

Study to assess the compliance of thermal power plants in India to new SO₂ emission norms (2015) and lay out phased plan for FGD implementation



Source: Google Images



Centre for Atmospheric Sciences
Indian Institute of Technology Delhi

Website: <https://cas.iitd.ac.in/>
June 27, 2022

CONTRIBUTORS

Overall Guidance & Supervision	Prof. Dilip Ganguly, CAS, IIT Delhi Prof. Sagnik Dey, CAS, IIT Delhi
Data Analysis and Report Preparation	Ms. Lovleen Kaur Arora, Project Scientist, IITD Ms. Sumitra Sharma, Project Scientist, IITD Ms. Isha Singh, Project Scientist, IITD Mr. Shubham, Project Scientist, IITD Mr. Indranil Nandi, Junior Research Fellow, IITD
Data Providers	Central Electricity Authority, Public & Private Developers of TPPs across India and CPCB website

CONTENTS

Chapter No.	Chapter Title	Page No.
Chapter 1	Introduction	1-3
Chapter 2	TRENDS IN STACK EMISSIONS AND AMBIENT AIR CONCENTRATIONS OF MAJOR AIR POLLUTANTS FROM COAL-BASED THERMAL POWER PLANTS ACROSS INDIA	4-55
Chapter 3	ANALYSIS OF SO ₂ AND SULFATE (SO ₄) AEROSOL DATA OVER THE INDIAN REGION USING SATELLITE OBSERVATIONS, EMISSION INVENTORY AND REANALYSIS DATASETS	56-68
Chapter 4	DISPERSION MODELLING OF AIR POLLUTANTS FROM SELECTED COAL BASED TPP's IN INDIA	69-153
Chapter 5	ASSESSMENT OF IMPACT OF FGD IMPLEMENTATION IN COAL BASED THERMAL POWER PLANTS ON THE AMBIENT CONCENTRATIONS OF SO ₂ AND SULFATE AEROSOL IN THE SURROUNDING REGION USING A CHEMICAL TRANSPORT MODELLING	154-200
Chapter 6	SOURCE APPORTIONMENT OF AIR POLLUTANTS FOR DELHI NATIONAL CAPITAL REGION (NCR)	201-219
Chapter 7	ACTION PLAN FOR PHASED IMPLEMENTATION OF FGD AT ALL COAL BASED THERMAL POWER PLANTS ACROSS THE COUNTRY	220-240

Executive Summary

Emissions from coal based thermal power plants (TPPs) are known to have adverse impacts on environment and human health. Combustion of coal in these TPPs release sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and various primary particulate matter (PM) into the air through stacks that can disperse this pollution over large areas. Both during emission and while in the atmosphere, gaseous SO_2 can become oxidized to form sulfate (SO_4) particulate matter. On 7th December 2015, the prevailing norms regarding the air pollution from TPPs were revised and new norms regarding limits of $\text{PM}_{2.5}$, SO_x , NO_x , and mercury emissions from TPPs were introduced. With environmental concerns becoming more pronounced, MoEF&CC notified “Environment (Protection) Amendment Rules, 2015” for thermal power plants. After notification of new emission norms, it has become necessary for several thermal power plants across the country to install Flue gas desulfurization (FGD) units to curtail the emission of SO_2 from the stacks to comply to the above stipulated SO_2 emission limits.

This report presents a study to assess the compliance of thermal power plants across India to the new SO_2 emission norms (2015) and lay out a phased plan for FGD implementation in TPPs across the country. Chapter-2 of this report presents an analysis of the trends in stack emissions and ambient air concentrations of major air pollutants emitted from coal based thermal power plants across India. Chapter-3 of the report presents an analysis of climatology and trends in SO_2 and sulfate (SO_4) aerosol data over the Indian region using satellite observations, emission inventory, and reanalysis datasets. Chapter-4 of the report presents results of dispersion modeling of air pollutants from selected coal based TPPs in India which are in different geographical areas and differ in terms of their age and power producing capacities for understanding and the quantifying the dispersion of SO_2 from these TPPs during different times of the year. Chapter-5 of the report investigates the impact of implementation of flue gas desulfurization (FGD) in selected coal based thermal power plants (TPPs) across the country on the near surface concentrations of two major air pollutants, namely SO_2 and sulfate aerosols, in the surrounding region of these TPPs by conducting chemical transport model simulations using the Weather Research Forecast model coupled with an interactive atmospheric chemistry module. Chapter-6 of the report presents the results from a series of systematically designed WRF-Chem model simulations that are performed to carry out source apportionment of air pollutants for Delhi National Capital Region (NCR). This helps us in understanding the contribution of different emissions sectors along with contributions of local versus remote emission contributions towards the air pollutant levels within Delhi National Capital Region (NCR) for the month of December 2018. Finally, Chapter-7 of the report recommends an action plan for phased implementation of FGD in all coal based TPPs across the country.

A detailed analysis of stack emissions and ambient air quality data from 240 stacks from 67 coal based TPPs across the country are performed in this study. A detailed analysis of SO_2 and sulfate (SO_4) aerosol data over the Indian region has been performed using satellite observations,

emission inventory and reanalysis data sets to identify areas within the country which has highest column burden and surface concentration of SO₂ and sulfate (SO₄) aerosols. A pollutant dispersion model has been used to understand and the quantify the dispersion of SO₂ from four different selected thermal plant plants (TPP) across the country based on their respective capacities and during four different months of the year 2019. Four coal based TPPs considered for the dispersion modeling study include: Mundra UMTTP (Tata Power (CGPL)) and Mundra TPS (Adani Power Ltd), Gujarat, Vindhychal Thermal Power Plant (Madhya Pradesh), Talcher Thermal Power Plant (Odisha) and Panipat Thermal Power Plant (Haryana). Additional model sensitivity simulations are performed to investigate and understand the sensitivity of dispersion of SO₂ from a selected TPP as a function of different choices of stack height. We further investigated the impact of implementation of flue gas desulfurization (FGD) in coal based thermal power plants (TPPs) across the country on the near surface concentrations of two major air pollutants, namely SO₂ and sulfate aerosols, in the surrounding region of these TPPs by conducting chemical transport model simulations using the Weather Research Forecast model coupled with an atmospheric chemistry module. Our study finds that while implementation of FGD in TPPs can result in significant decreases (up to 55%) in SO₂ concentrations that are mostly confined in the immediate surrounding areas of the TPP and up to a maximum distance of 60-80 km from the location of the TPP and in the direction of maximum dispersal of the air pollutants but, significant decreases (up to 30%) in the surface concentrations of sulfate (SO₄) aerosols can be expected at locations which could be as far as 200 Km from the location of the TPP. A series of systematically designed WRF-Chem model simulations are performed to carry out source apportionment of air pollutants for Delhi National Capital Region (NCR). Here we try understanding the contribution of different emissions sectors along with contributions of local versus remote emission contributions towards the air pollutant levels within Delhi National Capital Region (NCR) for the month of December 2018. Our results suggest that while the maximum contribution to sulfur dioxide (SO₂) surface mass concentration over Delhi NCR for the December month came from the energy sector emissions (~63%), maximum contribution to sulfate (SO₄) aerosol surface mass concentration over Delhi NCR for the same month came from the transportation sector emissions (~33%) followed by the energy sector emissions (26%).

Finally, an action plan for phased implementation of FGD in all coal based TPPs across the country is presented in this report. There are multiple ways for phased implementation of FGDs in TPPs across the country. We recommend a phased implementation of FGDs in TPPs across the country based on SO₂ surface concentration (in mg/m³) data throughout India obtained from AURA (OMI) satellite observations and MERRA2 reanalysis data during the last five years, that is 2015-2019. Considering the challenges involved in implementing FGDs in all TPPs across the country simultaneously as discussed in this report, it is recommended to adopt a graded action plan for phased implementation of FGDs by giving preference to areas which have highest surface concentration of SO₂ as per our analysis of satellite observations and MERRA2 reanalysis data. We recommend implementation of FGDs in all coal based TPPs across the country in five phases. Phase-1 of FGD implementation should be of 3-year period from July 2022 to July 2025 and it should include FGD implementation in around 40 TPPs across the

country. After Phase-1 of FGD implementation in around 40 TPPs, a study must be conducted to ascertain the performance of these FGDs at least over a period of next one year and confirm the tangible benefits of installation of FGDs in TPPs by considering its impact on extra CO₂ emission, accelerated warming of the regional climate, extra water consumption, limestone mining, transportation of limestone from the mines to the TPPs, and disposal of byproducts like gypsum etc. Phase-2 of FGD implementation should happen in around 49 TPPs should start from July 2026 and completed by July 2029. A four-year time period between start of the Phase-1 and Phase-2 of FGD implementation will also allow us to see the emergence of new FGD technologies which could possibly consume less water, avoid any extra emission of CO₂ into the atmosphere etc. Thereafter Phase-3 of FGD implementation should happen in around 27 TPPs and it can start from July 2029 and completed by July 2031. Phase-4 of FGD implementation should happen in around 21 TPPs and it can start from July 2031 and completed by July 2033. Phase-5 of FGD implementation should happen for the remaining 7 TPPs and it can start from July 2033 and completed in one year by July 2034. The report also provides the list of non-attainment cities across India which will benefit with the implementation of FGD in different phases of the suggested graded action plan.

This report recommends carrying out an immediate follow up investigation to quantify the socio-economic cost and benefits of FGD implementation in coal based thermal power plants across India. While reduction in SO₂ emissions from TPPs by FGD implementation is highly desirable but, it is also equally important to ensure that the benefit of SO₂ emission reduction is not coming at a cost of increased emission of greenhouse gases, extra consumption of valuable water, accelerated global warming, and various other problems associated with it.

CHAPTER 1: INTRODUCTION

Clean air is one of the basic requirements of human health and well-being. Rapid urbanization, industrialization, motorization, inadequate waste management etc. have aggravated air pollution levels in many cities across the world thus, posing significant challenges to both human health and economy. Air pollution is not strictly an urban problem. Emissions from urban, suburban, and rural sources together contribute to the air pollution problems we are facing today.

Air pollution is a growing concern in many countries including India. Air pollution in the form of particulate matter (PM), SO_x , NO_x , mercury, etc., comes from various sources such as industries, transportation, energy sector, agriculture, waste burning, construction and demolition work, wind-blown dust, etc. Recent data published by the World Health Organization lists New Delhi and 9 other North Indian cities rank among the world's top 25 cities with the worst air quality. Other Indian cities, which find a place in the list, are Kanpur, Faridabad, Ghaziabad, Gaya, Gurugram, Varanasi, Agra, Lucknow, and Patna.

India is one of the fastest developing countries across the globe and the second most populous country in the world having a population of about 1.38 billion, which comprises of 17.7% of the total world population. At present, India is the world's largest consumer as well as largest producer of electricity. The per capita consumption of electricity in the country has seen a gradual increase from 15 kWh in 1950 to about 1,181 kWh in the year 2018-19. Similarly, the overall electricity generation saw a significant growth from about 5.1 billion units in 1950 to 1390.467 billion units during 2019-20. Electricity in India is largely generated by Coal based Thermal power plants (TPPs). As per reports published by the Central Electricity Authority, total all India thermal power plants capacity was about 2,30,600 MW as on 31st March 2020. The installed capacity of Power Plants has surged to 370,106 MW (as on 31 March 2020) from a meagre 1,713 MW in 1950 over the years.

Emissions from coal based thermal power plants (TPPs) are known to have adverse impacts on environment and human health. Combustion of coal in these TPPs release sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and various primary particulate matter (PM) into the air through stacks that can disperse this pollution over large areas. Both during emission and while in the atmosphere, gaseous SO_2 can become oxidized to form sulfate (SO_4) particulate matter. The sulfate aerosol is mainly composed of sulfuric acid and corresponding salts such as ammonium sulfate. Coal based thermal power plants are responsible for more than 50% Sulphur dioxide (SO_2), 30% oxides of nitrogen (NO_x), about 20% particulate matter (PM), among other man-made emission sources in India. Over the last four decades, Government of India has been taking necessary action to control environmental pollution from various sources including thermal power plants through regulations framed by the CPCB. Norms for control of emissions from thermal power plants were first notified by Ministry of Environment, Forest & Climate Change (MoEF&CC) as early as in 1984, and thereafter they have undergone several changes over the last three decades. On 7th December 2015, the prevailing norms regarding the air

pollution from TPPs were revised and new norms regarding limits of PM_{2.5}, SO_x, NO_x, and mercury emissions from TPPs were introduced. With environmental concerns becoming more pronounced, MoEF&CC notified “Environment (Protection) Amendment Rules, 2015” for thermal power plants.

The Environment (Protection) Amendment Rules, 2015, amended existing norms and introduced new norms for emissions of PM, SO₂, and NO_x from TPPs. The new norms for total PM and NO_x emissions from the stacks are based on commissioning date of the TPPs (Table 1). For example, for the plants with commissioning date before 31-12-2003, the PM emission limit is 100 mg/Nm³ and for the plants with commissioning date on or after 01-01-2017, the limit is 30 mg/Nm³. The emission norms for SO₂ are based upon both the commissioning date and the capacity of thermal power plant. For example, the plants with generation capacity more than or equal to 500 MW, the SO₂ concentration limit is 200 mg/Nm³ and for the plants with generation capacity less than 500 MW, the limit is 600 mg/Nm³.

Date of Installation	PM	SO ₂	NO _x	Mercury (Hg)
Before 31-12 2003	100 mg/Nm ³	600 mg/Nm ³ for <500MW 200 mg/Nm ³ for ≥500MW	600 mg/Nm ³	0.03 mg/Nm ³ for ≥500MW
After 01-01-2004 & Upto 31-12-2016	50 mg/Nm ³	600 mg/Nm ³ for <500MW 200 mg/Nm ³ for ≥500MW	300 mg/Nm ³	0.03 mg/Nm ³
On or after 01-01-2017	30 mg/Nm ³	100 mg/Nm ³	100 mg/Nm ³	0.03 mg/Nm ³

Table 1: New (2015) regulation on emissions from TPPs in India

MoEF&CC has mandated the TPPs across India to use various emission control systems (ECSs) such as Flue Gas Desulphurization (FGD), Selective Catalytic Reduction (SCR)/ Selective Non-Catalytic Reduction (SNCR) along with measures such as combustion modification and retrofit of Electro-Static Precipitator (ESP) or whatever is necessary to restrict the emissions of PM, SO_x, and NO_x within the limits specified by CPCB as per the new guidelines mentioned in Table-1.

This report presents a study to assess the compliance of thermal power plants across India to the new SO₂ emission norms (2015) and lay out phased plan for FGD implementation in TPPs across the country. Chapter-2 of this report presents an analysis of the trends in stack emissions and ambient air concentrations of major air pollutants emitted from coal based thermal power

plants across India. Chapter-3 of the report presents an analysis of climatology and trends in SO₂ and sulfate (SO₄) aerosol data over the Indian region using satellite observations, emission inventory, and reanalysis datasets. Chapter-4 of the report presents results of dispersion modeling of air pollutants from selected coal based TPPs in India which are in different geographical areas and differ in terms of their age and power producing capacities for understanding and the quantifying the dispersion of SO₂ from these TPPs during different times of the year. Chapter-5 of the report investigates the impact of implementation of flue gas desulfurization (FGD) in selected coal based thermal power plants (TPPs) across the country on the near surface concentrations of two major air pollutants, namely SO₂ and sulfate aerosols, in the surrounding region of these TPPs by conducting chemical transport model simulations using the Weather Research Forecast model coupled with an interactive atmospheric chemistry module. Chapter-6 of the report presents the results from a series of systematically designed WRF-Chem model simulations that are performed to carry out source apportionment of air pollutants for Delhi National Capital Region (NCR). This helps us in understanding the contribution of different emissions sectors along with contributions of local versus remote emission contributions towards the air pollutant levels within Delhi National Capital Region (NCR) for the month of December 2018. Finally, Chapter-7 of the report recommends an action plan for phased implementation of FGD in all coal based TPPs across the country.

CHAPTER-2: TRENDS IN STACK EMISSIONS AND AMBIENT AIR CONCENTRATIONS OF MAJOR AIR POLLUTANTS FROM COAL-BASED THERMAL POWER PLANTS ACROSS INDIA

Combustion of coal in coal fired power plants results in emissions of Sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs) and primary particulate matter (PM) from the stacks (chimneys) of the TPPs into the atmosphere. Height and the diameter of the stacks in TPPs are designed in a way to minimize the environmental impact due to emissions of SO₂, NO_x and PM emissions from these TPPs. The impact of these pollutant emissions from the TPPs can be monitored from the ambient air quality and stack emission measurements made in these thermal power plants. It is to be noted here that the ambient air quality measurements are ground based while the emissions occur from the top of the stacks in all TPPs.

The long-term trends in the emissions of SO₂, NO_x, and PM from the stacks in TPPs across India are being analyzed to understand if the TPPs are complying with the new emission standards as per the Environment (Protection) Amendment Rules 2015 of MoEF&CC. This will help us in identifying the specific thermal plants that are meeting and those that are not meeting the latest emission standards and ambient air quality norms of CPCB. TPPs, which are not meeting the standards, will require immediate intervention in the form of emission control systems (ECSs) such as Flue Gas Desulphurization (FGD) to restrict the emissions of SO₂.

Methodology

The ambient air pollution and stack emissions data collected from all running thermal power plants across India are being analyzed. For checking the compliance of ambient air quality standards at all thermal power plants, monthly mean and annual mean time series and trends in four air pollutants namely, PM_{2.5}, PM₁₀, SO₂ and, NO_x has been considered in our analysis. Similarly, to check the compliance of the thermal power plants to the new regulations on emissions, we have analyzed the stack emissions data from various thermal power plants by examining the monthly and annual mean time series and trends in emissions of three pollutants namely total PM, SO₂ and NO_x.

The ambient air quality and stack emissions data from various thermal power plants across India as shared by CEA have been analyzed and further updated with latest information on ambient air quality and stack emissions data provided by various government and private developers of thermal power plants, CPCB websites and annual reports of the state pollution control boards and various electricity generation companies. The database includes geographical location in latitude and longitude, plant commissioning date, data, capacity of plant, number of boiler units and size of all known power plants operated by both public and private entities.

