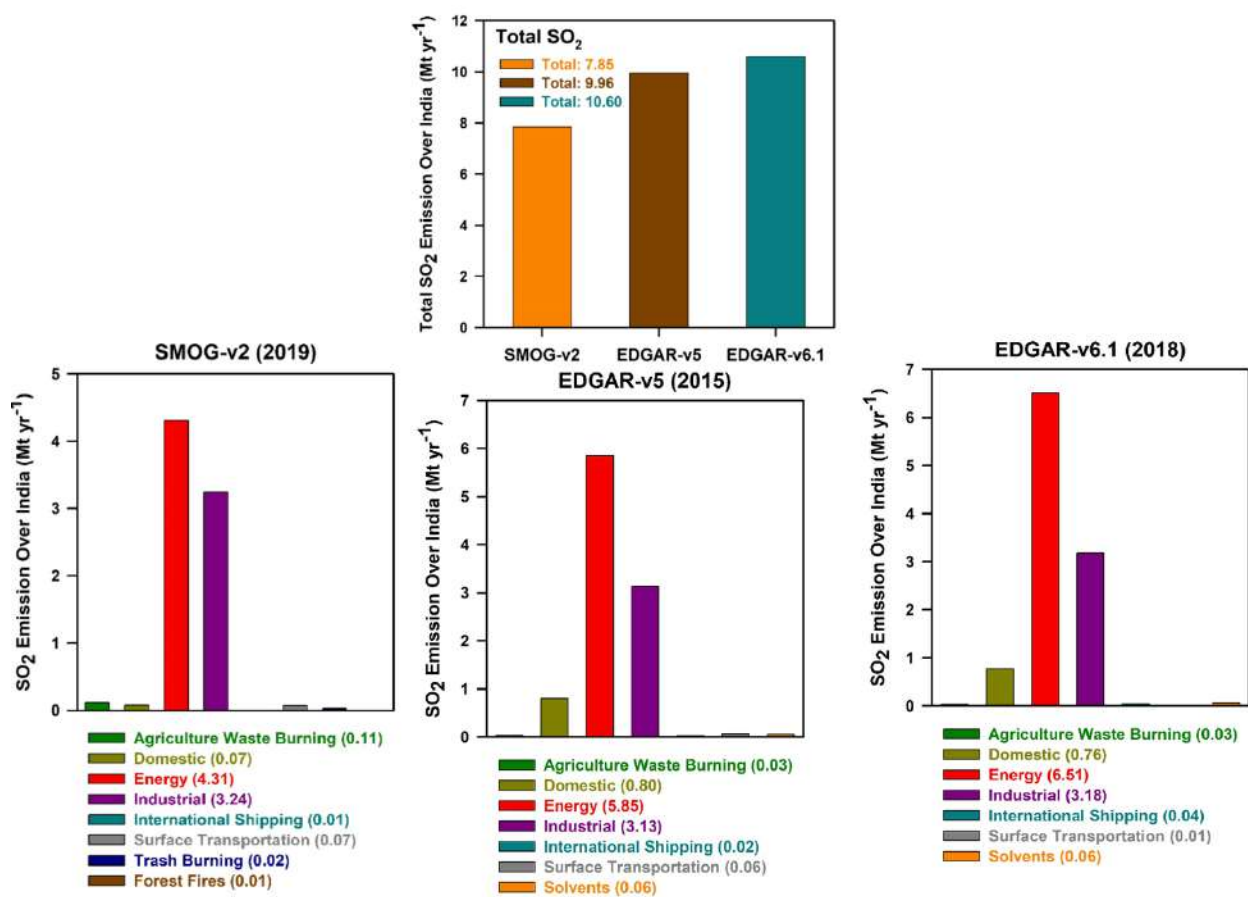


Figure 9.1: Comparison of total annual emission (MT per year) of SO₂ from India as per three different emission inventories namely, SMOG-India-v2 (2019), EDGAR-v5 (2015) & EDGAR-v6.1 (2018). Contribution of SO₂ emissions from various sectors are also shown.

The SO₂ removal efficiency of FGD systems generally ranges from 60% to 95%, depending on various factors such as mandatory compliance requirements based on the age of the TPP and FGD technology. Installing FGD systems with 87.5% SO₂ removal efficiency in all coal-based TPPs across India is expected to reduce total annual SO₂ emissions by 48.0% to 53.8%. In absolute

terms, this would mean a decrease in total annual SO₂ emissions between 3.77 MT/year and 5.70 MT/year.

Calculation of increase in CO₂ emissions with the implementation of FGD in coal-based TPPs across India (excluding long-term impacts):

We start our estimation by first calculating the total CO₂ emissions from a 600 MW Coal-Based TPP Unit with and without FGD installed in it. We do this calculation with following assumptions:

- Plant Load Factor (PLF): 60%
- Gross Calorific Value (GCV) of coal: 3800 Kcal/kg
- Fuel Emission Factor: 92.5 kg CO₂/GJ (as per Eggleston et al. 2006)
- Oxidation Factor: 0.98 (as per Eggleston et al. 2006)
- Carbon Content in Coal: 40%
- Transportation Distances:
 - Coal: 1000 km (by Rail)
 - Limestone: 500 km (by Road)
 - Gypsum: 200 km (by Road)
- Vehicle Load Capacity: 30 tons per trip
- Fuel Efficiency: 3.29 km per litre of diesel
- CO₂ Emission Factor for Diesel: 2.68 kg CO₂ per litre of diesel (as per Eggleston et al. 2006)
- CO₂ emissions in mining: 45.95 Kg CO₂ per Ton (as per CMPDI, Coal India Limited)
- FGD Efficiency: 87.5%

CO₂ emissions from the TPP will result from (i) the combustion of coal, (ii) chemical reactions during desulfurization using limestone, (iii) mining of coal and limestone, (iv) transportation of coal, limestone, and gypsum, and (v) auxiliary power consumption (APC) for operating the FGD system. Let's calculate the CO₂ emissions from each of these factors one by one.

First we calculate the total CO₂ emissions per day from this TPP operating without FGD

CO₂ emission due to combustion of coal:

Total energy generated by the TPP in one day = 600 MW x 24 hours x 0.60 x 1000 = 8640000 kWh
Assuming the specific coal consumption in TPPs across India to be 0.626315789 kg/KWh (source: CEA Coal Report) and all other assumptions mention earlier, it is possible to calculate the total coal consumption in the given TPP as approximately 5411.37 Tons/day.