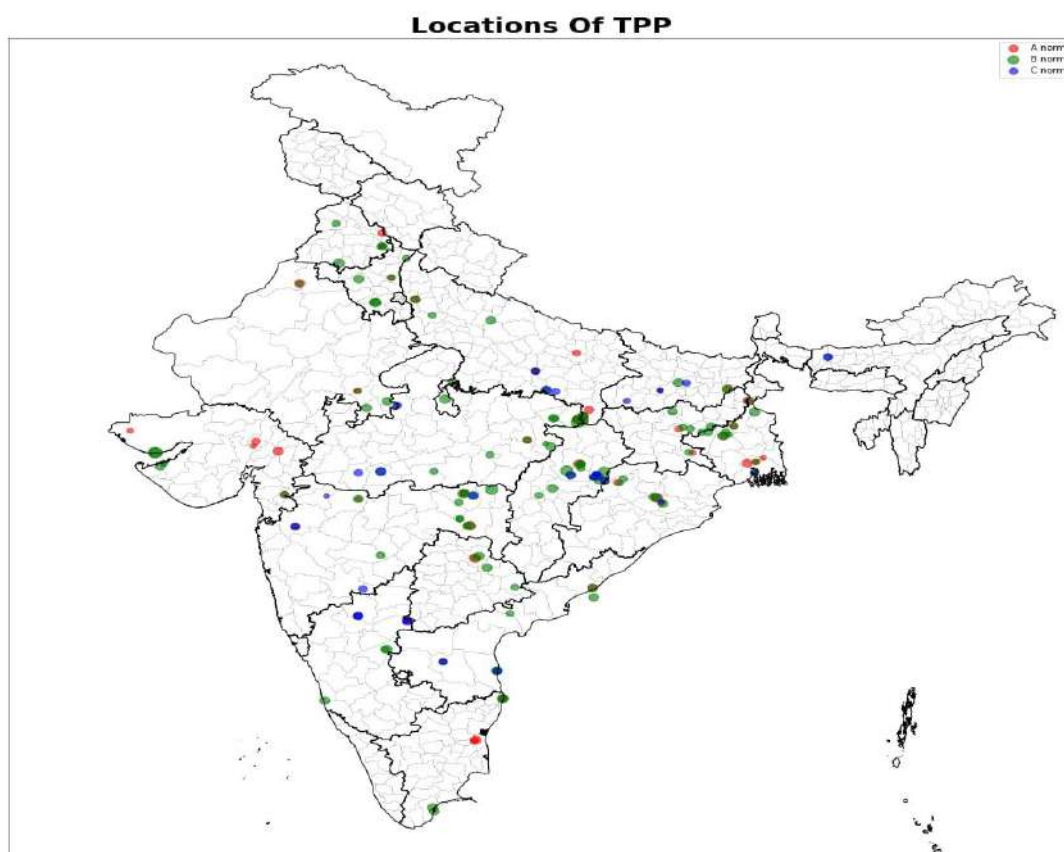


Figure 2.1: Location of Thermal Power plants across India

In **Figure-2.1**, Red dots represent TPPs installed before 31-12-2003, green dots represent TPPs installed after 01-01-2004 and up to 31-12-2016 and blue dots: TPPs installed on or after 01-01-2017

Statistics of the total number of coal based thermal power plants across India and the status of the ambient air quality and stack emissions data that has been analyzed in this report are mentioned below.

Total number of existing Coal based thermal power plants in India: **183**

Total number of units (stacks) in existing coal based thermal power plants in India: **448**

Total number of developers of coal based thermal power plants in India: **72**

Number of TPPs from which stack emissions and ambient air quality data received: **67**

Number of TPPs from which stack emissions and ambient air quality data received: **240**

Number of TPPs units for which stack emissions and ambient air quality are provided in this report: **240**

Detailed analysis of ambient air quality data from all the 67 thermal power plants and stack emissions data from all 240 thermal power plants have been carried out to find out if any of these

TPPs are able to meet the new emission norms for total PM, NO_x, and SO₂ as well as the national air quality standards. Here we present the analysis of ambient air quality and stack emissions data from one of the largest thermal power plants in India. Analysis of ambient air quality and stack emissions data from other coal based thermal power plants are provided in the Supplementary material provided along with this report.

SIPAT THERMAL POWER PLANT

Sipat Super Thermal Power Station is located at Sipat in Bilaspur district in state of Chhattisgarh, India. The power plant is one of the largest coal-based power plants of the National Thermal Power Corporation Limited (NTPC Limited) in India. The coal for this power plant is largely sourced from Dipika Mines of South-eastern Coalfields Limited.

Sipat Super Thermal Power Station has five stacks. Here we present the analysis of emissions of PM, SO₂ and NO_x from the 1st stack of this TPP and the ambient air pollutant concentrations of PM₁₀, PM_{2.5}, SO₂, & NO_x in the immediate neighborhood of this power plant. We analyzed the data for the last three years (2018-2020) as provided by NTPC Limited, which is the developer for Sipat Power Plant, Chhattisgarh, India.

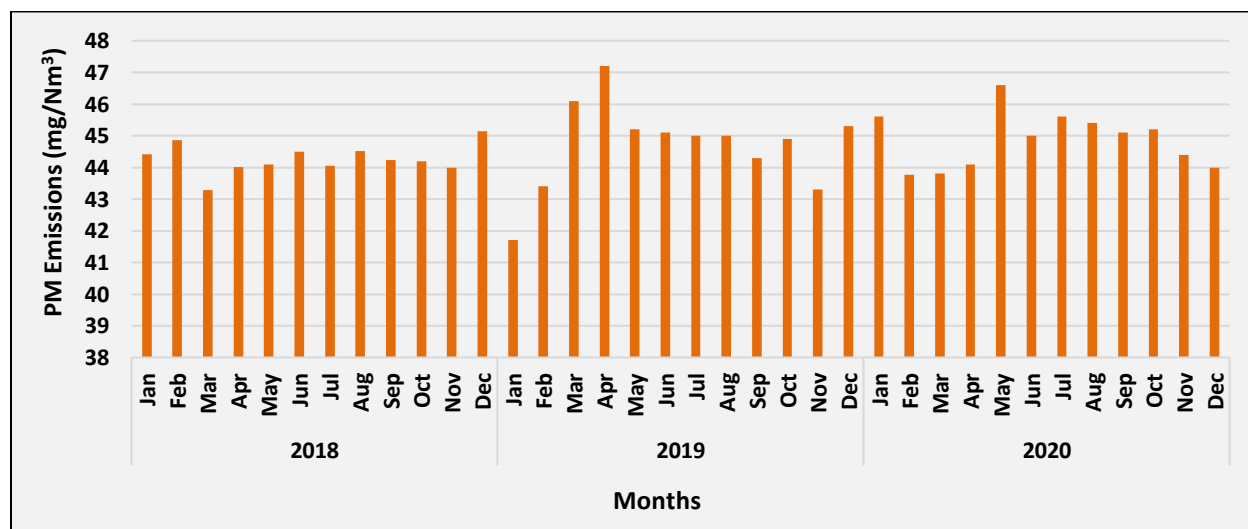


Figure 2.2: Time series of monthly average PM Emissions from Stack-1 in Sipat TPP

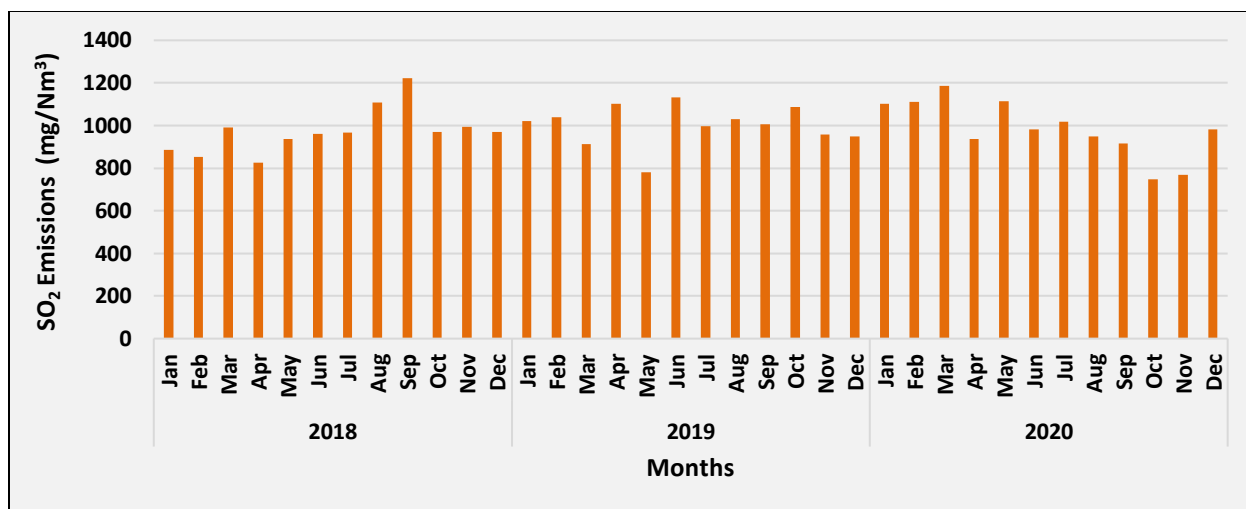


Figure 2.3: Time series of monthly average SO₂ Emissions from Stack-1 in Sipat TPP

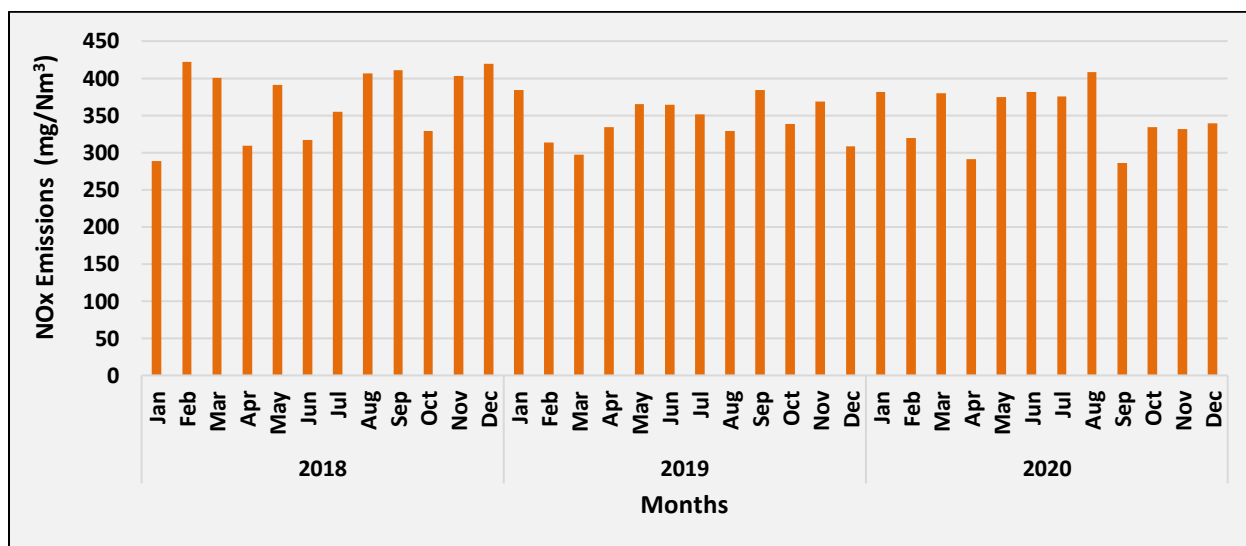


Figure 2.4: Time series of monthly average NO_x Emissions from Stack-1 in Sipat TPP

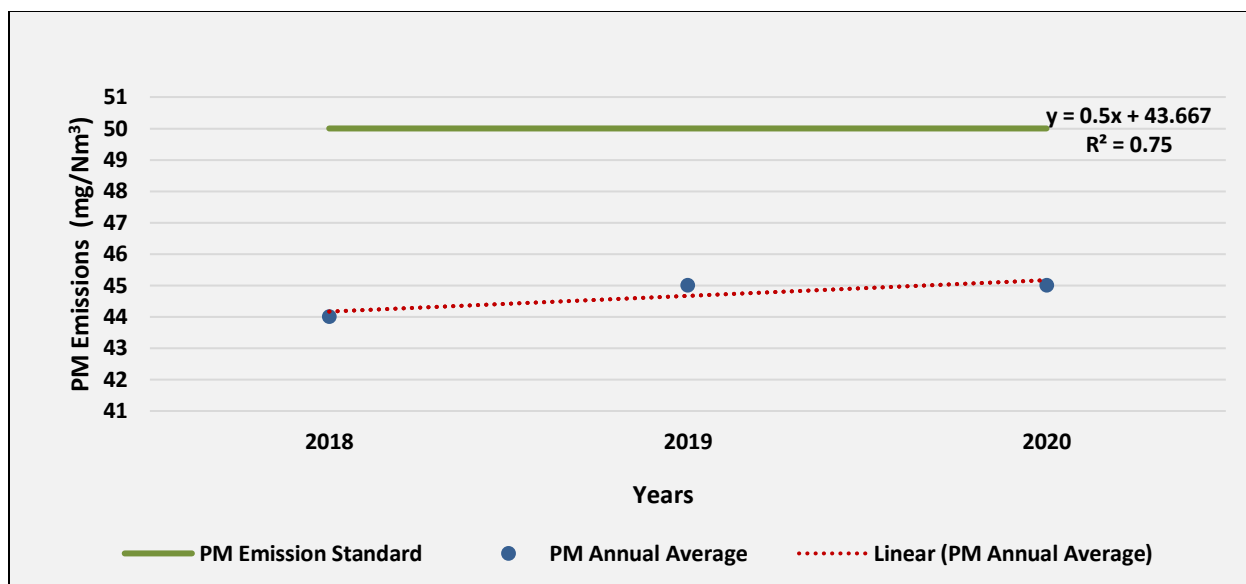


Figure 2.5: Trend of annual mean PM Emissions from Stack-1 in Sipat TPP

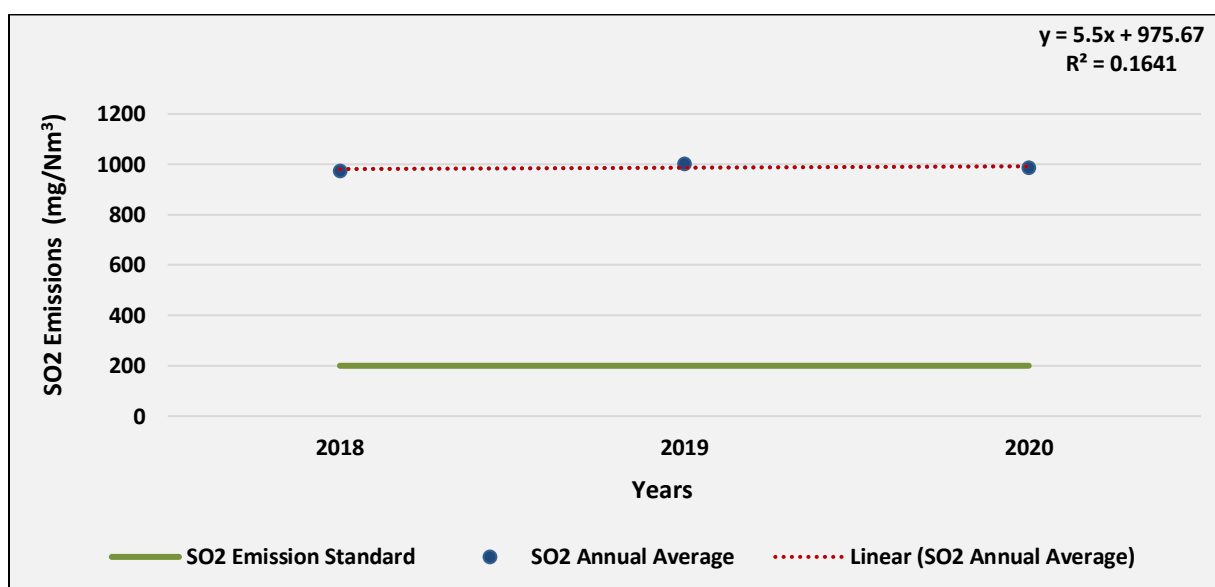


Figure 2.6: Trend of annual mean SO₂ Emissions from Stack-1 in Sipat TPP

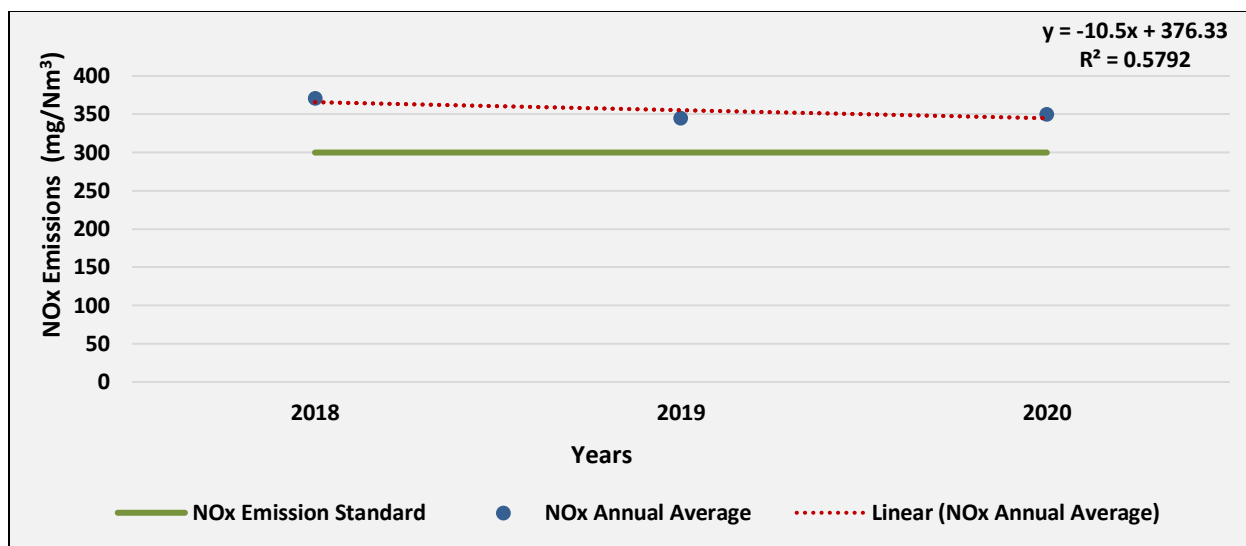


Figure 2.7: Trend of annual mean NO_x Emissions from Stack-1 in Sipat TPP

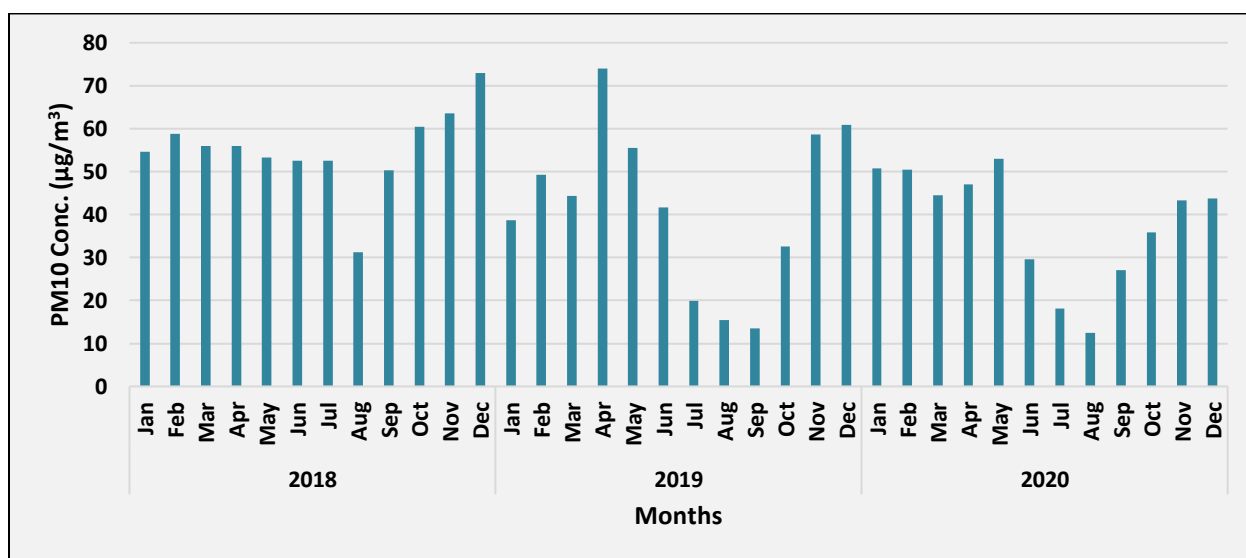


Figure 2.8: Time series of monthly average PM₁₀ ambient air concentrations in Sipat TPP (Ambient)

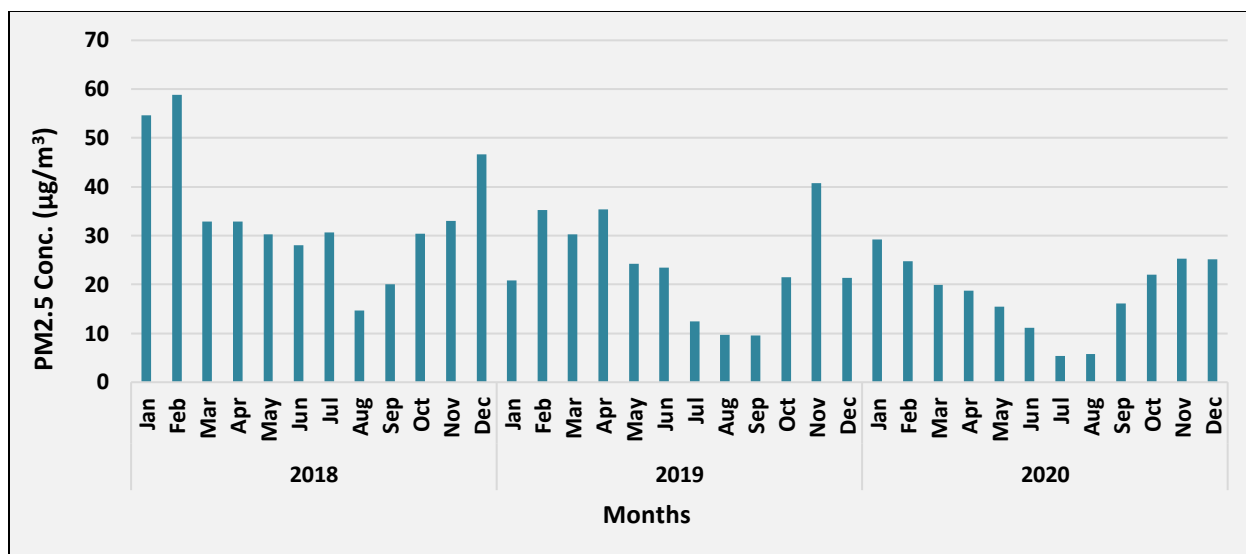


Figure 2.9: Time series of monthly average $PM_{2.5}$ ambient air concentrations in Sipat TPP (Ambient)

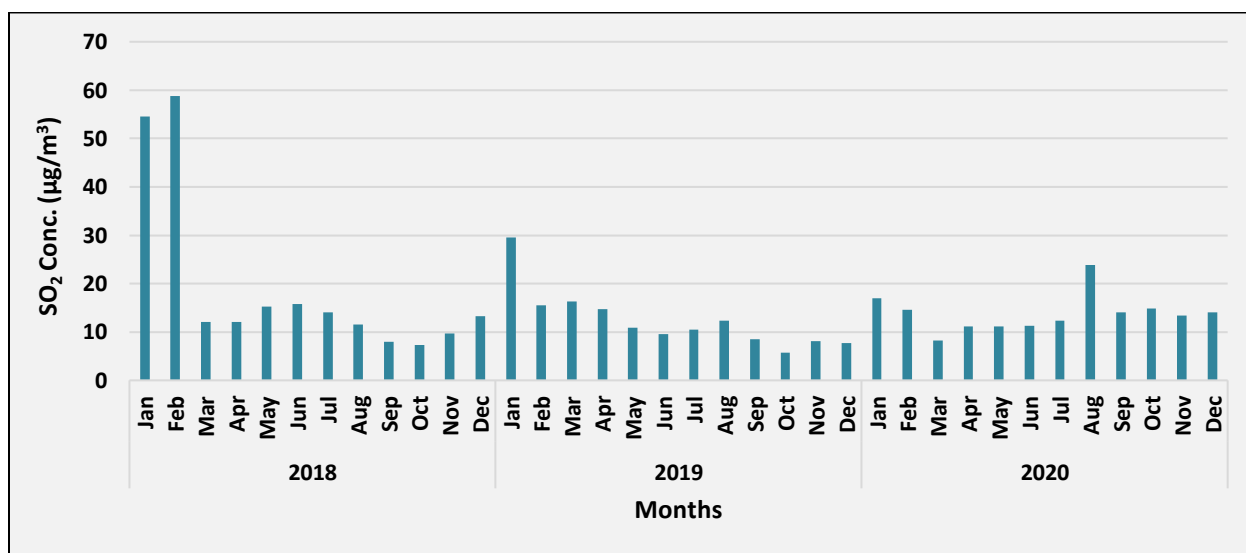


Figure 2.10: Time series of monthly average SO_2 ambient air concentrations in Sipat TPP (Ambient)

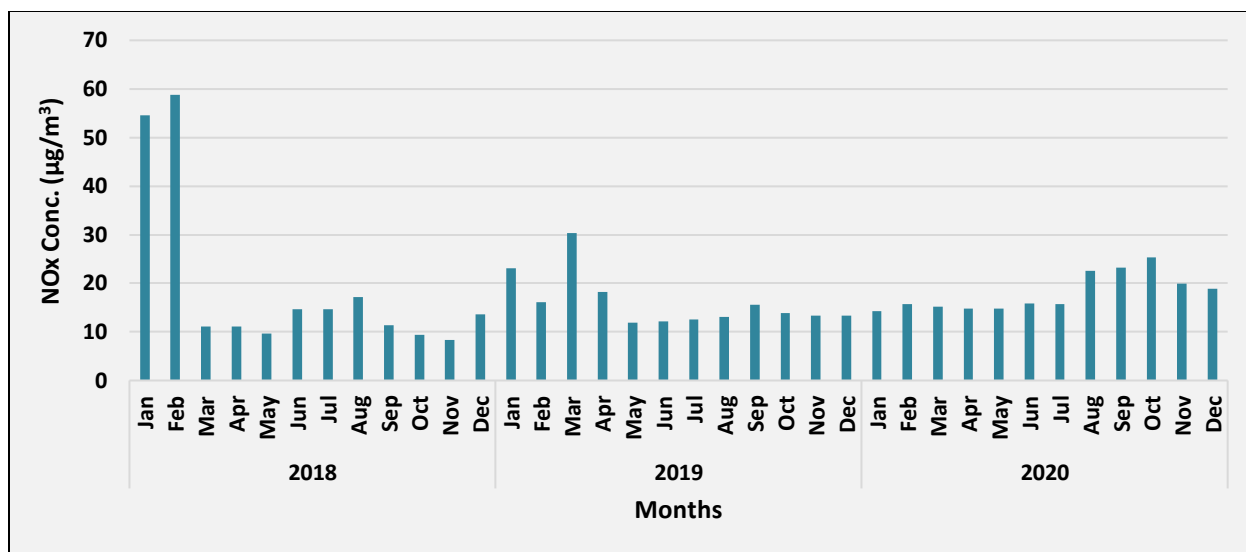


Figure 2.11: Time series of monthly average NO_x ambient air concentrations in Sipat TPP (Ambient)

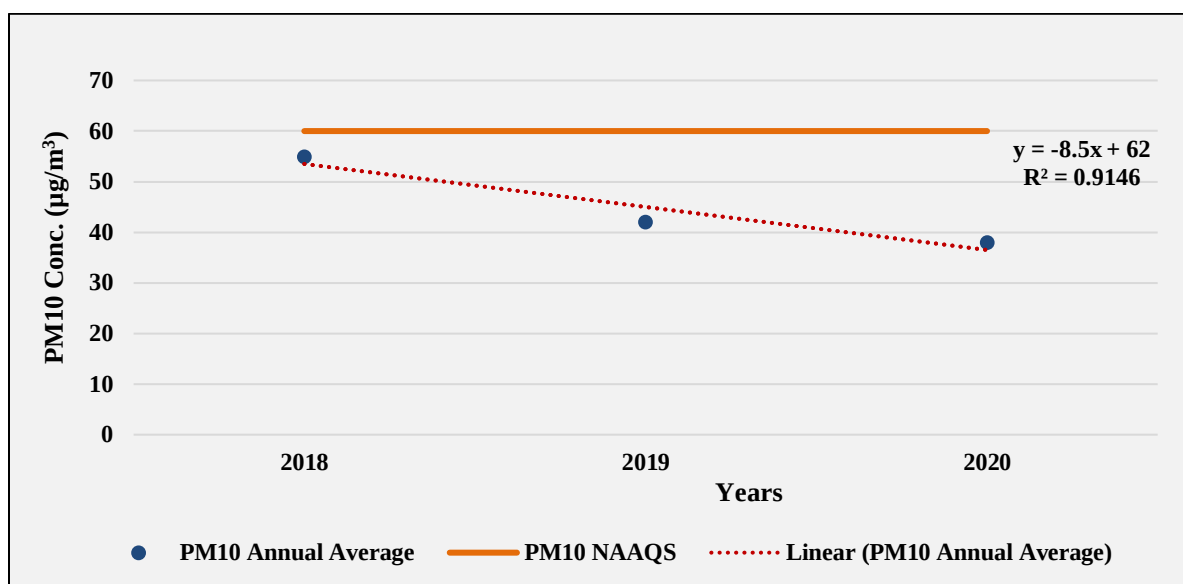


Figure 2.12: Trend of annual mean PM_{10} ambient air concentrations in Sipat TPP (Ambient)

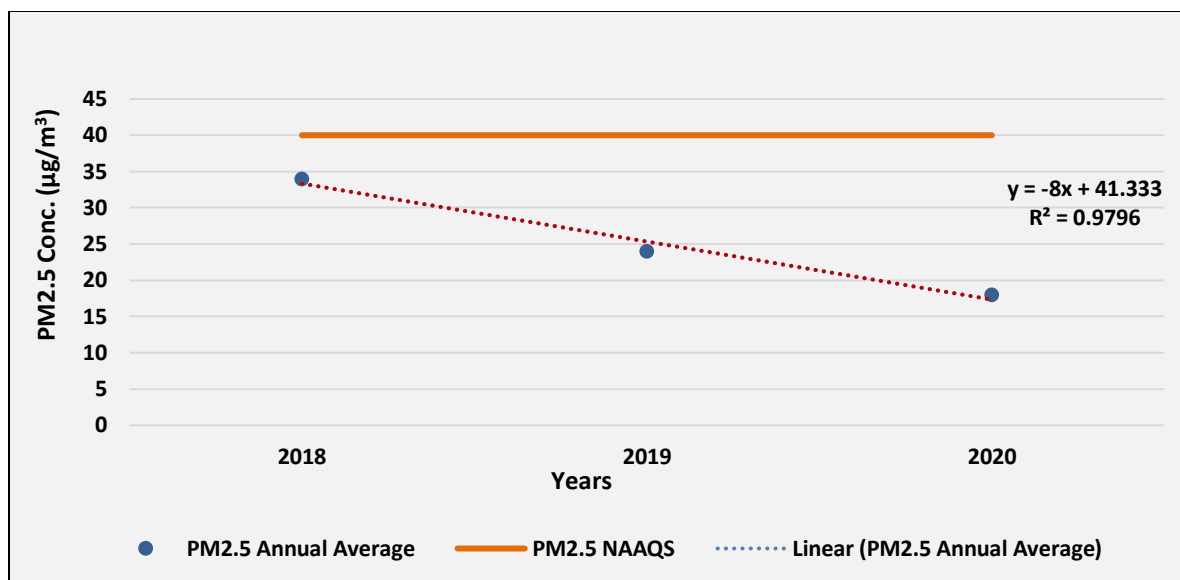


Figure 2.13: Trend of annual mean $PM_{2.5}$ ambient air concentrations in Sipat TPP (Ambient)

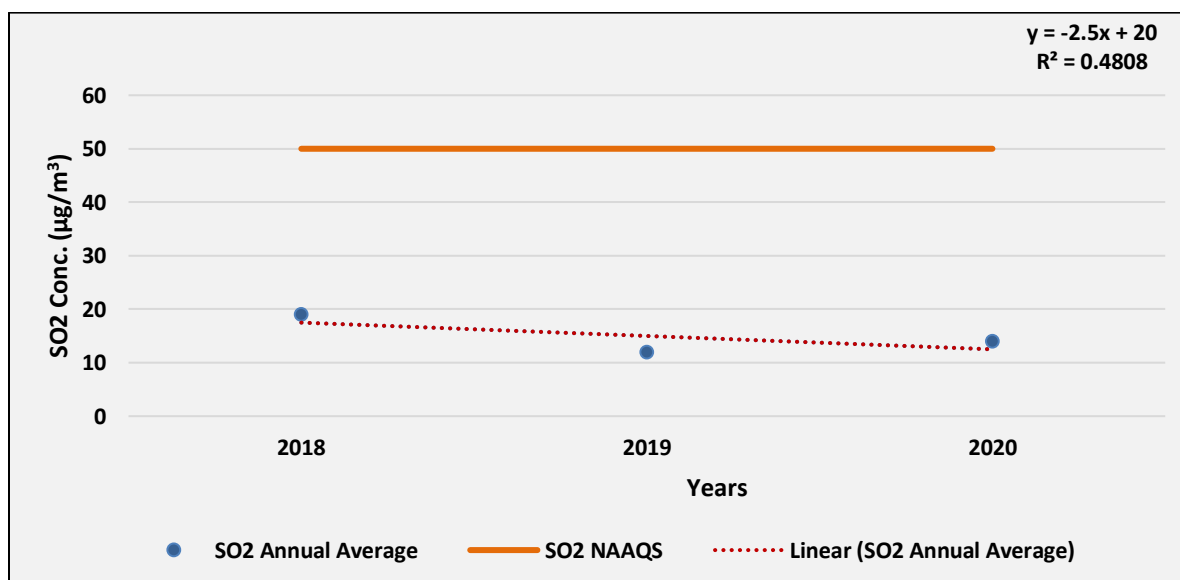


Figure 2.14: Trend of annual mean SO_2 ambient air concentrations in Sipat TPP (Ambient)

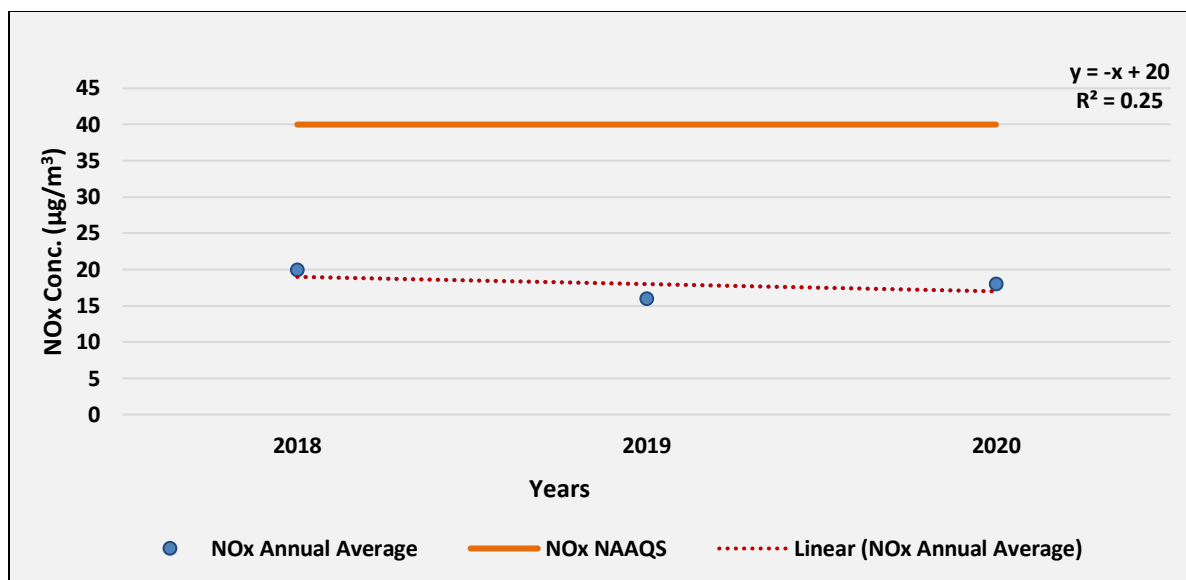


Figure 2.15: Trend of annual mean NO_x ambient air concentrations in Sipat TPP (Ambient)

It is evident from Figures 2.5-2.7 that the emissions of total PM, SO₂ and NO_x from the 1st stack of Sipat TPP are exceeding the limits for emissions of PM, SO₂, and NO_x from TPPs as per the Environment (Protection) Amendment Rules, 2015. However, it is also evident from Figures 2.12-2.15 that the monthly average and annual average near surface ambient air concentrations of PM₁₀, PM_{2.5}, SO₂ & NO_x in the immediate vicinity of this Sipat TPP are below the maximum limit specified for these air pollutant concentrations as per the National Ambient Air Quality Standards (NAAQS).