Assuming carbon content in coal as 40%, total carbon in 5411.37 Ton of coal = $0.40 \times 5411.37 \text{ Tons} = 2164.55 \text{ tons of carbon}$

As the molecular weight of CO₂ is 44 g/mole, 1 Ton of carbon will produce 3.67 tons of CO₂.

Hence, CO₂ emitted from coal combustion = 2164.55 Tons of carbon × 3.67 = 7943.9 Tons of CO₂ per day.

Assuming oxidation factor of carbon as 0.98 (that means 98% of carbon coal is oxidized to CO₂) during TPP operation, actual CO₂ emitted from coal combustion = 7943.9 × 0.98 = 7785 Tons of CO₂ per day.

Alternatively, as per the method suggested by Eggleston et al. (2006), CO₂ Emissions = (5411.37 Tons/day × 3800 Kcal/kg × 4.184 J/cal × 92.5 kg CO₂/GJ × 0.98) / (1000 kg/Ton × 1000 kJ/GJ) = 7799.2 Tons CO₂ per day

We consider 7799 tons of CO₂ emissions per day from coal combustion for further analysis.

CO₂ emissions due to Coal Mining

CO₂ emissions due to Coal Mining = 5411.37 tons/day × 45.95 kg CO₂/Ton = 248.65 Tons of CO₂/day

CO₂ emissions due to Coal Transportation

We assume that coal is transported from the mines to the TPP through railway.

CO₂ emission due to Coal Transportation = 5411.37 Ton/day × 1000 km × 0.00996 = 53.9 Tons/day

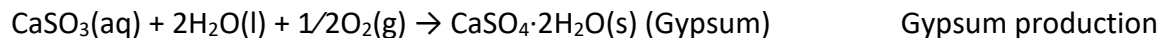
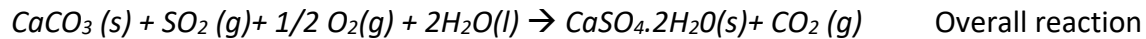
(We used the emission factor for freight transport mentioned on Indian railway website as 0.00996 kg CO₂/Ton-km.)

Thus total CO₂ Emissions due to operation of the TPP without FGD
= 7799 + 248.65 + 53.9 Tons per day
= 8101.55 Tons CO₂ per day

Now we calculate the extra CO₂ emissions per day from this TPP when Flue Gas Desulfurization (FGD) is implemented in the power plant.

CO₂ emissions due to chemical reactions during desulfurization using limestone:

Chemical reactions of desulfurization using limestone FGD is as follows:



While the overall chemical reaction remains consistent across all limestone-based FGD systems, the intermediate reactions and their sequence may vary depending on the specific FGD technology employed. This, in turn, influences the auxiliary power consumption and the by-products generated by the system. Nonetheless, regardless of the FGD technology used, each SO₂ molecule captured by FGD systems results in the release of a CO₂ molecule, and the operation of these systems also contributes to CO₂ emissions.

64 grams of SO₂ generates 44 grams of CO₂.

First determine the amount of sulfur in the coal assuming sulfur content in coal as 0.4%.

Amount of sulfur in coal = 5411.37 Ton × 0.004 = 21.65 Ton

As molecular weight of sulfur (S) is 32 g/mol, and the molecular weight of SO₂ is 64 g/mol. Therefore, 1 Ton of sulfur produces 2 Tons of SO₂.

Hence, 21.65 Ton of sulfur will produce 43.3 Tons of SO₂ per day

Amount of SO₂ that will be removed by the FGD = 43.3 Tons × 0.875 = 37.89 Tons per day

1 mole SO₂ produces 1 mole of CO₂

Therefore, 37.89 Ton SO₂ produces = 37.89 × 44/64 = 26.05 Tons of CO₂ per day

Limestone required and Gypsum Production due to FGD operation:

Limestone (CaCO₃) consumption for FGD operation = 37.89 × 100/64 = 59.2 Tons per day

Gypsum produced = 37.89 × 172/64 = 101.83 Tons per day

Thus, CO₂ emitted during desulfurization using limestone = 26.05 Tons per day

CO₂ emissions due to mining activities:

Limestone Mining Emissions: CO₂ from Limestone Mining = 59.2 Tons/day × 0.05 Tons CO₂/Ton
= 2.96 Tons of CO₂ per day

CO₂ emissions due to transportation of limestone, and gypsum:

Limestone Transportation: Number of Trips (Limestone)= 59.2 tons/30 tons/trip=2 trips/day

Gypsum Transportation: Number of Trips (Gypsum)= 101.83 tons/30 tons/trip=4 trips/day

Calculate the Total Distance Travelled

Total Distance (Limestone)=2 trips/day×500 km/trip=1000 km/day

Total Distance (Gypsum)=4 trips/day×200 km/trip=800 km/day

Calculate the Total Diesel Consumption

Diesel Consumption (Limestone)=1000 km/day/3.29 km/liter=304 liters/day

Diesel Consumption (Gypsum)=800 km/day/3.29 km/liter=243 liters/day

Calculate CO₂ Emissions from Diesel Consumption

CO₂ Emission Factor for Diesel used for GHG calculations in India =2.68 kg CO₂/liter

CO₂ from Diesel (Limestone)=304 ltrs/day×2.68 kg CO₂/liter=814.72 kg CO₂/day=0.815 tons CO₂/day

CO₂ from Diesel (Gypsum)=243 liters/day×2.68 kg CO₂/liter=651.24 kg CO₂/day=0.65 tons CO₂ per day

Thus total CO₂ Emissions from Transportation of limestone and gypsum:

CO₂ from Transportation of limestone and gypsum =0.815 +0.65 = 1.465 CO₂ Tons per day

CO₂ emissions due to auxiliary power consumption (APC):

When Flue Gas Desulfurization (FGD) is implemented, it typically increases the auxiliary power consumption (APC) of the plant. We assume a 1% increase in APC due to FGD and calculate the additional CO₂ emissions.

Extra CO₂ emitted due to increase in APC (1%) = 1 % of 8101.55 = 81.02 Tons CO₂ per day

Addition of CO₂ Emissions Due to 1% extra lime stone consumption due to Increased Auxiliary Power Consumption (APC) = 1% of 26.05 Tons per day = 0.26 Tons per day

Thus Total CO₂ Emissions in the TPP with FGD = 8101.55 + 26.05 + 2.96 + 1.465 + 81.02 + 0.26
Tons per day

$$= 8213.3 \text{ Tons CO}_2/\text{day}$$

Hence, the total CO₂ emissions from a 600 MW coal-based TPP unit operating at 60% PLF and having an operational FGD working (with 87.5% efficiency), considering all sources including combustion, limestone use, mining activities, transportation, and an increased APC due to FGD, is approximately 8213 Tons of CO₂ per day.

This means that with the implementation of an FGD system, CO₂ emissions from this 600 MW coal-based TPP will increase by approximately 1.38%. In absolute terms, this translates to an additional emission of 111.8 Tons of CO₂ per day from the 600 MW coal-based TPP.

According to the Central Electricity Authority (CEA), the total power generated from coal-based TPPs across India, based on the total installed capacity as of May 31, 2023, is approximately 211.86 GW. Assuming all coal-based TPPs across India operate under the same conditions as the above 600 MW TPP unit, the total CO₂ emissions from all TPPs in India without FGD installation would be approximately 2.86 million tons (MT) of CO₂ per day. This equates to 1044.14 MT of CO₂ per year.

Thus, installing FGD systems with 87.5% SO₂ removal efficiency in all coal-based TPPs across India is expected to reduce total annual SO₂ emissions by 4.88 MT per year but this will also result in an additional 14.4 MT of CO₂ emissions per year immediately.

However, it is important to emphasize here that the above calculation only accounts for the immediate and direct additional CO₂ emissions (~1.38%) expected in coal-based thermal power plants (TPPs) due to the implementation of flue gas desulfurization (FGD) systems. Several previous studies have demonstrated that the total environmental impact, including the overall increase in CO₂ emissions resulting from FGD implementation, is likely to be significantly higher when considering the life cycle assessment (LCA) of such air pollution control technologies in coal-based TPPs (Xu et al., 2010; Feng et al., 2014; Shi et al., 2017; Fort and Cerny, 2018; Xiong et al., 2020; Phungrassami and Usubharatana, 2021; Kim et al., 2021; Zhang et al., 2024). LCA is an internationally standardized methodology used to systematically and scientifically assess the environmental impacts associated with all stages of a product's life cycle, from inception to disposal. A comprehensive LCA of FGD systems should consider not only the immediate and direct increases in CO₂ emissions from TPPs but also the long-term environmental impacts, including secondary pollutant generation, wastewater production, freshwater depletion, land-use and land-cover changes, deforestation, changes in ecotoxicity, impacts on surface ozone, and

alterations in weather and climate. These impacts should be quantified in terms of additional equivalent CO₂ emissions resulting from FGD implementation (Xu et al., 2010).

We argue that the LCA and Life Cycle Costing (LCC) of FGD implementation in coal-based TPPs across India, along with the estimation of additional equivalent CO₂ emissions—considering various long-term environmental impacts—must be region-specific and dependent on the particular FGD technology adopted in each TPP (Feng et al., 2014; Fort and Cerny, 2018; Kim et al., 2021; Zhang et al., 2024). Given that conducting a comprehensive LCA and LCC analysis of FGD implementation across all coal-based TPPs in India is beyond the scope of our current study, we focus on summarizing key findings from previous research and identifying critical areas that warrant further investigation in subsequent studies.

Kim et al. (2021) estimated that the removal of 1 kg of SO₂ using conventional wet limestone scrubbing FGD and carbonate melt FGD (CMFGD) techniques results in approximately 177.3 kg and 32.14 kg of additional equivalent CO₂ emissions, respectively. Furthermore, Kim et al. (2021) estimated that removing 1 kg of SO₂ using conventional wet limestone scrubbing FGD requires an additional 67.79 litres of freshwater. These estimates are based on a life cycle assessment (LCA) that considers both the immediate CO₂ increase and the long-term environmental impacts of 18 different factors, including freshwater depletion, land-use changes, deforestation, ecotoxicity, impacts on ozone, weather, and climate change.

Phungrassami and Usubharatana (2021) conducted an environmental problem-shifting analysis of various air pollution control technologies used in coal-fired TPPs based on LCA methodology. Their findings indicate that while FGD implementation may effectively reduce SO₂ emissions, it ultimately results in greater adverse environmental impacts due to the increased energy demands associated with the construction, operation, and maintenance of FGD systems. This is true even when carbon capture and storage (CCS) technology is employed alongside FGD, as it leads to higher overall CO₂ emissions, human toxicity, and terrestrial acidification effects. Phungrassami and Usubharatana (2021) estimated that for every kilogram of SO₂ emission reduction achieved by wet limestone-gypsum-based FGD systems, an additional 4.64 kg of CO₂ is emitted, and a significant 60–80 tons per hour of water is consumed for a 600 MW TPP, which also reduces the overall boiler efficiency of the TPP. Their study underscores the necessity of conducting a thorough LCA and LCC study to minimize environmental trade-offs associated with the implementation of air pollution control technologies such as FGD systems.

Shi et al. (2017) demonstrated that wet limestone-based FGD systems, which dominate the market share in China, significantly increase fly ash emissions that contribute to haze and generate secondary gypsum particles, which are primarily less than 2.5 µm in size. Additionally, Shi et al. (2017) found that these systems emit substantial amounts of extra CO₂ and consume

considerable energy, raw materials, and water resources. Their study further estimated that for every ton of SO₂ emission reduction achieved by wet limestone-gypsum-based FGD systems, an additional 4.13 tons of CO₂ is emitted, and approximately 16.79 tons of freshwater is consumed.

In another study, Cordoba (2015) showed that in conventional wet limestone based FGD systems, limestone is usually used after being pulverized to an average size of 5–20 µm, which consumes significant amount of extra energy. Furthermore, in circulating fluidized bed flue gas desulfurization (CFB-FGD) systems, quicklime is typically made by the thermal decomposition of limestone in a lime kiln. This process requires heating the material above 825°C, called calcination or lime-burning, to release CO₂ and produce quicklime.