The analysis of emissions of PM, SO₂ and NO_x from other four stacks of Sipat TPP are provided in the Supplementary material provided along with this report. Additionally, detailed analysis of stack emissions and ambient air quality data from 240 stacks from 67 coal based TPPs across the country are provided in the Supplementary material provided along with this report.

Here we provide summary tables of the emissions of PM, SO₂ and NO_x as well as ambient air quality data from 240 stacks from 67 coal based TPPs across the country (For detailed analysis, see the Supplementary material provided along with this report). In all the following tables, if the monthly average and annual average near surface ambient air concentrations of PM₁₀, PM_{2.5}, SO₂ & NO_x in the immediate vicinity of any of the TPPs are within the maximum limit specified for these air pollutant concentrations as per the National Ambient Air Quality Standards (NAAQS) then such values are shown in green color while any violations of the NAAQS are shown in red color. Similarly, if the emissions of total PM, SO₂ and NO_x from the stacks of various TPPs are below the maximum limits for emissions of PM, SO₂, and NO_x from TPPs as per the Environment (Protection) Amendment Rules, 2015 then such values are shown in green color and if the emissions from any of the stacks in any of the TPPs exceed the maximum limits as per the same rules, they are shown in red color.

Summary for ambient concentration (Units: $\mu\text{g}/\text{m}^3$)

Sr. No.	TPP Name	Years	Ambient Concentration			
			PM10	PM2.5	SO2	NOx
1	Sipat TPP	2018	55	34	19	20
		2019	42	24	12	16
		2020	38	18	14	18
2	Korba TPP	2018	74	35	25	16
		2019	49	33	18	24
		2020	45	25	22	20
3	Mouda TPP	2018	67	31	11	16
		2019	56	31	17	19
		2020	64	42	11	23
4	Dadri TPP	2018	86	48	17	20
		2019	98	62	17	20
		2020	110	66	9	16
5	Ramagundam TPP	2018	61	29	24	26
		2019	72	36	19	22
		2020	60	23	17	20
6	Singrauli TPP	2018	73	48	10	19
		2019	73	44	9	17
		2020	76	48	10	17
7	Kudgi TPP	2018	69	31	10	17
		2019	67	30	11	19
		2020	76	33	18	15
8	Simhadri TPP	2018	47	29	13	22
		2019	42	26	18	21
		2020	44	25	16	20
9	Tanda TPP	2018	73	42	17	22
		2019	75	41	15	22
		2020	79	41	15	24
10	Vindychal TPP	2018	59	37	25	24
		2019	75	40	25	23
		2020	79	43	23	22
11	Rihand TPP	2018	50	34	17	19
		2019	66	39	12	20
		2020	60	36	13	21
12	Unchahar TPP	2018	78	49	8	26
		2019	71	36	12	27
		2020	68	40	9	23

Sr. No.	TPP Name	Years	Ambient Concentration			
			PM10	PM2.5	SO2	NOx
13	Kahalgaon TPP	2018	69	38	9	22
		2019	68	35	12	25
		2020	68	35	12	21
14	Farakka TPP	2018	77	36	14	21
		2019	67	34	16	21
		2020	44	24	14	19
15	Darlipali TPP	2020	57	31	16	12
16	Barh TPP	2018	73	37	8	15
		2019	78	39	9	15
		2020	72	35	8	13
17	Khargone TPP	2019	83	43	21	18
		2020	63	31	15	13
18	Solapur TPP	2018	70	36	6	8
		2019	69	34	7	13
		2020	60	32	11	16
19	Gadarwara TPP	2019	56	19	9	15
		2020	70	27	11	9
20	Lara TPP	2019	58	29	17	21
		2020	45	24	18	21
21	Baruani TPP	2020	79	46	12	16
22	Bongaigaon TPP	2018	60	28	8	12
		2019	60	30	8	17
		2020	69	37	7	18
23	Talcher TPP	2018	64	26	14	26
		2019	57	30	18	19
		2020	68	33	17	18

			Ambient 1				Ambient 2				Ambient 3				Ambient 4				Ambient 5				Ambient 6				
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
24	GSECL	Wanakbori Thermal Power Station	2016	68	37	16	13	46	46	46	46	63	30	16	13	43	22	12	11								
			2017	71	41	16	14	50	50	50	50	71	40	20	13	43	23	12	10								
			2018	65	39	14	11	51	51	51	51	68	38	21	14	48	21	10	8								
			2019	69	41	14	11	46	46	46	46	73	45	29	15	46	23	10	8								
			2020	67	41	15	13	51	51	51	51	76	45	34	16	46	26	12	9								
25		Gandhinagar Thermal Power Station	2016	92	48	9	10	110	49	10	10	86	48	9	9	75	44	8	8	101	53	9	10				
			2017	110	50	10	11	125	54	10	11	89	42	9	10	86	42	9	10	116	48	10	11				
			2018	105	46	11	13	118	53	11	13	91	43	10	11	79	41	11	12	105	43	12	14				
			2019	108	45	12	13	114	47	12	14	98	39	11	13	80	32	11	12	100	39	12	13				
			2020	103	39	11	13	112	47	12	14	100	43	11	13	78	32	10	12	88	33	11	15				
26		Sikka Thermal Power Station	2016	69	30	12	17	61	24	10	16	56	23	11	17	70	28	10	14	62	26	9	13	67	27	10	16
			2017	84	43	36	36	76	35	29	30	67	30	16	19	68	31	18	20	67	30	20	22	63	29	17	19
			2018	109	44	42	37	96	39	35	31	93	36	26	26	100	33	25	28	86	32	22	21	89	35	26	25
			2019	86	29	11	15	91	20	10	13	99	25	9	18	100	35	10	11	143	59	6	20	116	29	7	8
			2020	76	44	26	18	70	40	25	17	65	36	20	12	67	37	16	24	73	42	13	20	62	36	12	19
27		Ukai Thermal Power Station	2016	77	41	24	21	76	38	28	22	74	40	24	20	71	36	23	20								
			2017	73	28	21	20	73	28	25	21	74	28	27	19	57	18	18	19								
			2018	76	25	17	18	77	23	18	18	71	23	17	18	62	18	16	18								
			2019	78	26	19	20	80	30	21	21	81	27	17	18	76	26	15	18								
			2020	64	29	14	15	69	33	20	22	77	33	14	14	66	26	16	14								
28		Kutch Lignite Thermal Power Station	2016	64	29	22	24	63	28	23	26	63	27	22	26	60	27	23	26								
			2017	65	34	22	25	66	35	21	24	67	37	22	25	65	38	21	24								
			2018	64	33	21	24	66	35	23	28	63	34	22	27	66	31	21	25								
			2019	61	24	24	22	66	28	26	25	61	30	27	25	65	28	26	25								
			2020	62	25	19	21	64	28	21	24	62	27	22	23	62	27	22	24								

				Ambient 1				Ambient 2				Ambient 3			
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
29	Adani	Kawai Thermal Power Station	2018	76	32	12	12								
			2019	60	28	12	13								
			2020	61	31	15	16								
30		Raigarh Thermal Power Station	2020	68	35	22	14								
31		Raikheda Thermal Power Station	2020	56	31	14	15	56	22	11	14	71	27	33	13
32		Tirora Thermal Power Station	2015	80	33	12	20	78	33	12	20	74	30	12	19
			2016	68	31	10	19	65	31	10	18	66	31	11	19
			2017	61	33	11	28	62	32	11	28	61	31	11	28
			2018	66	31	12	26	60	27	12	26	65	30	12	26
			2019	51	24	12	23	48	20	12	22	53	23	13	23
			2020	63	26	11	21	50	25	11	20	67	28	13	24

				Ambient 1				Ambient 2				Ambient 3				Ambient 4			
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
33	Tata Power Co	Jojobera Thermal Power Station	2016	57	34	29	37	57	34	30	37	57	35	31	38	34	37	54	36
			2017	55	30	26	37	53	30	27	37	54	30	26	36	45	31	33	35
			2018	65	34	20	36	64	33	20	37	65	33	20	36	66	34	20	35
			2019	55	32	29	39	56	32	31	40	55	32	31	41	56	32	31	40
			2020	47	29	30	36	47	29	30	37	47	28	29	36	48	29	31	36
34		Maithon Thermal Power Station	2018	72	35	8	35												
			2019	72	35	8	35												
			2020	70	33	8	32												
35		Trombay Thermal Power Station	2016	74	33	27	24												
			2017	70	40	30	26												
			2018	71	39	24	26												
			2019	76	37	25	19												
			2020	63	26	26	25												
36	OP Jindal	Raigarh Thermal Power Station	2010	64	31	7	14	60.7	29	7	14	67	34	6	14	65.9	34	7	14
			2011	62.9	31	7	15	58	28	7	15	66.8	34	8	15	64.3	32	7	15
			2012	55	29	8	18	50	26	8	18	58	31	8	19	53	28	8	18
			2013	51	26	8	20	48	24	8	19	52	27	8	21	50	26	8	21
			2014	53	25	9	21	51	24	8	21	53	24	9	20	54	25	9	21
			2015	53	22	9	22	52	22	9	22	49	21	9	20	48	21	8	20
			2016	50	18	8	19	48	18	8	19	47	17	8	19	50	18	8	18
			2017	48	17	10	21	54	23	8	19	45	19	8	21	44	15	9	20
			2018	56	21	8	23	51	22	9	22	52	24	8	19	53	21	9	22
			2019	57	20	10	23	58	25	10	24	56	22	10	23	51	21	9	22
			2020	54	17	10	24	58	23	10	26	52	20	12	22	56	21	11	23
37		Tamnar Thermal Power Station	2010	60	30	7	14	57	27	6	13	49	25	6	13				
			2011	57	28	7	15	50	25	6	13	45	23	7	17	59	31	7	15
			2012	51	26	8	18	47	24	7	17	45	23	7	17	53	28	8	18
			2013	52	27	9	20	51	27	9	19	47	25	8	18	53	28	9	20
			2014	53	25	8	21	53	25	8	21	51	24	8	20	54	25	8	21
			2015	49	21	8	20	47	21	8	20	44	20	8	20	49	21	8	20
			2016	50	18	8	19	49	18	8	18	43	16	8	18	48	17	8	18
			2017	51	19	8	19	47	18	8	19	43	16	7	18	50	19	8	19
			2018	59	21	9	22	56	23	10	21	48	18	8	18	57	20	9	21
			2019	65	23	10	24	55	23	9	22	51	21	9	22	62	21	10	22
			2020	60	22	11	22	51	20	11	23	48	19	8	21	57	20	11	22

				Ambient 1			
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx
38	DVC	Durgapur Steel Thermal Power Station	2016	238	119	13	36
			2017	115	54	8	31
			2018	102	48	13	34
			2019	79	38	17	31
			2020	98	49	15	28
39		Bokaro -A Thermal Power Plant	2018	63	39	33	31
			2019	84	51	42	42
			2020	82	48	32	44
40		Chandrapura Thermal Power Plant	2016	63	32	43	33
			2017	76	41	29	36
			2018	77	42	26	42
			2019	81	49	31	43
			2020	74	51	41	45
41		Koderma Thermal Power Plant	2016	80	46	21	34
			2017	60	36	26	25
			2018	46	29	26	26
			2019	122	91	2	5
			2020	103	65	10	13
42		Mejia Thermal Power Plant	2016	62	34	40	45
			2017	70	33	28	39
	2018		49	30	28	36	
	2019		50	27	19	29	
	2020		42	20	16	24	
43	Raghunathpur Thermal Power Plant	2017	80	41	7	31	
		2018	69	39	7	36	
		2019	82	41	10	31	
		2020	101	47	15	31	

				Ambient 1				Ambient 2				Ambient 3				Ambient 4			
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
44	GMR	Kamalanga Energy Limited	2014	56	32	7	13												
			2015	57	33	7	13												
			2016	61	34	7	17												
			2017	67	35	8	18												
			2018	76	40	10	20												
			2019	60	32	12	16												
			2020	67	35	14	17												
45		Warora Energy Limited	2014	20	13	16	12												
			2015	22	10	15	12												
			2016	19	13	12	9												
			2017	21	8	10	7												
			2018	21	11	13	10												
			2019	19	13	13	12												
			2020	17	13	9	5												
46	Sembcorp Energy India Ltd.	Sembcorp Gayatri P.Ltd.	2019	68	29	16	21	56	27	15	19	54	46	15	19	49	25	14	18
2020			61	24	14	17	51	20	12	15	51	19	12	15	50	19	12	15	
47		PAINAMPURAM TPP	2019	71	32	16	18	57	24	14	16	59	26	14	16	59	26	14	16
2020			53	21	18	23	60	26	15	17	62	28	16	17	61	27	15	17	

Sr. No.	Developer	TPP Name	Years	Ambient 1				Ambient 2				Ambient 3				Ambient 4			
				PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
48	CHINA LIGHT POWER	MAHATMA GANDHI TPS/Jhajjar TPP	2012	87	52	22	36												
			2013	71	43	11	23												
			2014	62	30	10	25												
			2015	123	54	7	43												
			2016	135	50	10	29												
			2017	101	53	26	34												
			2018	102	59	21	36												
			2019	146	72	24	40												
			2020	104	59	22	38												
49	HPGCL	Panipat Thermal Power Station	2011	229	NA	15	17												
			2012	228		12	13												
			2013	133		11	18												
			2014	93	56	22	27												
			2015	87	50	28	33												
			2016	90	49	28	33												
			2017	70	34	14	24												
			2018	84	46	17	26												
			2019	88	47	18	29												
50		Yamuna Nagar Thermal Power Station	2020	90	47	14	24												
			2014	88	53	28	25	94	50	29	25								
			2015	85	47	28	31	91	51	30	34								
			2016	82	44	22	31	81	44	22	29								
			2017	83	46	15	27	84	46	17	27								
			2018	88	44	15	20	89	45	18	23								
51	GVK	Nabha Thermal Power Plant	2019	92	51	11	25	86	48	10	28								
			2020	92	51	11	18	88	49	11	29								
			2014	NA				NA				83	49	4	20	83	47	4	18
			2015	89	50	4	14	83	49	7	17	84	45	4	13	82	45	4	11
			2016	82	46	4	10	87	48	4	12	80	46	4	13	80	46	3	10
			2017	70	38	7	22	75	45	4	10	71	37	8	21	72	37	7	16
			2018	72	38	8	26	69	38	10	16	67	38	10	19	65	38	11	25
52		Goindwal Thermal Power Plant	2019	72	38	9	24	70	39	8	27	72	41	10	19	72	41	9	20
			2020	79	38	9	17	69	40	9	20	73	42	9	22	67	40	9	22
			2017	83	48	39	34												
			2018	86	49	19	24												
53	TAQA	TAQA, Neyveli	2019	74	38	11	17												
			2020	69	40	11	22												
			2015	38	14	10	16												
			2016	42	15	10	18												
			2017	49	14	10	19												
53			2018	50	17	11	19												
			2019	52	20	11	20												
			2020	52	21	10	15												

				Ambient 1				Ambient 2				Ambient 3				Ambient 4				Ambient 5				Ambient 6				Ambient 7				Ambient 8			
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx				
54	Mahagenco	Parli Thermal Power Station	2016	53	14	22	29																												
			2017	50	13	21	28																												
			2018	49	14	21	27																												
			2019	49	17	20	23																												
			2020	49	18	20	21																												
55		Chandrapur Thermal Power Plant	2011	28	60	10	22																												
			2012	26	54	12	20																												
			2013	23	47	11	15																												
			2014	25	58	16	20																												
			2015	18	57	16	18																												
			2016	17	57	18	23																												
			2017	28	67	21	25																												
			2018	25	58	21	28																												
			2019	29	56	32	37																												
			2020	29	55	28	32																												
56		Paras Thermal Power Plant	2010	149	54	29	25	129	45	26	23	144	54	29	25																				
			2011	78	40	45	35	73	37	41	35	78	43	42	36																				
			2012	69	37	45	41	67	37	49	45	66	41	45	42																				
			2013	56	19	20	17	48	17	19	17	54	18	21	17																				
			2014	66	17	23	19	55	15	20	17	67	18	24	20																				
			2015	71	17	20	18	59	14	18	16	70	17	21	19																				
			2016	70	19	21	20	59	17	18	18	64	19	20	19																				
			2017	72	20	23	21	66	18	20	20	70	18	21	20																				
			2018	66	19	16	19	60	17	15	18	63	18	16	18																				
			2019	59	23	15	17	60	22	14	16	57	22	15	21																				
2020		63	13	14	14	60	13	14	13	67	14	16	15																						
57		Bhusawal Thermal Power Plant	2017	71	22	16	21	88	28	21	27	69	21	17	21	74	25	18	23	85	26	20	26	92	28	22	28	70	22	15	22	90	28	20	26
			2018	67	22	14	20	80	27	19	24	68	22	14	21	68	23	15	21	81	26	17	24	87	27	20	26	69	23	14	20	87	26	18	23
			2019	61	23	13	19	77	28	17	23	62	23	13	20	62	23	14	20	68	25	14	19	71	26	16	21	58	22	12	18	70	26	15	20
			2020	65	25	10	19	71	27	13	22	69	26	10	19	62	24	10	18	66	30	12	19	73	35	15	23	59	27	11	18	72	35	15	22