Feng et al. (2014) highlighted that the production of FGD system manufacturing materials (such as various categories of steel, aluminium, cement, etc.), transport of raw materials required for FGD system manufacturing, manufacturing of the FGD system itself, transport of the FGD system to the TPP site, production of desulfurizer, quarrying of limestone, and FGD system operation and maintenance must all be considered as part of the LCA and LCC analysis when quantifying the total environmental impact, including the overall increase in CO₂ emissions resulting from FGD implementation in coal-based TPPs. For example, Feng et al. (2014) estimated that manufacturing a wet limestone FGD system for a 2x300 MW coal-fired TPP in China requires approximately 1761 tons of steel as well as various other resources. Feng et al. (2014) further compared the estimates of atmospheric emissions and resource consumption based on the LCA of two different FGD technologies for a 2x300 MW coal-fired TPP in China. According to their estimates, the LCA of a CFB-FGD and a conventional wet limestone-based FGD system for a 2x300 MW coal-fired TPP in China results in an extra 111,815 and 82,402 Tons of equivalent CO₂ emissions per year, respectively (considering 7,000 hours of annual operating time of the FGD systems), in addition to the immediate and direct additional CO₂ emissions due to SO₂ emission scrubbing by limestone. Furthermore, Feng et al. (2014) estimated that the operation of a CFB-FGD and a conventional wet limestone-based FGD system for a 2x300 MW coal-fired TPP in China requires 453 and 630 million litres of freshwater per year.

While there is considerable variability and significant uncertainty in the estimates of additional CO₂ emissions due to FGD implementation, previous studies consistently indicate that the overall increase in CO₂ emissions, beyond the immediate impact, and the associated freshwater consumption are likely to be significantly higher when considering the life cycle assessment (LCA) of FGD implementation in coal-based thermal power plants. These studies highlight the critical need to comprehensively assess both the immediate and long-term environmental impacts, including the estimation of additional equivalent CO₂ emissions, associated with FGD implementation. This underscores the importance of conducting thorough LCA and LCC analyses

to fully understand and mitigate potential adverse outcomes, while minimizing the environmental trade-offs involved in deploying FGD systems across all coal-based TPPs in India.

The implementation of carbon capture technologies in thermal power plants (TPPs) is essential to mitigate the CO₂ emissions generated by these facilities. As coal-based TPPs are significant contributors to global greenhouse gas emissions, incorporating carbon capture can help reduce their environmental impact. These technologies can capture a substantial portion of the CO₂ produced during combustion, preventing it from entering the atmosphere. By integrating carbon capture systems, we can lower the carbon footprint of TPPs, contributing to climate change mitigation efforts and supporting cleaner energy production. This approach is crucial for balancing the need for reliable energy with the urgent need to reduce greenhouse gas emissions.

It's worth noting in this discussion that sulfur dioxide (SO₂) and carbon dioxide (CO₂) have significantly different atmospheric lifetimes, which carries important implications for climate policy. SO₂ has a short atmospheric lifetime, ranging from several hours to a maximum of about 15 days. This means that any SO₂ molecule emitted is likely to be removed from the atmosphere within roughly two weeks. In contrast, CO₂ has a much longer atmospheric lifetime, persisting for over 100 years. This means that any CO₂ molecule emitted can remain in the atmosphere for about a century.

A recent article (Pearse, 2024) published by the Yale School of the Environment highlights how cleaning up air pollution, while beneficial for public health, can significantly contribute to global warming. Another study by Wang et al. (2024) attributes the recent extraordinary heating over the Northeast Pacific region to a dramatic reduction in Chinese air pollution, which coincided with the installation of FGD systems in coal-based TPPs. Both studies explain that reducing sulfate aerosols, which reflect sunlight and cool the atmosphere, has led to more heat waves, such as the "Blob" in the Pacific Ocean. This phenomenon underscores the complex relationship between air quality improvements and climate change, suggesting that decreased aerosol emissions may exacerbate warming and demands more research in this direction. These findings highlight the need for balanced strategies to address both air quality and climate goals. India should heed the lessons from China's experience, as the idea that cleaning up air pollution can worsen atmospheric warming may seem counterintuitive, but it is a real and ongoing issue.

In another recent study, Gao et al. (2022) propose that reducing sources of atmospheric oxidants could be a promising approach for sustainably mitigating secondary sulfate aerosols. They advocate for an oxidant control strategy, adjusted seasonally or during pollution episodes, targeting dominant oxidants specific to those periods. However, further research is needed to confirm the feasibility of this oxidant control approach in reducing secondary pollutants like sulfate aerosols in the Indian atmosphere.

While SO₂ is a significant air pollutant and its emissions should be reduced, the trade-off between reducing SO₂ and increasing CO₂ emissions must be carefully considered. If reducing a relatively smaller amount of SO₂ emissions comes at the cost of a larger increase in CO₂ emissions, it raises serious concerns. This scenario necessitates a broader debate among stakeholders to ensure that efforts to improve air quality do not inadvertently strain valuable water resources, exacerbate global warming, and impact the Earth's climate system, particularly the regional weather and climate of India.

When deciding on the installation of FGD systems in coal-based TPPs across India, it is crucial to consider both health and climate impacts. While reducing sulfate aerosols from sulfur dioxide (SO₂) emissions can lower respiratory and chronic diseases, providing clear health benefits, these aerosols also have a cooling effect by reflecting sunlight. Their reduction could lead to unintended climate consequences, such as accelerated warming, which could increase heat stress and potentially cause more severe health impacts than those from chronic exposure to sulfate aerosols. For instance, in 2022, Europe experienced significant mortality from extreme heat, with 60,000 deaths (Ballester et al., 2023; Choudhary et al., 2023). Schumacher et al. (2024) demonstrated that many climate models failed to capture the exacerbated summer warming in Europe, primarily due to their neglect of long-term aerosol changes, particularly the regional brightening and associated warming caused by global sulfate aerosol reductions. Additionally, removing reflecting aerosols could negatively impact agricultural productivity and food security due to higher temperatures and altered precipitation patterns (Mbow et al., 2019). Therefore, comprehensive studies are necessary to fully understand these impacts and guide policymakers in preparing for potential extreme weather conditions that could increase heat stress on humans, plants, and animals, affect food production, and increase electricity demand due to the installation of FGD systems in all coal-based TPPs in India. This underscores the need for balanced strategies that address both air quality improvements and climate change mitigation to avoid unintended consequences such as increased heat stress and its associated health impacts.

9.3 Cost of FGD Implementation In TPPs Across India

To assess the indigenous FGD manufacturing capacity within India, we reached out to various private and public sector companies, including international firms operating in India. This survey was conducted almost two years ago, during March-April 2022. We requested information regarding FGD technologies, sources of raw materials used in FGD manufacturing, costs of FGD systems, and the timeframe for manufacturing FGD units. Ganguly and Dey (2022) provides complete details of this survey.

Based on our survey conducted more than two years ago and discussions with the CEA, considering subsequent price escalations due to inflation, it is reasonable to assume that the current cost of FGD systems is approximately Rs. 1.20 Crore per MW. The total installed capacity of coal-based TPPs across India as of May 31, 2023, is approximately 211.86 GW or 211,860 MW. Therefore, the total cost of installing FGD systems in all coal-based TPPs across India would be approximately Rs. 2,54,232 Crore. This cost estimate is only for the initial installation and does not include running and maintenance costs, which will directly impact the current electricity unit price in India. Furthermore, the actual installation costs are likely to increase if carbon capture technologies are mandated along with FGD systems. Hence, we strongly recommend conducting a follow-up study to comprehensively assess the overall life-cycle costs (LCC) and benefits of implementing FGD in coal-based TPPs across India for various available FGD technologies, including an assessment of the cost impact on the current electricity unit price in India, as well as the operating and maintenance expenses of these systems.

Once a comprehensive LCA and LCC assessment and evaluation of the benefits of installing FGD systems in all coal-based TPPs across the country are completed, it is essential to initiate a broader debate among stakeholders. This discussion should address whether it is prudent to invest heavily in these non-sustainable, CO₂-emitting energy sources or whether it would be more beneficial to redirect these funds toward the rapid expansion of renewable energy sources such as solar and wind power. Furthermore, there is an urgent need to aggressively phase out coal-based thermal power plants, particularly the older and less efficient ones, to ensure a more sustainable and environmentally friendly energy future. Installing FGD systems to reduce air pollution should not serve as a smokescreen to justify continuing power generation from these environmentally harmful, CO₂-intensive sources. Instead, the focus should be on transitioning to cleaner energy alternatives that offer long-term benefits for the environment and public health. This strategy would mitigate the adverse effects of air pollution and climate change and promote energy security and sustainability for future generations.

CHAPTER-10: CONCLUSIONS AND RECOMENDATIONS

A comprehensive measurement-based survey of ambient air SO₂ concentrations was conducted across three different city categories during three distinct survey periods: Phase I (pre-monsoon season, February to May 2023), Phase II (summer monsoon season, July to August 2023), and Phase III (winter season, November 2023 to February 2024). The survey was conducted in 10 cities, categorized as follows: Category 1 - Cities with no coal-based TPP; Category 2 - Cities with a coal-based TPP without FGD installed, located within 10 km from the city boundary; and Category 3 - Cities with a coal-based TPP with FGD installed, also located within 10 km from the city boundary. In Category 1, the survey was conducted in three cities: New Delhi and Hyderabad during Phase I (pre-monsoon season), and Lucknow during Phase II (summer monsoon season). For Category 2, the survey included four cities: Kolkata and Nagpur during Phase I (pre-monsoon season), Kota during both Phase II (summer monsoon season) and Phase III (winter season), and Shahdol during Phase III (winter season). In Category 3, the survey was conducted in three cities: Ghaziabad and Gautam Buddha Nagar during Phase I (pre-monsoon season), Gautam Buddha Nagar again during Phase II (summer monsoon season) and Phase III (winter season), and Khargone during Phase III (winter season).

Major findings of this survey are listed below:

- The daily mean ambient air SO₂ concentrations in Category 1 cities ranged from 2.48 to 9.26 µg/m³. In Category 1 cities, New Delhi recorded the highest maximum instantaneous SO₂ concentration of 29.37 µg/m³ during Phase I (pre-monsoon season). The lowest minimum instantaneous SO₂ concentration in Category 1 cities was 0.83 µg/m³, also in New Delhi during Phase I.
- The daily mean ambient air SO₂ values in Category 2 cities ranged from 3.12 to 11.23 µg/m³. Among these cities, Kota exhibited the highest maximum instantaneous SO₂ concentration of 48.56 µg/m³ under normal conditions, with values peaking at 68.09 µg/m³ during festival days in Phase III (winter season). The lowest minimum instantaneous SO₂ concentration in Category 2 cities was 0.75 µg/m³, recorded in Kota during Phase II (summer monsoon season).
- The daily mean SO₂ concentrations in Category 3 cities ranged from 4.24 to 12.51 µg/m³. In Category 3 cities, Gautam Buddha Nagar had the highest maximum instantaneous SO₂ concentration of 36.41 µg/m³ under normal conditions, with values peaking at 70.14 µg/m³ during festival days in Phase III (winter season). The lowest minimum instantaneous SO₂ concentration in Category 3 cities was 0.54 µg/m³, also observed in Gautam Buddha Nagar during Phase III.
- **Compliance with NAAQS:** Ambient air SO₂ levels across all city categories and phases remained well within the National Ambient Air Quality Standards (NAAQS) of 80 µg/m³, which is the maximum permissible limit for 24-hour average measurements as notified by the

MoEF&CC, Government of India. Even the instantaneous maximum values never exceeded this daily mean standard limit.

- **Spatial Variability and Impact of Proximity to TPPs:** Measurement sites downwind of TPPs exhibited higher ambient air SO₂ concentrations than upwind sites, and SO₂ levels decreased with increasing distance from TPPs in Category-2 and Category-3 cities. Proximity to thermal power plants significantly affected ambient air SO₂ concentrations, with locations closer to TPPs showing higher values.
- **Variability in ambient air SO₂ concentrations:** Significant diurnal variations and intra-day fluctuations were observed in ambient air SO₂ concentrations, with multiple peaks likely caused by local sources within 60 km, such as transportation, residential activities, and industrial emissions. Although TPPs contributed significantly to the baseline SO₂ concentrations, especially in Category-2 and Category-3 cities, they were ruled out as causes for these short (lasting 2-4 hours) spikes due to their continuous operation. Boundary layer dynamics and wind characteristics significantly influenced ambient air SO₂ concentrations across all cities and phases.
- **Effectiveness of FGD:** No notable systematic differences in ambient air SO₂ concentrations were observed between Category 2 and Category 3 cities. The operation of FGD units in the two Category 3 cities selected for our survey, namely GBN and Khargone, did not significantly affect SO₂ levels, despite large day-to-day variability. Additionally, this variability did not correlate with the operation or the number of FGD units in operation at either of these TPPs, raising doubts about the effectiveness of the installed FGD systems in lowering SO₂ concentrations in the ambient air around these two TPPs.