Sr. No.		TPP Name	Years	Ambient 1				Ambient 2				Ambient 3				Ambient 4				Ambient 5			
				PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx
58		Koradi Thermal Power Plant	2011	NA				31	96	11	23	NA											
			2012	33	97	11	24	22	84	10	21	32	97	12	23								
			2013	22	87	10	21	12	67	10	20	22	82	11	21								
			2014	11	80	10	20	12	79	12	21	11	73	10	20								
			2015	13	90	12	22	13	79	13	22	13	89	12	22								
			2016	15	91	15	24	23	65	13	20	14	82	14	23								
			2017	29	84	17	24	28	69	13	21	26	72	15	23								
			2018	34	96	16	24	31	69	12	18	31	79	15	23								
			2019	36	101	16	22	24	60	12	16	33	81	15	21								
			2020	30	96	15	19	38	33	20	30	26	72	14	18								
59	Mahagenco	Khaperkheda Thermal Power Plant	2001	37	32	19	30	42	37	14	29	34	30	18	56	NA				NA			
			2002	41	36	14	27	58	47	14	20	37	32	13	25								
			2003	57	44	14	20	105	54	22	23	53	48	15	20								
			2004	90	48	21	23	87	51	16	22	91	47	21	22								
			2005	80	47	15	21	102	64	11	21	77	47	15	21								
			2006	93	59	10	20	81	87	11	21	87	55	10	19								
			2007	71	79	11	20	190	112	11	22	72	79	10	20								
			2008	174	104	11	21	212	103	11	20	180	97	11	21								
			2009	203	100	11	20	251	121	12	21	183	91	17	21								
			2010	249	121	12	20	255	123	12	20	210	104	13	19								
			2011	257	124	12	20	106	64	14	22	218	106	11	18								
			2012	105	61	14	22	103	45	13	22	91	54	13	21								
			2013	98	41	12	21	83	41	14	23	84	38	11	19								
			2014	78	33	14	23	88	30	14	24	61	27	10	18								
			2015	82	27	12	28	77	28	13	24	68	22	9	20	80	26	12	23	87	29	13	24
			2016	69	24	12	23	79	36	15	25	59	20	10	20	75	27	13	24	71	25	12	23
			2017	72	33	13	23	79	35	12	22	63	29	11	21	65	30	12	21	80	36	15	25
			2018	73	31	12	20	67	30	12	20	69	28	10	18	53	25	10	17	79	34	13	22
			2019	68	30	12	20	71	27	13	20	57	26	10	18	49	25	10	17	64	29	12	20
			2020	65	24	12	20	32	18	20	28	52	21	10	16	50	20	10	16	63	24	12	19
60		Nashik Thermal Power Plant	2012	33	19	21	29	36	18	26	18	40	24	27	36	46	30	36	48				
			2013	33	17	25	19	52	17	18	14	54	25	31	21	58	26	35	24				
			2014	41	14	16	13	44	23	15	11	61	19	20	17	71	23	23	18				
			2015	38	21	13	10	56	22	14	13	53	29	20	15	60	29	23	17				
			2016	57	22	12	12	59	21	9	8	67	23	22	20	68	23	24	21				
			2017	65	23	9	8	60	15	7	6	79	27	18	17	80	28	20	19				
			2018	58	15	6	5	63	20	8	8	79	19	16	15	81	19	17	16				
			2019	57	18	7	8	39	16	7	8	72	23	11	13	80	27	14	15				
			2020	36	14	6	7	NA				45	19	8	9	49	23	9	10				

				Ambient 1				Ambient 2				Ambient 3				Ambient 4				Ambient 5				
Sr. No.	Developer	TPP Name	Years	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	PM10	PM2.5	SO2	NOx	
61	Karnataka Power Corporation Ltd.	Bellary Thermal Power Station	2017	161	65	37	38	NA				NA				NA				NA				
			2018	97	50	25	31																	
			2019	79	36	26	30																	
			2020	96	40	26	35																	
62		Raichur Thermal Power Plant	2015	54	31	17	12	50	29	10	14	54	26	14	14	37	10	5	8	39	11	5	7	
			2016	61	32	19	13	46	23	9	15	54	30	16	18	53	15	7	9	47	14	7	9	
			2017	57	29	9	14	56	21	12	22	58	29	7	20	67	19	10	13	60	17	9	13	
			2018	58	23	17	27	51	19	11	11	48	22	11	35	65	20	9	13	61	18	9	13	
			2019	54	21	11	9	59	19	10	12	48	17	9	9	70	20	8	11	70	21	9	12	
63		Yermarus Thermal Power Station	2020	66	21	11	14					55	20	9	12	64	22	10	13	61	21	9	12	
			2018	109	54	98	25																	
				2019	85	40	87	20																
				2020	27	41	72	5																
64	APGENCO	Dr.Narla Tata Rao Thermal Power Station	2012	80	23	39	49	69	24	34	47	NA				67	17	34	46	62	22	32	44	
			2013	72	24	37	48	61	26	28	38	76	27	41	51	61	18	33	44	62	22	35	45	
			2014	70	31	32	42	84	35	29	37	77	36	36	44	59	25	28	36	67	28	32	41	
			2015	99	44	33	42	60	29	24	30	90	43	33	42	63	23	25	33	82	36	31	39	
			2016	84	37	30	37	57	31	17	24	95	38	31	39	45	20	19	25	75	28	27	34	
			2017	88	35	24	32	73	32	21	28	90	38	26	34	52	22	17	23	84	35	25	33	
			2018	89	42	27	35	71	29	19	26	93	44	28	37	61	26	18	27	82	37	26	34	
			2019	90	42	27	34	72	32	22	28	79	35	23	31	69	29	20	26	75	32	22	29	
				2020	90	43	28	35	NA				84	42	26	33	66	31	18	24	71	33	20.8	28
65		Rayalaseema Thermal Power Station	2000	NA				164	29	15	12	NA												
			2008	171	30	16	13	171	30	18	14	147	27	12	10	148	26	11	10	NA				
			2009	169	30	16	14	165	29	20	18	154	28	15	13	148	28	14	12					
			2010	159	31	20	17	143	40	25	21	146	26	17	15	142	24	16	15					
	2011		138	38	24	20	177	55	35	31	130	35	21	19	123	33	20	18						
	2012		164	52	33	30	181	63	39	37	150	46	31	29	135	41	29	28	187	57	40	37		
	2013		179	62	38	35	77	52	25	24	171	61	37	34	155	52	34	33	181	63	38	35		
	2014		74	51	27	25	72	52	21	19	72	48	25	24	69	47	25	24	77	52	27	26		
	2015		68	47	20	19	65	46	18	17	65	44	19	19	61	42	19	18	72	51	20	19		
	2016		62	44	17	17	57	42	17	16	59	42	17	18	56	42	17	17	66	45	17	18		
	2017		56	40	15	16	54	31	15	14	51	39	15	16	49	37	16	15	55	41	15	17		
	2018		53	28	14	14	51	23	16	15	49	27	12	14	46	24	13	13	54	29	12	14		
66	NLC India Limited	Barsingsar Thermal Power Station	2019	52	22	16	15	39	19	13	12	50	25	17	16	48	21	15	15	50	23	15	16	
			2020	41	17	12	12	NA				37	15	12	12	36	16	13	12	38	17	13	12	
			2012	215	65	26	34																	
			2013	251	71	18	20																	
			2014	200	67	12	19																	
			2015	92	45	8	24																	
			2016	94	40	9	25																	
			2017	96	47	8	27																	
			2018	109	43	8	25																	
			2019	78	36	8	21																	
67		Neyveli New Thermal Power Station	2020	82	15	5	9																	

Summary for Particulate Matter Emissions (Units: mg/Nm³)

				PM						
Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
1	NTPC	Korba Super Thermal Power Station	2018	42	40	37	45	41	41	41
			2019	43	41	41	41	39	38	42
			2020	42	42	37	42	43	40	46
2		Unchahar TPP	2018	95	79	39	33	39	45	
			2019	93	78	38	26	40	40	
			2020	86	67	40	27	35	38	
3		Sungrauli TPP	2018	96	92	94	90	94	94	93
			2019	88	87	86	85	84	84	86
			2020	90	87	87	80	87	85	88
4		Talcher Super TPP	2018	54	74	67	68	43	42	
			2019	54	62	67	67	61	41	
			2020	69	62	62	62	74	43	
5		Farakka TPP	2018	111	79	112	134	141	41	
			2019	118	77	113	134	136	42	
			2020	78	79	83	105	106	43	
6		Barauni TPP	2020	43						
7		Gadarwara TPP	2019	26						
			2020	25						
8		Darlipalii TPP	2020	23						

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	Stack 9	Stack 10	Stack 11	Stack 12	Stack 13
9		Lara TPP	2019	26												
			2020	26	29											
10		Kudgi TPP	2018	22	25	25										
			2019	22	26	22										
			2020	24	20	17										
11		Khargone TPP	2020	20	26											
12		Bongaigaon TPP	2018	32	39											
			2019	34	39	38										
			2020	43	36	38										
13		Solapur TPP	2018	28												
			2019	26												
			2020	26	24											
14		Vindhyachal	2018	108	108	108	105	109	105	70	69	49	47	45	45	44
			2019	95	95	94	94	94	95	73	73	46	46	46	46	45
			2020	93	94	94	94	94	94	73	76	45	45	45	44	45
15		Tanda	2018	107	116	126	101									
			2019	80	79	75	75	29								
			2020	81	80	76	74	26								
16		Sipat TPP	2018	44	38	38	37	38								
			2019	45	40	37	37	37								
			2020	45	39	33	37	41								

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	Stack 9	Stack 10	Stack 11	Stack 12	Stack 13
17		Rihand TPP	2018	69	70	45	43	43	42							
			2019	77	78	45	43	44	44							
			2020	82	76	46	44	43	42							
18		Barh TPP	2018	30	29											
			2019	33	34											
			2020	27	29											
19		Simhadhri TPP	2018	52	56	33	39									
			2019	45	40	30	29									
			2020	47	40	17	31									
20		Kahalgaon TPP	2018	137	146	146	146	47	46	46						
			2019	141	144	145	141	46	46	45						
			2020	140	143	138	141	43	44	43						
21		Ramagundam TPP	2018	84	85	86	96	98	97	44						
			2019	84	87	91	96	97	91	41						
			2020	84	86	83	73	91	86	46						
22		Mouda TPP	2018	43	43	46	27									
			2019	46	46	46	27									
			2020	43	45	41	28									
23		Dadri TPP	2018	49	48	47	51	30	30							
			2019	50	46	44	46	32	31							
			2020	45	38	39	42	31	30							

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
24	GSECL	Wanakbori Thermal Power Station	2016	198	162	190	154	127	157	95
			2017	113	184	195	117	116	103	88
			2018	78	85	78	106	96	105	75
			2019	91	82	95	107	95	113	70
			2020	96	91	86	84	88	98	80
25		Gandhinagar Thermal Power Station	2016			91	89	84		
			2017			96	108	87		
			2018			102	111	74		
			2019			101	97	66		
			2020			112	94	60		
26		Sikka Thermal Power Station	2016			33	34			
			2017			31	34			
			2018			43	35			
			2019			10	9			
			2020			13	12			
27		Ukai Thermal Power Station	2016			133	169	149	67	
			2017			115	107	106	47	
			2018			93	94	80	37	
			2019			93	93	78	44	
			2020			82	84	90	47	
28		Kutch Lignite Thermal Power Station	2016	131	134	136				
			2017	147	147	141				
			2018	150	142	144				
			2019	168	176	176				
			2020			158				

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
29	Adani	Kawai Thermal Power Station	2018	21	43						
			2019	44	43						
			2020	46	44						
30		Raigarh Thermal Power Station	2020	46							
31		Raikheda Thermal Power Station	2020	35							
32		Tirora Thermal Power Station	2015	35	33	40	37	36			
			2016	36	36	40	35	35			
			2017	45	41	43	37	32			
			2018	45	44	44	43	41			
			2019	44	37	36	45	42			
			2020	44	43	43	43	41			
	33	Jojobera Thermal Power Station	2016	74	74	74	49	49			
			2017	75	75	75	50	49			
			2018	74	74	73	48	48			
			2019	73	74	74	49	49			
2020			69	70	70	46	46				
34	Tata Power Co	Maithon Thermal Power Station	2018	35	37						
			2019	28	29						
			2020	38	38						
35	Trombay Thermal Power Station	2016					95			26	
		2017					94			24	
		2018					79			28	
		2019					39			31	
		2020					28			28	
36	OP Jindal	Raigarh Thermal Power Station	2008	36	38	37	40				
			2009	35	34	36	37				
			2010	40	40	40	43				
			2011	38	39	38	42				
			2012	37	39	39	40				
			2013	38	38	38	39				
			2014	38	38	38	39				
			2015	39	38	39	39				
			2016	39	38	39	39				
			2017	37	39	38	37				
			2018	40	38	39	40				
			2019			39	37				
37		Tamnar Thermal Power Station	2020	40	41	40	41				
			2014	41	41						
			2015	38	38						
			2016	39	38						
			2017	39	39						
			2018	38	40	38	43				
			2019	37	40	36	42				
			2020	41	42	41	40				

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	
38	DVC	Durgapur Steel Thermal Power Station	2016	34	32							
			2017	44	42							
			2018	30	31							
			2019	40	34							
2020		44	38									
39		Bokaro -A Thermal Power Plant	2018	30								
			2019	29								
			2020	32								
40		Chandrapura Thermal Power Plant	2016	38	42							
			2017	40	44							
			2018	37	39							
			2019	45	44							
			2020	43	43							
41		Koderma Thermal Power Plant	2016	37	43							
			2017	38	38							
			2018	41	40							
			2019	36	33							
			2020	33	31							
42		Mejia Thermal Power Plant	2016	105	105	95	129	70	66	36	43	
			2017	107	83	98	37	35	29	34	19	
			2018	111	115	187	48	54	47	31	33	
			2019	184	150	183	54	46	42	28	26	
			2020	105	99	108	36	41	36	32	34	
43		Raghunathpur Thermal Power Plant	2017	16	16							
			2018	42	36							
			2019	53	44							
	2020		53	50								

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3
44	GMR	Kamalanga Energy Limited	2014	34	33	35
			2015	34	34	30
			2016	43	39	34
			2017	40	42	38
			2018	41	44	44
			2019	38	28	30
			2020	34	34	34
45		Warora Energy Limited	2014	41	40	
			2015	40	40	
			2016	30	31	
			2017	37	38	
			2018	41	35	
			2019	42	42	
			2020	36	44	
46	Sembcorp Energy India Ltd.	Sembcorp Gayatri P.Ltd.	2019	33	37	
		2020	40	36		
47		PAINAMPURAM TPP	2019	34	32	
			2020	35	30	

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2
---------	-----------	----------	-------	---------	---------

48	CHINA LIGHT POWER	MAHATMA GANDHI TPS/Jhajjar TPP	2012	27	
			2013	109	
			2014	90	
			2015	68	
			2016	37	
			2017	34	
			2018	34	
			2019	23	
			2020	25	
49	HPGCL	Panipat Thermal Power Station	2011	162	159
			2012	202	173
			2013	343	244
			2014	136	133
			2015	126	126
			2016	117	110
			2017	119	126
			2018	37	42
			2019	40	39
			2020	40	37
50		Yamuna Nagar Thermal Power Station	2008	126	173
			2009	95	118
			2010	136	137
			2011	93	110
			2012	97	91
			2013	101	99
			2014	116	120
			2015	99	94
			2016	90	90
			2017	103	102
			2018	62	98
			2019	40	99
2020		42	39		

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
51	GVK	Nabha Thermal Power Plant	2014	43	47						
			2015	43	41						
			2016	45	41						
			2017	40	42						
			2018	42	41						
			2019	41	43						
			2020	46	42						
52		Goindwal Thermal Power Plant	2017	44	43						
			2018	43	45						
			2019	44	44						
			2020	37	37						
53	TAQA	TAQA, Neyveli	2015	34							
			2016	17							
			2017	20							
			2018	36							
			2019	33							
			2020	18							
54		Parli Thermal Power Station	2018						72	62	43
			2019						52	47	47
			2020						52	47	47
55		Chandrapur Thermal Power Plant	2016			107	107	107	108	109	49
			2017			94	88	108	105	101	53
			2018			91	87	95	94	93	32
			2019			88	85	93	92	93	28
			2020			89	89	92	93	95	26
56	Mahagenco	Paras Thermal Power Plant	2010			87	81				
			2011			86	82				
			2012			88	76				
			2013			93	81				
			2014			98	86				
			2015			90	86				
			2016			90	85				
			2017			87	85				
			2018			84	84				
			2019			79	82				
			2020			75	69				
57		Bhusawal Thermal Power Plant	2017	82	83	90					
			2018	71	85	82					
			2019	76	72	73					
			2020	NA	45	47					

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	
58	Mahagenco	Koradi Thermal Power Plant	2011						375	259		
			2012						829	259		
			2013						837	361		
			2014						575	283		
			2015						732	416		
			2016						NA	302		
			2017						NA	241		
			2018						NA	314		
			2019						163	238		
			2020						128	NA		
59		Khaperkheda Thermal Power Plant	2001	210	193							
			2002	169	158	103	108					
			2003	185	172	106	108					
			2004	208	186	122	120					
			2005	163	163	106	118					
			2006	132	149	126	124					
			2007	134	136	129	122					
			2008	140	127	126	121.5					
			2009	138	138	128	116					
			2010	134	131	118	127					
			2011	135	132	113	127					
			2012	130	114	118	110	76				
			2013	133	133	124	107	67				
			2014	166	164	144	120	55				
			2015	144	148	121	107	57				
			2016	183	192	130	109	50				
			2017	238	253	144	124	48				
			2018	232	260	98	95	47				
			2019	224	232	102	93	44				
			2020	203	204	98	94	44				
60		Nashik Thermal Power Plant	2016	74	236	239						
			2017	87	164	167						
			2018	89	138	137						
			2019	89	140	139						
			2020	102	142							
61	Karnataka Power Corporation Ltd.	Bellary Thermal Power Station	2017	120	93	112						
			2018	136	152	162						
			2019	145	151	121						
			2020	68	99	81						
62		Raichur Thermal Power Station	2013	87	99	95	103	106	114	97	110	
			2014	99	93	115	104	107	105	104	98	
			2015	123	121	133	107	117	131	108	90	
			2016	139	140	143	138	140	142	134	92	
			2017	132	134	147	122	128	133	117	72	
			2018	135	132	148	85	118	127	129	66	
			2019	151	129	141	95	123	130	133	73	
63		Yermarus Thermal Power Station	2020	106	152	142	122	97	117	162	106	
			2018	48								
	2020		43									