Major findings of our investigation on the contribution of energy sector (coal-based TPPs) emissions towards ambient air SO₂ concentration in different category cities are listed below:

Our study reveals that the contribution of SO₂ emissions from coal-based thermal power plants (TPPs) to ambient atmospheric SO₂ concentrations exhibited significant spatial and seasonal variability across different cities.

Category-1 Cities: The energy sector's contribution to ambient air SO₂ concentrations was relatively low in these cities. The average contribution of TPPs to ambient SO₂ concentrations was 13.18%, ranging from 11.44% to 16.53%. New Delhi showed a contribution of 16.53% (1.36 µg/m³) during Phase-I (pre-monsoon season), Hyderabad 11.57% (0.41 µg/m³) in the same phase, and Lucknow 11.44% (0.66 µg/m³) during Phase-II (monsoon season).

Category-2 Cities: The energy sector's contribution to ambient air SO₂ concentrations was generally significant, averaging 31.68%. The energy sector's contribution ranged from 27.99% to 38.57%. Kolkata showed a contribution of 28.66% (1.55 µg/m³) and Nagpur 32.27% (1.56 µg/m³) during Phase-I (pre-monsoon season). Kota showed 28.9% (1.11 µg/m³) in Phase-II (monsoon

season) and 27.99% (1.82 $\mu\text{g}/\text{m}^3$) in Phase-III (winter season). Shahdol had the highest contribution of 38.57% (1.99 $\mu\text{g}/\text{m}^3$) in Phase-III.

Category-3 Cities: Significant contributions of coal-based thermal power plants (TPPs) to ambient atmospheric SO_2 concentrations were observed in these cities, averaging 20.38%, with contributions ranging from 17.37% to 22.54%. Ghaziabad showed contributions of 17.37% (1.43 $\mu\text{g}/\text{m}^3$) during Phase-I (pre-monsoon season). Gautam Buddha Nagar (GBN) had contributions of 19.82% (1.80 $\mu\text{g}/\text{m}^3$) in Phase-I, 21.97% (1.33 $\mu\text{g}/\text{m}^3$) in Phase-II, and 22.54% (2.17 $\mu\text{g}/\text{m}^3$) in Phase-III. Khargone showed 19.8% (0.86 $\mu\text{g}/\text{m}^3$) in Phase-III.

Overall Findings: The energy sector's contribution to ambient air SO_2 concentrations ranged from 11.44% (0.66 $\mu\text{g}/\text{m}^3$) to 38.57% (1.99 $\mu\text{g}/\text{m}^3$) across all cities and phases. Category-2 cities exhibited the highest contributions, followed by Category-3 and Category-1 cities, underscoring the significant impact of coal-based TPP emissions. However, other sources such as industrial, residential, and transportation sectors also significantly contribute to ambient air SO_2 levels in all cities.

Major findings on the contribution of sulfate aerosols (SO_4) originating from SO_2 emissions by TPPs towards ambient air $\text{PM}_{2.5}$ and PM_{10} mass concentrations in different category cities are listed below:

Category-1 cities: These cities, which have no coal-based TPPs, showed the lowest contributions of sulfate aerosols originating from SO_2 emissions by TPPs towards ambient air $\text{PM}_{2.5}$ and PM_{10} mass concentrations. For example, Hyderabad had contributions of 0.96% to $\text{PM}_{2.5}$ (0.44 $\mu\text{g}/\text{m}^3$) and 0.57% to PM_{10} (0.49 $\mu\text{g}/\text{m}^3$) during Phase I, while Lucknow had contributions of 1.22% to $\text{PM}_{2.5}$ (0.42 $\mu\text{g}/\text{m}^3$) and 0.90% to PM_{10} (0.47 $\mu\text{g}/\text{m}^3$) during Phase II. Despite being a Category-1 city, Delhi showed significantly higher contributions due to regional transport of SO_2 or sulfate aerosols from nearby TPPs, with contributions of 3.94% to $\text{PM}_{2.5}$ (3.64 $\mu\text{g}/\text{m}^3$) and 2.58% to PM_{10} (4.07 $\mu\text{g}/\text{m}^3$) during Phase I. On average, Category-1 cities had contributions of approximately 1.79% to $\text{PM}_{2.5}$ (0.93 $\mu\text{g}/\text{m}^3$) and 1.04% to PM_{10} (1.07 $\mu\text{g}/\text{m}^3$), with a range of 0.44 to 3.64 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 0.47 to 4.07 $\mu\text{g}/\text{m}^3$ for PM_{10} .

Category-2 cities: These cities, which are near TPPs with FGD systems, had the highest contributions. In Gautam Buddha Nagar during Phase I, the contributions were 2.78% to $\text{PM}_{2.5}$ (2.17 $\mu\text{g}/\text{m}^3$) and 1.94% to PM_{10} (2.55 $\mu\text{g}/\text{m}^3$). In Phase II, the contributions were 2.26% to $\text{PM}_{2.5}$ (1.06 $\mu\text{g}/\text{m}^3$) and 1.76% to PM_{10} (1.25 $\mu\text{g}/\text{m}^3$), increasing to 2.93% to $\text{PM}_{2.5}$ (3.23 $\mu\text{g}/\text{m}^3$) and 2.15% to PM_{10} (3.80 $\mu\text{g}/\text{m}^3$) in Phase III. Ghaziabad showed contributions of 2.15% to $\text{PM}_{2.5}$ (1.55 $\mu\text{g}/\text{m}^3$) and 1.49% to PM_{10} (1.83 $\mu\text{g}/\text{m}^3$) during Phase I. Khargone, in Phase III, showed contributions of 2.14% to $\text{PM}_{2.5}$ (1.05 $\mu\text{g}/\text{m}^3$) and 1.51% to PM_{10} (1.23 $\mu\text{g}/\text{m}^3$). On average,

Category-3 cities had contributions of approximately 2.45% to PM_{2.5} (1.61 µg/m³) and 1.97% to PM₁₀ (2.13 µg/m³), with a range of 1.99 to 5.72 µg/m³ for PM_{2.5} and 2.23 to 5.75 µg/m³ for PM₁₀.

Category-3 cities: These cities, which are near TPPs with FGD systems, had the highest contributions. In Gautam Buddha Nagar during Phase I, the contributions were 2.78% to PM_{2.5} (2.17 µg/m³) and 1.94% to PM₁₀ (2.55 µg/m³). In Phase II, the contributions were 2.26% to PM_{2.5} (1.06 µg/m³) and 1.76% to PM₁₀ (1.25 µg/m³), increasing to 2.93% to PM_{2.5} (3.23 µg/m³) and 2.15% to PM₁₀ (3.80 µg/m³) in Phase III. Ghaziabad showed contributions of 2.15% to PM_{2.5} (1.55 µg/m³) and 1.49% to PM₁₀ (1.83 µg/m³) during Phase I. Khargone, in Phase III, showed contributions of 2.14% to PM_{2.5} (1.05 µg/m³) and 1.51% to PM₁₀ (1.23 µg/m³). On average, Category-3 cities had contributions of approximately 2.45% to PM_{2.5} (1.61 µg/m³) and 1.97% to PM₁₀ (2.13 µg/m³), with a range of 1.99 to 5.72 µg/m³ for PM_{2.5} and 2.23 to 5.75 µg/m³ for PM₁₀.

Overall findings: The contribution of SO₂ emissions from coal-based TPPs to ambient sulfate aerosols in PM_{2.5} and PM₁₀ mass concentrations was highest in Category-2 cities, with an average contribution of 3.83% to PM_{2.5} (2.19 µg/m³) and 2.87% to PM₁₀ (2.49 µg/m³). Category-3 cities showed intermediate contributions, averaging 2.45% to PM_{2.5} (1.61 µg/m³) and 1.97% to PM₁₀ (2.13 µg/m³), while Category-1 cities had the lowest contributions, averaging 1.79% to PM_{2.5} (0.93 µg/m³) and 1.04% to PM₁₀ (1.07 µg/m³). The range of contribution of sulfate aerosols (SO₄) formed due to SO₂ emissions from coal-based TPPs to ambient air PM_{2.5} and PM₁₀ mass concentrations across all cities and phases varied from 0.96% (0.44 µg/m³) to 5.21% (3.30 µg/m³) for PM_{2.5} and from 0.57% (0.49 µg/m³) to 3.67% (3.60 µg/m³) for PM₁₀.

Implications of our findings: Our study indicates that installing FGD systems with an 87.5% SO₂ removal efficiency in all coal-based TPPs across India would lead to a maximum reduction in PM_{2.5} concentrations of up to 4.56% (2.89 µg/m³) and PM₁₀ concentrations of up to 3.21% (3.15 µg/m³). This reveals that SO₂ emissions from TPPs contribute relatively little to ambient air PM_{2.5} and PM₁₀ mass concentrations in the surveyed cities and seasons. Consequently, there would be only a marginal improvement (5%) in particulate matter air quality even after eliminating all SO₂ emissions from TPPs. It should be noted that SO₂, a colourless gas, does not directly reduce visibility but contributes to haze formation after being converted into sulfate particles. Therefore, eliminating SO₂ emissions from TPPs is likely to result in a modest improvement in visibility and a reduction in haze formation. Comprehensive emission control measures targeting all major pollutants and particulate matter precursors emitted from various sources, including TPPs, are necessary to achieve meaningful improvements in air quality.

Major points based on our discussion on the lifecycle of SO₂ in the atmosphere and the potential for acid rain in India, and lifecycle costs and benefits of FGD implementation in TPPs across India are listed below:

- SO₂ has an atmospheric lifetime ranging from a few hours to about 15 days due to its rapid conversion to sulfate aerosols and removal via dry and wet deposition. In contrast, CO₂ has a much longer atmospheric lifetime, persisting for over 100 years. This means that while an SO₂ molecule is likely to be removed from the atmosphere within roughly two weeks, a CO₂ molecule can remain in the atmosphere for about a century.
- Due to the high soil dust content rich in carbonate minerals like calcium carbonate (CaCO₃) and the abundance of ammonia (NH₃) in the ambient air across India, both of which are alkaline, acid rain is not a serious issue in most parts of the country, except for southern peninsular India where the concentrations of alkaline substances like ammonia and carbonate-rich dust in the air are relatively low. However, frequent dilution caused by the sea breeze naturally keeps ambient SO₂ levels lower in coastal areas of peninsular India. Additionally, the inherent alkalinity of seawater droplets, due to the presence of bicarbonate ions (HCO₃⁻) and carbonate ions (CO₃²⁻), effectively neutralizes sulfuric acid (H₂SO₄) in the atmosphere over coastal areas.
- The combustion of coal in coal-fired thermal power plants, in addition to being a major source of carbon dioxide (CO₂) emissions, also results in the direct emission of primary particulate matter (PM) such as fly ash, black carbon (BC), and various heavy metals. Additionally, it emits several particulate matter precursors, including sulfur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), from the stacks (chimneys) of the TPPs into the atmosphere. Together, these emissions contribute significantly to ambient air PM_{2.5} and PM₁₀ mass concentrations. However, eliminating only SO₂ emissions from TPPs using FGD technology, which can reduce SO₂ emissions by anywhere between 50% to 99%, is unlikely to result in a significant overall improvement in PM_{2.5} and PM₁₀ mass concentrations in the different category cities surveyed in this study.
- While FGD implementation will significantly reduce SO₂ emissions from TPPs, there are no credible studies quantifying the overall life-cycle costs and benefits of FGDs in the Indian context. Current FGD technologies will increase CO₂ emissions, water consumption, and secondary pollution due to the mining and transportation of limestone/gypsum, FGD system manufacturing, operation and maintenance.
- Our study estimates that installing FGD systems with 87.5% SO₂ removal efficiency in all coal-based TPPs across India would reduce annual SO₂ emissions by 4.88 MT per year, but this would result in an immediate increase of approximately 14.4 MT per year in CO₂ emissions from mining, transportation, reagent operations, and increased auxiliary power consumption.