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
64	APGENCO	Dr.Narla Tata Rao Thermal Power Station	2012	122	140	115	121	127	159	75
			2013	106	129	119	111	111	109	76
			2014	110	119	111	103	106	108	73
			2015	107	104	126	107	113	111	86
			2016	104	103	133	115	106	104	79
			2017	124	127	151	149	106	113	82
			2018	137	123	139	135	110	120	96
			2019	123	117	124	133	100	102	93
			2020	109	112	120	114	96	101	91
65		Rayalaseema Thermal Power Station	2008	103	102	102	93	159		
			2009	101	106	106	77	82		
			2010	96	100	100	56	90		
			2011	98	97	97	53	85		
			2012	115	112	112	65	89		
			2013	107	108	108	69	98		
			2014	106	108	108	73	83		
			2015	109	108	108	88	67		
			2016	106	104	104	66	68		
			2017	106	105	105	62	74		
			2018	107	101	101	56	68		
			2019	103	102	102	67	74		
			2020	102	102	102	73			
66	NLC India Limited	Barsingsar Thermal Power Station	2012	93	91					
			2013	74	71					
			2014	38	37					
			2015	85	86					
			2016	79	78					
			2017	78	63					
			2018	78	62					
			2019	61	58					
			2020	60	58					
67			Neyveli New Thermal Power	2020	26					

Summary for SO₂ Emissions (Units: mg/Nm³)

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
1	Korba Super Thermal Power Station	2018	1030	1077	1074	1111	1079	1184	1082
		2019	1084	1047	1070	1095	1081	1118	1079
		2020	1125	1118	1145	1127	1150	1151	1160
2	Unchahar TPP	2018	1089	1300	1101	1119	1155	1209	
		2019	1057	1303	1156	1179	1129	1220	
		2020	1065	2336	1181	1098	1129	1201	
3	Singrauli TPP	2018	1021	1136	949	983	1010	1067	1000
		2019	1006	1135	954	1007	980	1011	1042
		2020	1021	1114	993	973	981	1077	1050
4	Talcher Super TPP	2018	951	945	1334	1201	1179	1089	
		2019	990	954	1188	1188	1203	1125	
		2020	889	1039	1099	1099	1075	1071	
5	Farakka TPP	2018	1157	1159	1174	1179	1123	1123	
		2019	1129	1102	1134	1204	1161	1154	
		2020	1043	1086	1069	1229	1205	1243	
	Barauni TPP	2020	1079						
7	Gadarwara TPP	2019	1440						
		2020	1544						
8	Darlipalii TPP	2020	1169						
9	Lara TPP	2019	1049	1354					
		2020	1447						

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	Stack 9	Stack 10	Stack 12	Stack 13
10	Kudgi TPP	2018	1045	1060	1151									
		2019	1215	1255	1228									
		2020	1141	938	934									
11	Khargone TPP	2020	1147	1126										
12	Bongaigaon TPP	2018	1099	1021										
		2019	1123	987	950									
		2020	1264	1046	1040									
13	Solapur TPP	2018	1288											
		2019	1329											
		2020	1125	1145										
14	Vindhyachal	2018	1024	1023	1020	1042	1008	1022	995	978	1019	1071	1069	1017
		2019	934	930	945	937	955	951	952	928	948	934	956	955
		2020	1010	1022	1003	1016	1009	1040	1022	1001	1035	1037	1031	1036
15	Tanda	2018	1261	1239	1126	906								
		2019	1194	1100	967	873	1033							
		2020	1127	1023	857	766	1080							
16	Sipat TPP	2018	974	956	959	917	959							
		2019	1001	1015	1004	970	1030							
		2020	985	971	1016	1001	1020							

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
17	Rihand TPP	2018	859	865	865	899	958	951	
		2019	1157	1222	1247	1114	1294	1341	
		2020	1305	1394	1373	1244	1407	1460	
18	Barh TPP	2018	1240	1218					
		2019	1324	1223					
		2020	1091	1067					
19	Simhadhri TPP	2018	1230	1359	1406	1278			
		2019	1146	1258	1419	1219			
		2020	1152	1106	1156	1349			
20	Kahalgaon TPP	2018	928	952	908	943	904	925	869
		2019	1145	1148	1142	1127	1073	1048	1078
		2020	1112	1095	1091	1105	1083	1079	1053
21	Ramagundam TPP	2018	1634	1569	1606	1574	1604	1683	1578
		2019	1471	1509	1568	1642	1616	1627	1534
		2020	1293	1301	1351	1352	1477	1491	1399
22	Mouda TPP	2018	1313	1313	1388	1378			
		2019	1342	1284	1517	1523			
		2020	1339	1354	1478	1529			
23	Dadri TPP	2018	861	813	814	820	1035	10060	
		2019	906	902	876	876	1066	1071	
		2020	565	560	749	543	1060	1092	

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
24	GSECL	Wanakbori Thermal Power Station	2016	359	315	357	331	304	370	265
			2017	804	833	763	828	873	986	796
			2018	1293	1285	1326	1296	1285	1349	1247
			2019	1249	1413	1391	1309	1342	1340	1203
			2020	1103	985	1191	1217	1102	1086	999
25		Gandhinagar Thermal Power Station	2016			317	290	301		
			2017			506	582	568		
			2018			881	885	824		
			2019			1024	1082	1185		
			2020			112	1446	1169		
26		Sikka Thermal Power Station	2016			167	126			
			2017			1003	1072			
			2018			844	821			
			2019			809	906			
			2020			1944	1905			
27		Ukai Thermal Power Station	2016			662	543	599	494	
			2017			910	980	932	928	
			2018			1324	1408	1311	1382	
			2019			1108	1061	1113	1314	
			2020			1056	1137	1000	1273	
28		Kutch Lignite Thermal Power Station	2016	1660	1767	1754				
			2017	2090	2126	2281				
			2018	2366	2279	2371				
			2019	2794	2607	2758				
			2020			3472				
29	Adani	Kawai Thermal Power Station	2018	1853	1748					
2019			1349	1283						
2020			1359	1477						
30		Raigarh Thermal Power Station	2020	1001						
31		Raikheda Thermal Power Station	2020	1141						
32		Tirora Thermal Power Station	2015	938	1022	1019	957	985		
			2016	917	879	894	992	964		
			2017	1081	886	866	953	944		
			2018	893	960	905	899	882		
			2019	935	949	931	947	840		
			2020	949	953	962	946	923		

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
33	Tata Power Co	Jojobera Thermal Power Station	2016	456	524	526	488	423			
			2017	564	583	584	575	577			
			2018	641	650	660	633	625			
			2019	844	901	893	872	849			
			2020	823	909	911	932	848			
34		Maithon Thermal Power Station	2018	494	492						
			2019	1066	1035						
			2020	891	828						
35		Trombay Thermal Power Station	2016					144			157
			2017					188			188
			2018					138			207
			2019					109			177
			2020					113			161
36	OP Jindal	Raigarh Thermal Power Station	2008	1070	997	934	1060				
			2009	1019	1035	1054	1075				
			2010	1054	1039	1069	1068				
			2011	1060	1081	1062	1063				
			2012	1070	1096	1096	1099				
			2013	1108	1105	1108	1109				
			2014	1167	1163	1166	1174				
			2015	1015	1062	1050	1026				
			2016	741	745	723	748				
			2017	796	879	877	815				
			2018	1257	1060	1313	1307				
			2019			1313	1311				
			2020	1094	1082	1037	1214				
37		Tamnar Thermal Power Station	2016	1058							
			2017	1112	1162						
			2018	1251	1305	1346	1254				
			2019	1443	1293	1353	1479				
			2020	1165	1139	1123	1157				

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
38	DVC	Durgapur Steel Thermal Power Station	2016	568	591						
			2017	635	632						
			2018	545	523						
			2019	614	556						
			2020	897	522						
39		Bokaro -A Thermal Power Plant	2018	1309							
			2019	1393							
			2020	1280							
40		Chandrapura Thermal Power Plant	2016	484	404						
			2017	516	437						
			2018	582	554						
			2019	598	590						
			2020	564	563						
41		Koderma Thermal Power Plant	2016	287	411						
			2017	170	192						
			2018	287	184						
			2019	679	623						
			2020	478	487						
42		Mejia Thermal Power Plant	2016	380	454	363	328	370	383	409	474
			2017	530	525	597	623	530	547	551	539
			2018	627	616	653	540	662	587	656	772
			2019	680	641	656	688	679	647	716	681
			2020	716	593	641	748	552	584	672	691
43		Raghunathpur Thermal Power Plant	2017	527	556						
			2018	491	506						
			2019	631	670						
			2020	740	790						
44	GMR	Kamalanga Energy Limited	2014	902	861	1346					
			2015	801	722	638					
			2016	380	356	332					
			2017	534	534	511					
			2018	979	914	920					
			2019	1152	1135	1147					
			2020	1154	1213	1159					
45		Warora Energy Limited	2014	601	610						
			2015	589	609						
			2016	520	486						
			2017	423	427						
			2018	644	576						
			2019	897	894						
			2020	998	1075						

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2
46	Sembcorp Energy India Ltd.	Sembcorp Gayatri P.Ltd.	2019	952	785
			2020	1098	934
47		PAINAMPURAM TPP	2019	970	909
			2020	938	798
48	CHINA LIGHT POWER	MAHATMA GANDHI TPS/Jhajjar TPP	2013	1058	
			2014	1121	
			2015	1029	
			2016	913	
			2017	867	
			2018	756	
			2019	155	
			2020	138	
49	HPGCL	Panipat Thermal Power Station	2011	195	168
			2012	426	306
			2013	219	243
			2014	335	302
			2015	385	356
			2016	417	411
			2017	380	347
			2018	782	811
			2019	839	875
			2020	834	914
50		Yamuna Nagar Thermal Power Station	2008	263	275
			2009	230	251
			2010	242	249
			2011	261	253
			2012	221	259
			2013	231	250
			2014	252	261
			2015	362	373
			2016	208	206
			2017	289	278
			2018	594	604
			2019	1468	1534
			2020	1016	1011

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	
51	GVK	Nabha Thermal Power Plant	2014	329	403							
			2015	329	460							
			2016	447	473							
			2017	500	526							
			2018	532	559							
			2019	555	504							
			2020	467	531							
52		Goindwal Thermal Power Plant	2017	513	518							
			2018	535	509							
			2019	663	643							
			2020	889	856							
53	TAQA	TAQA, Neyveli	2015	1141								
			2016	861								
			2017	807								
			2018	2172								
			2019	5177								
			2020	3426								
54		Parli Thermal Power Station	2018						750	748	650	
			2019						835	860	753	
			2020						838	842	789	
55		Chandrapur Thermal Power Plant	2016			804	786	894	886	871	1582	NA
			2017			1256	1259	1332	1319	1380	1459	1457
			2018			1237	1254	1301	1269	1339	1304	1322
			2019			1206	1195	1298	1303	1337	1330	1331
			2020			1173	1172	1213	1226	1205	1177	1187
56	Mahagenco	Paras Thermal Power Plant	2010			2510	2806					
			2011			3514	3340					
			2012			2988	3111					
			2013			2981	2772					
			2014			2687	2592					
			2015			2112	2145					
			2016			1511	1381					
			2017			1338	1300					
			2018			1291	1320					
			2019			1507	1491					
			2020			1467	1431					

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
57	Mahagenco	Bhusawal Thermal Power Plant	2017	706	1206	1204				
			2018	695	1202	1163				
			2019	689	1327	1223				
			2020	NA	1196	1193				
58		Koradi Thermal Power Plant	2011						660	680
			2012						691	694
			2013						685	684
			2014						697	691
			2015						694	694
			2016						NA	674
			2017						NA	778
			2018						NA	1048
			2019						1372	1527
			2020						1347	NA
59		Khaperkheda Thermal Power Plant	2001	698	710					
			2002	674	679	678	689			
			2003	674	613	669	671			
			2004	652	658	653	654			
			2005	669	611	550	666			
			2006	675	673	680	677			
			2007	670	666	673	676			
			2008	675	673	678	672			
			2009	683	679	682	678			
			2010	676	674	677	677			
			2011	691	687	687	684			
			2012	707	647	714	714	762		
			2013	696	697	707	708	949		
			2014	644	652	645	640	1069		
			2015	653	669	641	625	1030		
			2016	765	743	744	722	1047		
			2017	1132	1090	1147	1052	1518		
			2018	1200	1275	1206	1217	1542		
			2019	1278	1280	1196	1187	1656		
			2020	1275	1282	1239	1237	1650		
60		Nashik Thermal Power Plant	2016	7031	7304	7291				
			2017	8945	8848	8734				
			2018	10912	10926	10303				
			2019	12295	12905	12612				
			2020	12711	12687					

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
61	Karnataka Power Corporation Ltd	Bellary Thermal Power Station	2017	2109	2057	181					
			2018	2506	2589	2822					
			2019	2241	2188	2036					
			2020	1872	1945	1895					
62		Raichur Thermal Power Station	2013	1448	1590	1468	1515	1787	1580	1546	1838
			2014	1561	1435	1618	1535	1708	1895	1727	1466
			2015	1473	1514	1505	1681	1831	1811	1705	1538
			2016	1471	1569	1438	1481	1532	1787	1696	1565
			2017	1703	1539	1701	1650	1766	1691	1613	1516
			2018	1977	1804	1851	1943	1944	1929	1937	1845
			2019	2149	2052	2020	2137	2259	2183	2218	2207
			2020	2619	2089	2640	2523	2675	2974	2498	2194
63		Yermarus Thermal Power Station	2018	1395							
			2020	1238							
64	APGENCO	Dr.Narla Tata Rao Thermal Power Station	2012	1027	977	1114	1050	1238	1065	1189	
			2013	975	968	1027	1069	1086	1057	1100	
			2014	977	950	937	1059	1012	995	1047	
			2015	1239	1256	1259	1251	1249	1257	1332	
			2016	1243	1253	1290	1348	1337	1275	1339	
			2017	1330	1289	1269	1312	1336	1333	1308	
			2018	1268	1209	1239	1250	1202	1233	1393	
			2019	1116	1123	1188	1137	1104	1130	1355	
65		Rayalaseema Thermal Power Station	2020	1159	1119	1156	1208	1211	1185	1389	
			2008	650	661	633	550	31			
			2009	643	662	626	624	625			
			2010	667	667	640	626	633			
			2011	637	633	610	612	635			
			2012	637	635	622	623	496			
			2013	636	635	595	644	659			
			2014	512	509	495	500	735			
			2015	666	664	640	641	752			
			2016	787	796	757	764	797			
			2017	780	774	751	755	1179			
			2018	873	973	815	846	797			
			2019	1150	1124	1123	1142	1179			
66	NLC India Limited	Barsingsar Thermal Power Station	2020	1235	1204	1078	1079				
			2012	192	187						
			2013	179	187						
			2014	256	251						
			2015	264	264						
			2016	265	257						
			2017	567	549						
			2018	586	580						
67		Neyveli New Thermal Power Station	2019	544	547						
			2020	572	569						
			2020	665							

Summary for NO_x Emissions (Units: mg/Nm³)

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
1	Korba Super Thermal Power Station	2018	399	360	370	368	360	397	365
		2019	441	432	452	428	357	429	345
		2020	432	439	437	352	343	455	359
2	Unchahar TPP	2018	291	296	299	426	362	362	
		2019	331	338	323	334	347	368	
		2020	363	362	354	346	347	357	
3	Singrauli TPP	2018	427	413	425	419	408	416	398
		2019	411	404	411	412	412	404	402
		2020	411	406	420	405	415	403	410
4	Talcher Super TPP	2018	375	372	451	401	330	325	
		2019	387	364	416	416	415	381	
		2020	399	410	436	436	507	399	
5	Farakka TPP	2018	352	370	378	360	342	355	
		2019	356	352	365	361	378	351	
		2020	391	412	407	428	424	360	
6	Barauni TPP	2020	311						
7	Gadarwara TPP	2019	312						
		2020	314						
8	Darlipalli TPP	2020	296						
9	Lara TPP	2019	329						
		2020	354	376					

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	Stack 9	Stack 10	Stack 11	Stack 12	Stack 13
10	Kudgi TPP	2018	303	315	318										
		2019	294	291	332										
		2020	301	270	284										
11	Khargone TPP	2020	292	295											
12	Bongaigaon TPP	2018	295	343											
		2019	293	329	351										
		2020	343	335	345										
13	Solapur TPP	2018	265												
		2019	269												
		2020	277	252											
14	Vindhyachal	2018	550	546	554	552	556	566	551	547	560	557	552	560	525
		2019	555	558	549	553	540	550	535	526	453	422	449	564	393
		2020	526	542	550	551	562	550	532	528	437	315	440	439	358
15	Tanda	2018	321	318	328	293									
		2019	348	378	370	303	359								
		2020	410	394	434	314	300								
16	Sipat TPP	2018	371	332	321	353	357								
		2019	345	382	358	337	344								
		2020	350	364	354	335	349								
17	Rihand TPP	2018	334	336	334	326	337	330							
		2019	474	480	375	370	407	387							
		2020	533	532	431	395	424	418							

Sr. No.	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
18	Barh TPP	2018	236	224					
		2019	267	246					
		2020	292	260					
19	Simhadhri TPP	2018	403	416	400	380			
		2019	410	401	388	423			
		2020	389	416	430	412			
20	Kahalgaon TPP	2018	564	584	584	583	358	335	333
		2019	551	523	533	534	336	354	351
		2020	548	515	517	519	350	372	348
21	Ramagundam TPP	2018	453	462	439	336	329	352	420
		2019	377	375	394	350	341	393	391
		2020	457	463	469	427	467	430	400
22	Mouda TPP	2018	355	356	367	368			
		2019	355	347	374	375			
		2020	344	348	371	367			
23	Dadri TPP	2018	350	331	336	358	350	353	
		2019	390	417	418	439	401	398	
		2020	436	420	434	400	391	408	

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
24	GSECL	Wanakbori Thermal Power Station	2016	52	36	43	238	29	47	37
			2017	321	340	249	594	326	363	273
			2018	293	306	324	338	356	354	297
			2019	362	359	420	387	417	391	332
			2020	419	390	447	482	440	385	420
25		Gandhinagar Thermal Power Station	2016			19	17	21		
			2017			32	37	40		
			2018			180	174	204		
			2019			240	327	346		
			2020			112	406	368		
26		Sikka Thermal Power Station	2016			104	106			
			2017			474	528			
			2018			422	385			
			2019			306	274			
			2020			308	304			
27		Ukai Thermal Power Station	2016			339	307	352	274	
			2017			501	564	498	476	
			2018			367	447	358	309	
			2019			439	508	336	445	
			2020			459	497	473	483	
28		Kutch Lignite Thermal Power Station	2016	216	16	19				
			2017	21	25	24				
			2018	99	105	83				
			2019	123	123	112				
			2020			92				
29	Adani	Kawai Thermal Power Station	2018	590	560					
2019			565	541						
2020			547	510						
30		Raigarh Thermal Power Station		2020	595					
31		Raikheda Thermal Power Station		2020	533					
32		Tirora Thermal Power Station	2015	461	416	432	357	441		
			2016	340	350	364	361	362		
			2017	352	341	379	357	332		
			2018	265	243	271	249	272		
			2019	274	279	273	279	257		
	2020		280	278	284	279	267			

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
33	Tata Power Co	Jojobera Thermal Power Station	2016	306	312	326	259	262			
			2017	341	362	368	281	303			
			2018	366	380	401	286	380			
			2019	541	578	594	545	577			
			2020	535	557	556	549	557			
34		Maithon Thermal Power Station	2018	474	458						
			2019	774	638						
			2020	699	662						
35		Trombay Thermal Power Station	2016					219			233
			2017					189			189
			2018					170			166
			2019					145			176
			2020					205			155
36	OP Jindal	Raigarh Thermal Power Station	2008	370	367	340	346				
			2009	336	339	346	357				
			2010	351	367	350	376				
			2011	340	354	345	361				
			2012	357	360	365	370				
			2013	383	381	397	398				
			2014	403	397	417	421				
			2015	358	373	371	366				
			2016	345	369	372	361				
			2017	358	370	373	349				
			2018	438	399	458	442				
			2019			458	484				
			2020	472	437	414	391				
37		Tamnar Thermal Power Station	2016	402							
			2017	430	433						
			2018	485	507	523	472				
			2019	569	554	594	506				
			2020	443	492	430	479				

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
38	DVC	Durgapur Steel Thermal Power Station	2016	517	528						
			2017	554	533						
			2018	408	399						
			2019	442	508						
			2020	458	289						
39		Bokaro -A Thermal Power Plant	2018	454							
			2019	449							
			2020	445							
40		Chandrapura Thermal Power Plant	2016	446	365						
			2017	390	275						
			2018	427	417						
			2019	302	312						
			2020	266	266						
41		Koderma Thermal Power Plant	2016	298	432						
			2017	250	255						
			2018	304	284						
			2019	449	462						
			2020	413	522						
42		Mejia Thermal Power Plant	2016	40	318	267	161	271	264	298	312
			2017	42	354	356	430	362	337	344	371
			2018	295	269	262	255	281	268	285	425
			2019	280	424	283	284	294	328	294	320
			2020	345	412	272	457	275	331	313	373
43		Raghunathpur Thermal Power Plant	2017	244	317						
			2018	335	258						
			2019	277	387						
			2020	557	683						
44	GMR	Kamalanga Energy Limited	2014	302	225	257					
			2015	310	270	246					
			2016	216	217	193					
			2017	253	270	258					
			2018	269	262	259					
			2019	277	278	282					
			2020	274	276	279					
45		Warora Energy Limited	2014	102	113						
			2015	109	117						
			2016	124	104						
			2017	187	175						
			2018	245	217						
			2019	252	251						
			2020	153	190						

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2
46	Sembcorp Energy India Ltd.	Sembcorp Gayatri P.Ltd.	2019	296	356
			2020	330	343
47		PAINAMPURAM TPP	2019	374	341
			2020	349	362
48	CHINA LIGHT POWER	MAHATMA GANDHI TPS/Jhajjar TPP	2013	255	
			2014	242	
			2015	196	
			2016	206	
			2017	220	
			2018	212	
			2019	205	
			2020	225	
49	HPGCL	Panipat Thermal Power Station	2011	112	132
			2012	128	141
			2013	140	143
			2014	73	86
			2015	74	78
			2016	310	322
			2017	408	424
			2018	457	431
			2019	466	457
			2020	471	460
50		Yamuna Nagar Thermal Power Station	2008	NA	
			2009	75	58
			2010	232	218
			2011	311	267
			2012	324	335
			2013	307	327
			2014	227	263
			2015	90	89
			2016	87	85
			2017	242	245
			2018	440	441
			2019	507	509
			2020	506	505
51	GVK	Nabha Thermal Power Plant	2014	85	165
			2015	85	196
			2016	172	188
			2017	164	144
			2018	162	155
			2019	197	174
			2020	171	223
52		Goindwal Thermal Power Plant	2017	232	171
			2018	261	248
			2019	285	277
			2020	391	379

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
53	TAQA	TAQA, Neyveli	2015	76							
			2016	70							
			2017	67							
			2018	108							
			2019	160							
			2020	136							
54	Mahagenco	Parli Thermal Power Station	2018						202	195	186
			2019						206	211	203
			2020						199	196	197
55		Chandrapur Thermal Power Plant	2016			137	138	149	147	145	287
			2017			281	278	287	291	307	293
			2018			323	315	355	358	361	271
			2019			289	288	313	308	335	276
			2020			302	302	310	313	313	283
56		Paras Thermal Power Plant	2010			288	285				
			2011			256	256				
			2012			267	264				
			2013			239	238				
			2014			260	261				
			2015			250	253				
			2016			240	281				
			2017			264	259				
			2018			259	261				
			2019			359	337				
			2020			272	277				
57		Bhusawal Thermal Power Plant	2017	161	184	184					
			2018	181	188	184					
			2019	196	271	266					
			2020	NA	218	219					

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8	
58	Mahagenco	Koradi Thermal Power Plant	2011						106	105		
			2012						106	106		
			2013						105	104		
			2014						110	109		
			2015						106	109		
			2016						NA	121		
			2017						NA	144		
			2018						NA	186		
			2019						269	254		
2020							293	NA				
59		Khaperkheda Thermal Power Plant	2001	155	155							
			2002	175	172	167	184					
			2003	172	153	169	168					
			2004	162	162	161	158					
			2005	157	144	130	155					
			2006	134	134	137	136					
			2007	116	115	117	117					
			2008	117	115	116	117					
			2009	117	117	118	118					
			2010	118	107	118	118					
			2011	119	119	118	118					
			2012	120	109	120	119	125				
			2013	119	119	120	119	111				
			2014	119	119	123	120	125				
			2015	118	117	116	115	121				
			2016	167	163	159	156	162				
			2017	315	310	285	286	188				
			2018	384	366	357	335	294				
			2019	360	352	330	325	298				
			2020	330	334	323	318	310				
60		Nashik Thermal Power Plant	2016	116	116	117						
			2017	110	111	114						
			2018	117	117	114						
			2019	104	117	116						
			2020	124	109							
61	Karnataka Power Corporation Ltd.	Bellary Thermal Power Station	2017	398	479	269						
			2018	428	435	442						
			2019	164	132	151						
			2020	329	324	317						
62		Raichur Thermal Power Station	2013	566	519	581	511	502	467	545	566	
			2014	428	498	616	420	520	406	558	518	
			2015	457	470	585	489	513	457	559	662	
			2016	449	462	516	495	481	462	577	613	
			2017	405	388	486	488	516	516	667	640	
			2018	531	533	529	554	466	390	589	562	
			2019	410	372	371	419	423	336	465	476	
			2020	378	401	317	422	391	330	510	534	
63		Yermarus Thermal Power Station	2018	385								
			2020	309								

Sr. No.	Developer	TPP Name	Years	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7
64	APGENCO	Dr.Narla Tata Rao Thermal Power Station	2012	161	169	168	175	183	188	372
			2013	273	245	228	283	262	268	357
			2014	253	286	260	256	277	306	313
			2015	292	284	282	282	276	295	376
			2016	284	353	339	336	334	304	378
			2017	334	350	359	348	338	371	425
			2018	259	256	289	290	293	313	470
			2019	263	261	276	266	272	276	386
			2020	246	242	252	268	269	255	390
65		Rayalaseema Thermal Power Station	2008	33	34	30	26	21		
			2009	34	35	30	31	33		
			2010	37	37	35	34	36		
			2011	36	35	31	31	145		
			2012	37	36	33	32	366		
			2013	151	160	132	143	282		
			2014	348	342	345	355	231		
			2015	305	308	250	280	320		
			2016	300	295	255	251	272		
			2017	330	333	316	302	338		
			2018	291	341	285	298	272		
			2019	346	325	349	331	338		
			2020	371	358	351	363			
66	NLC India Limited	Barsingsar Thermal Power Station	2012	116	119					
			2013	117	117					
			2014	186	189					
			2015	232	234					
			2016	232	221					
			2017	234	222					
			2018	217	215					
			2019	236	235					
			2020	225	221					
67		Neyveli New Thermal Power Station	2020	199						

CHAPTER 3: ANALYSIS OF SO₂ AND SULFATE (SO₄) AEROSOL DATA OVER THE INDIAN REGION USING SATELLITE OBSERVATIONS, EMISSION INVENTORY AND REANALYSIS DATASETS

AURA(OMI) Satellite data

The Ozone Monitoring Instrument (OMI) onboard NASA's Aura satellite has been providing global observations of key atmospheric pollutant gases including sulfur dioxide (SO₂), since October 2004. OMI observations have proved valuable in documenting rapid changes in air quality over different parts of the world during last one and half decade. In this study, we use the OMI/Aura Total Column L3 1 day Best Pixel in 0.25 degree x 0.25 degree V3 (OMSO2e) global sulfur dioxide (SO₂) data product for the years 2005 to 2019. We analyzed both annual mean SO₂ column burden data as well as trend in annual mean SO₂ column burden data over the Indian region during the period from 2005 to 2019.

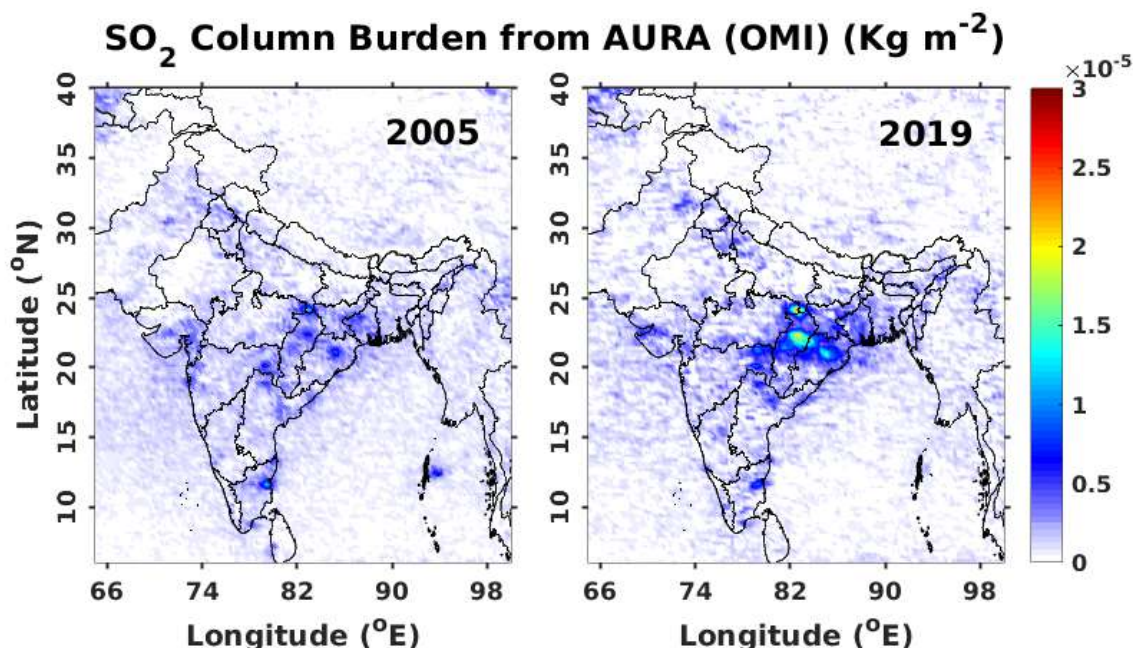


Figure 3.1: Annual mean SO₂ column burden (in Kg/m²) data from OMI/Aura observations for the years 2005 and 2019

Figure 3.1 shows the annual mean SO₂ column burden (in Kg/m²) data from OMI/Aura observations for the years 2005 and 2019. OMI/Aura data is able to identify several hot spot regions with higher column burden of SO₂ over parts of the states like Chattisgarh, Odisha, Maharashtra, Jharkhand, Tamil Nadu, Gujarat and West Bengal. It is also evident from Figure 3.1 that there has been significant increases in annual mean SO₂ column burden across most of the Indian region from the year 2005 to 2019. In order to understand the changes in SO₂ column burden across the Indian region in a better way, we examined the trends in SO₂ column burden based on OMI/Aura observations during the period 2005 to 2019.

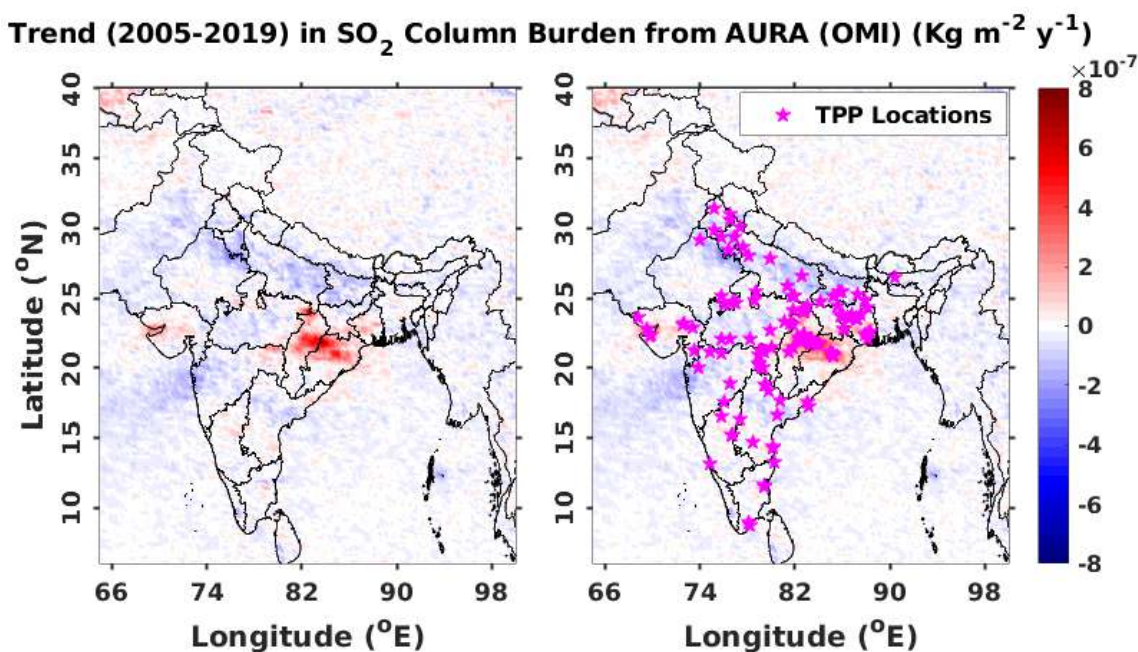


Figure 3.2: Trend in annual mean SO₂ column burden (in Kg/m²/year) data from OMI/Aura observations during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in SO₂ column burden in the right panel of the figure.

Figure 3.2 shows the trend in annual mean SO₂ column burden (in Kg/m²/year) data from OMI/Aura observations during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in SO₂ column burden helps us identify the potential areas where the changes in SO₂ burden could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.2 that some of the TPPs located in the states of Chhattisgarh and Odisha could at least in part be responsible for the noted positive trend in SO₂ column burden over this part of India.

CMIP6 Emission inventory data

We also analyzed the data for historical emissions of aerosols and their precursors from anthropogenic sources as per the Community Emissions Data System (CEDS) developed for the CMIP6 (Coupled Model Intercomparison Project Phase 6) as described by Hoesly et al. [2018].

Figure 3.3 shows the annual mean emission rates (in Kg/m²/year) of SO₂ from all anthropogenic sources as per the CMIP6 emissions inventory data for the years 2005 and 2014 (as historical emissions data is not available beyond the year 2014). It is also evident from Figure 3.1 that there has been significant increases in annual mean emission rates of SO₂ across most of the Indian region from the year 2000 to 2014.