- While the above estimate only accounts for the immediate and direct additional CO₂ emissions, several previous studies have demonstrated that the total environmental impact, including the overall increase in CO₂ emissions beyond the immediate impact and freshwater consumption is likely to be significantly higher when considering the life cycle assessment (LCA) of FGD implementation in coal-based TPPs. These studies highlight the critical need to comprehensively assess both the immediate and long-term environmental impacts, including the estimation of additional equivalent CO₂ emissions, associated with FGD implementation. This underscores the importance of conducting thorough LCA and LCC analyses to fully understand and mitigate potential adverse outcomes, while minimizing the environmental trade-offs involved in deploying FGD systems across all coal-based TPPs in India.
- Although it is well known that sulfate aerosols are highly efficient at blocking solar radiation from reaching the Earth's surface, partially offsetting the global warming caused by greenhouse gases like CO₂, there are no credible studies on the impacts of a sudden reduction in SO₂ emissions combined with simultaneous increases in CO₂ emissions on India's regional weather and climate, including the Indian monsoon system, extreme weather events such as floods and droughts, surface ozone levels, human health, agriculture, etc. Therefore, it is crucial to quantify the long-term environmental and climate change impacts of FGD implementation in India to ensure that our clean air goals do not conflict with our climate change mitigation targets. Additionally, the increased warming due to reduced SO₂ emissions and increased CO₂ emissions is likely to exacerbate the adverse impacts of heat stress on human health and agriculture, which also needs to be quantified.
- India should heed the lessons from China's experience, as the idea that cleaning up air pollution can worsen atmospheric warming may seem counterintuitive but is a real and ongoing issue. Recently published research articles (Wang et al. 2024; Pearse, 2024) highlight how a dramatic reduction in Chinese air pollution, coinciding with the installation of FGD systems in coal-based TPPs, has been attributed to the recent extraordinary heating over the Northeast Pacific region, leading to more heat waves with global climate consequences. These findings underscore the complex relationship between air quality improvements and climate change, suggesting that decreased aerosol emissions, accompanied by increased greenhouse gas emissions, are likely to exacerbate warming. This demands more research in this direction and highlights the need for balanced strategies to address both air quality and climate goals.
- While SO₂ is a significant air pollutant and its emissions should be reduced, the trade-off between reducing SO₂ and increasing CO₂ emissions must be carefully considered. If reducing a relatively smaller amount of SO₂ emissions comes at the cost of a larger increase in CO₂ emissions, it raises serious concerns. This scenario necessitates a broader debate among stakeholders to ensure that efforts to improve air quality do not inadvertently strain valuable water resources, exacerbate global warming, and impact the Earth's climate system, particularly the regional weather and climate of India.

- Policy decisions regarding the installation of FGD systems in coal-based TPPs in India should balance the health benefits and climate impacts. While reducing sulfate aerosols can mitigate respiratory diseases, the concurrent increase in CO₂ emissions may exacerbate global warming, leading to heightened heat stress and potentially more severe health consequences (Ballester et al., 2023; Choudhary et al., 2023; Schumacher et al., 2024). Comprehensive studies are required to fully understand these impacts and to develop strategies to cope with extreme weather conditions that could affect food production and electricity generation and demand in India (Mbow et al., 2019).
- Based on our survey conducted over two years ago, discussions with the CEA, and considering subsequent price escalations due to inflation, it is reasonable to assume that the current cost of FGD systems is approximately Rs. 1.20 Crore per MW. As of May 31, 2023, the total installed capacity of coal-based TPPs across India is about 211.86 GW or 211,860 MW. Therefore, the total cost of installing FGD systems in all coal-based TPPs across India would be approximately Rs. 2,54,232 Crore. This estimate does not include the running and maintenance costs of the FGD systems.

Recommendations and Way Forward

- Considering that present ambient air SO₂ levels across all cities in our survey are well within the National Ambient Air Quality Standards (NAAQS), and recognizing that eliminating all SO₂ emissions from TPPs would result in only a marginal improvement in particulate matter air quality in these cities, along with the fact that current FGD technologies will increase CO₂ emissions, water consumption, and cause secondary pollution due to the mining and transportation of limestone/gypsum, the urgency of FGD installation across India must be reassessed. It may be prudent to halt the installation of FGD systems in thermal power plants that have not yet started this process and revisit this decision after considering these factors and taking the following suggested steps.
- FGD projects currently being implemented may be allowed to complete/operate for a year. After this period, a review of the impact of FGD operation on ambient air quality and regional meteorological changes may be conducted to determine any further necessary actions.
- Conduct a follow-up study to comprehensively evaluate the life-cycle assessment (LCA) and life-cycle costs (LCC) and benefits of implementing FGD technology in coal-based TPPs across India. This LCA and LCC estimate should encompass various available FGD technologies, operating and maintenance expenses, and the impact of FGD implementation on the current electricity unit price in India.
- Conduct another detailed study to evaluate the health benefits of reducing sulfate aerosols, specifically in mitigating respiratory diseases, vis-à-vis the potential health consequences of heat stress that are likely to be caused by the sudden disappearance of regional cooling effects from sulfate aerosols and the concurrent increase in CO₂ emissions. This study should

also consider the broader climate impacts, such as intensified warming and heightened heat stress, to prepare for extreme weather conditions affecting human health, food production, and electricity generation and demand resulting from FGD implementation across India.

- Initiate a broader debate among stakeholders after completing the life-cycle cost assessment to discuss the prudence of investing heavily in non-sustainable, CO₂-emitting energy sources versus redirecting funds towards rapidly expanding renewable energy sources like solar and wind power.
- Gradually phase out older and less efficient coal-based thermal power plants to transition to a sustainable and environmentally responsible energy future, while ensuring the country's energy security remains intact. The installation of FGD systems and carbon capture technologies should not be used as a smokescreen to justify the continued power generation from these unsustainable, CO₂-intensive sources. Prioritize transitioning to cleaner energy alternatives, which offer long-term environmental and public health benefits, and promote energy security and sustainability for future generations.
- It is recommended to develop balanced strategies that effectively address both air quality and climate goals.

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