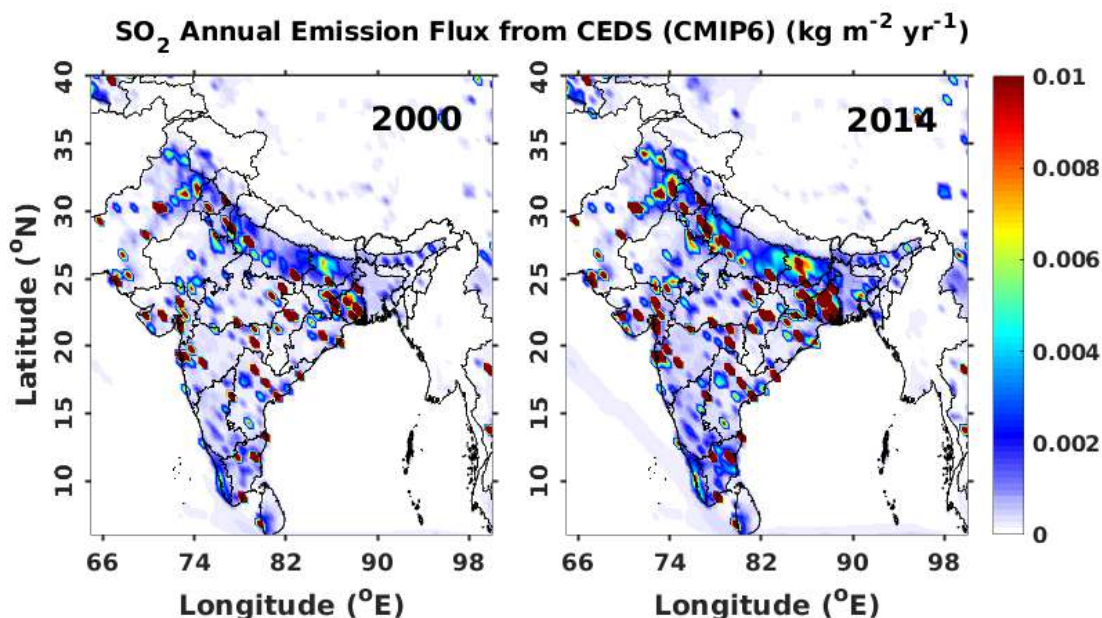


Figure 3.3: Annual mean emission rates (in Kg/m²/year) of SO₂ from all anthropogenic sources as per the CMIP6 emissions inventory data for the years 2000 and 2014

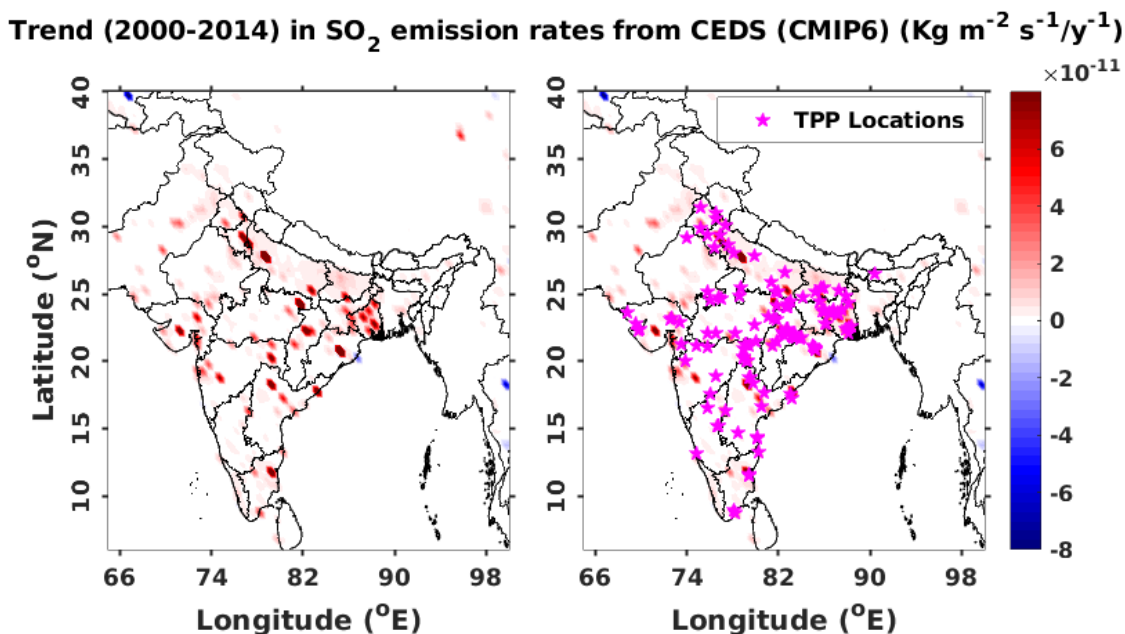


Figure 3.4: Trend in emission rates (in Kg/m²/s/year) of SO₂ from all anthropogenic sources as per the CMIP6 emissions inventory data during the period 2000 to 2014. Locations of various coal based TPPs across India are overlaid on the trends in emission rates of SO₂ in the right panel of the figure.

In order to understand the changes in SO₂ emission rates over the Indian region in a better way, we examined the trends in SO₂ emission rates based on the CMIP6 emissions inventory data for the period 2000 to 2014. Figure 3.4 shows the trend in emission rates of SO₂ from from all anthropogenic sources as per the CMIP6 emissions inventory data during the period 2000 to 2014. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in

emission rates of SO₂ helps us identify the potential areas where the changes in SO₂ emission rates could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.4 that some of the hot spot regions with increasing trend trends in emission rates of SO₂ are colocated with some of the TPPs across the country and they could at least in part be responsible for the noted positive trend in emission rates of SO₂ over these regions.

MERRA-2 reanalysis dataset

We analyzed SO₂ column burden and surface concentration data from MERRA-2 (Modern-Era Retrospective analysis for Research and Application) aerosol reanalysis data generated by the GEOS-5 atmospheric model at 0.5°×0.625° horizontal resolution (Gelaro et al., 2017). MERRA-2 aerosol analysis assimilates quality-controlled AOD at 550 nm from four different sensors (MISR onboard Terra, MODIS onboard Terra and Aqua, AVHRR, and AERONET). Both the aerosol and meteorology observations are jointly assimilated in the GEOS-5 model. We analyzed annual mean SO₂ column burden and surface concentration data as well as trends in both these quantities from MERRA-2 data over the Indian region during the period from 2005 to 2019 (we purposely choose the same time period to compare with satellite derived AURA(OMI) data).

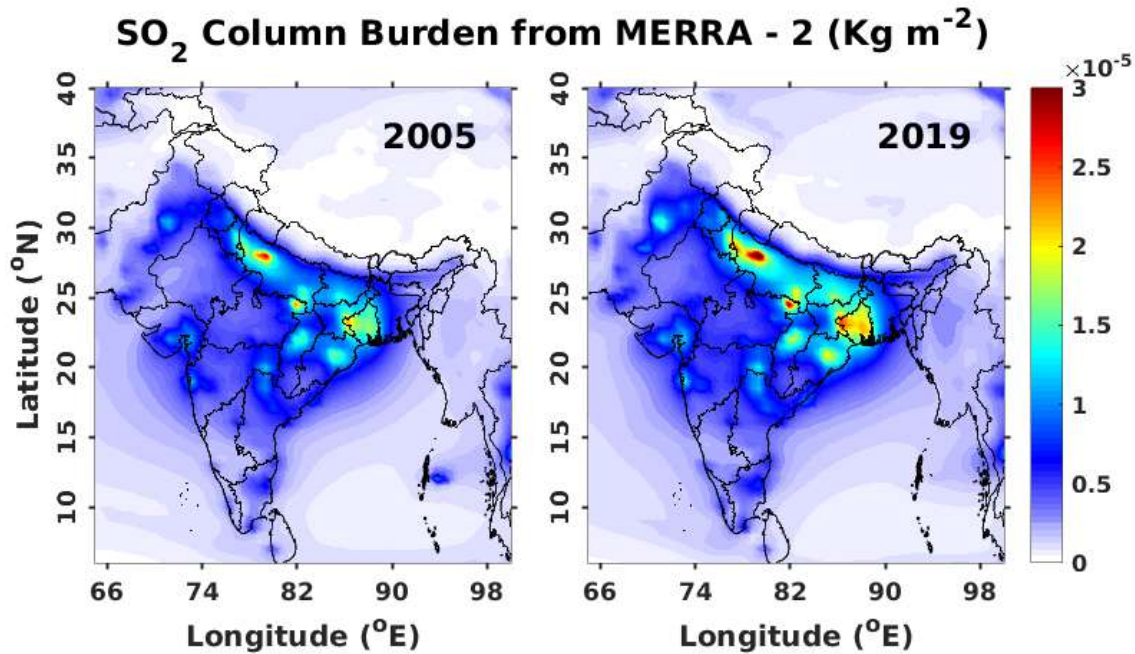


Figure 3.5: Annual mean SO₂ column burden (in Kg/m²) data from MERRA-2 for the years 2005 and 2019

Figure 3.5 shows the annual mean SO₂ column burden (in Kg/m²) data from MERRA-2 for the years 2005 and 2019. MERRA-2 data is able to identify several hot spot regions with higher column burden of SO₂ over parts of the states like western Uttar Pradesh, Vindhyaachal region in north eastern Madhya Pradesh, parts of Chattishgarh, Bihar, Jharkhand, Odisha, West Bengal, Maharashtra, Andhra Pradesh, and Gujarat. It is also evident from Figure 3.5 that there has been significant increases in annual mean SO₂ column burden across most of the Indian region from the year 2005 to 2019. Interestingly, although there are significant overlaps in the hot spot

regions with higher column burden of SO₂ as identified by OMI/Aura observations and MERRA-2 data but there are also some areas with higher column burden of SO₂ that are noted in one of the dataset but not in the other one. Anyway, in order to understand the changes in SO₂ column burden across the Indian region based on the MERRA-2 data in a better way, we examined the trends in SO₂ column burden from this dataset during the period 2005 to 2019.

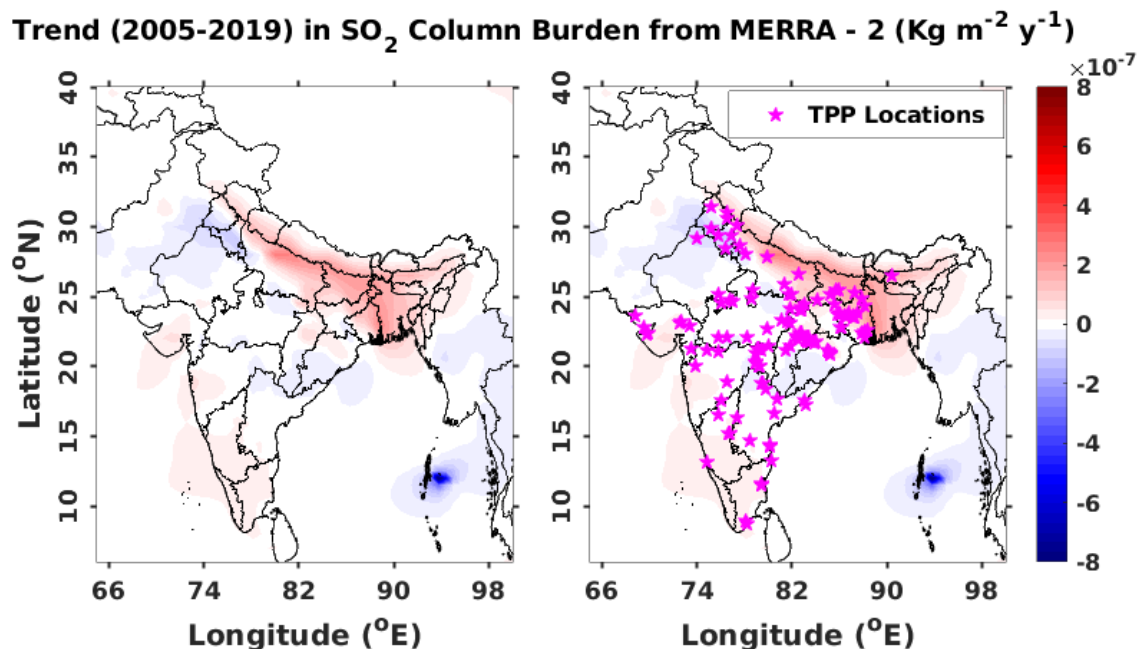


Figure 3.6: Trend in annual mean SO₂ column burden (in Kg/m²/year) data from MERRA-2 data during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in SO₂ column burden in the right panel of the figure.

Figure 3.6 shows the trend in annual mean SO₂ column burden data from MERRA-2 during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in SO₂ column burden helps us identify the potential areas where the changes in SO₂ burden could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.6 that some of the TPPs located in the states of Uttar Pradesh, Bihar, West Bengal, Odhisa and Chattisgarh could at least in part be responsible for the noted positive trend in SO₂ column burden over this part of India based on MERRA-2 datasets.

As mentioned earlier that MERRA-2 also provides SO₂ surface concentration data globally. Hence, we analyzed the SO₂ surface concentration data for different years as well as trend in SO₂ surface concentration data from MERRA-2 data over the Indian region during the period from 2005 to 2019.

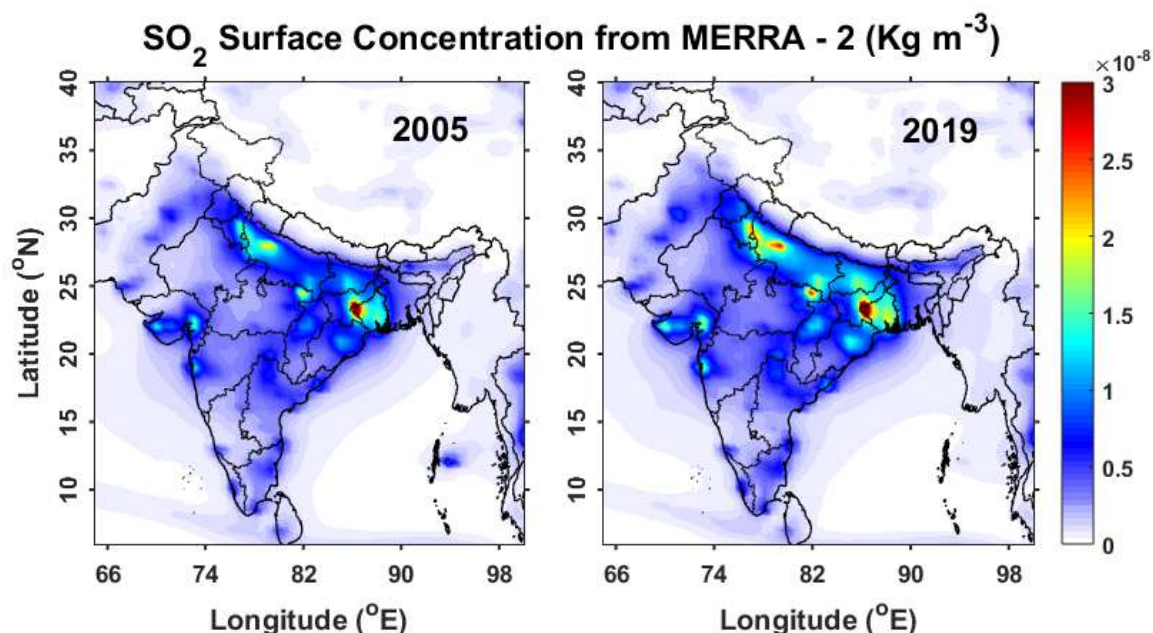


Figure 3.7: Annual mean SO₂ surface concentration (in Kg/m³) data from MERRA-2 for the years 2005 and 2019

Figure 3.7 shows the annual mean SO₂ surface concentration data from MERRA-2 for the years 2005 and 2019. MERRA-2 data is able to identify several hot spot regions with higher surface concentration of SO₂ mostly over the Indo-Gangetic plain region. Some of the areas with high surface concentration of SO₂ as noted MERRA-2 data include parts of western Uttar Pradesh, Vindhyachal region in north eastern Madhya Pradesh and south-east Uttar Pradesh, parts of Jharkhand, Odisha, West Bengal, Chattishgarh, Bihar, Maharashtra, and Gujarat. It is also evident from Figure 3.7 that there has been significant increases in annual mean SO₂ surface concentrations almost across the Indian region from the year 2005 to 2019. In order to understand the changes in SO₂ surface concentration across the Indian region based on the MERRA-2 data in a better way, we examined the trends in SO₂ surface concentration during the period 2005 to 2019.

Figure 3.8 shows the trend in annual mean SO₂ surface concentration data from MERRA-2 during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in SO₂ surface concentration helps us identify the potential areas where the changes in SO₂ surface concentration could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.8 that some of the TPPs located in the states of Uttar Pradesh, Bihar, West Bengal, Odhisa and Chattisgarh could at least in part be responsible for the noted positive trend in SO₂ surface concentration over this part of India based on MERRA-2 datasets.

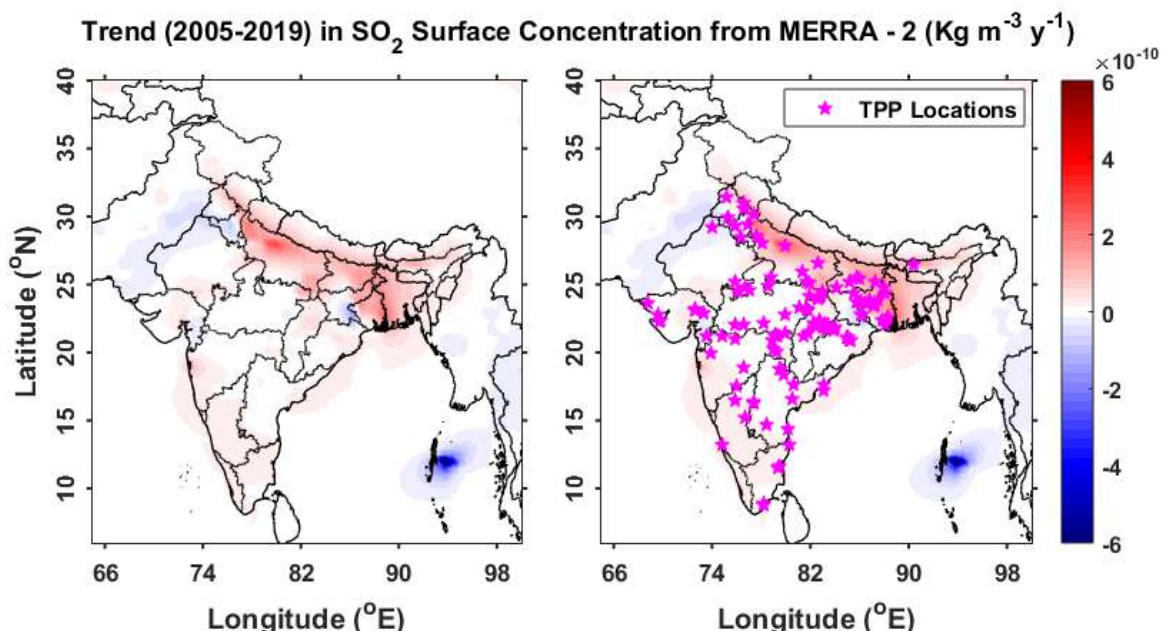


Figure 3.8: Trend in annual mean SO₂ surface concentration (in Kg/m³/year) data from MERRA-2 data during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in SO₂ surface concentration in the right panel of the figure.

We also analyzed the sulfate (SO₄) aerosol column burden and surface concentration data from MERRA-2 reanalysis data. Sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO₂ emitted from various sources including coal based TPPs. While the primary oxidant responsible for the gaseous phase oxidation of SO₂ in the atmosphere is OH radical, the aqueous phase oxidation of SO₂ largely happens through its reaction with hydrogen peroxide (H₂O₂). Sulphuric acid (H₂SO₄) molecules which form through the oxidation of SO₂ by various oxidants subsequently reacts with ammonia gas (NH₃) and water vapor (H₂O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. We analyzed annual mean sulfate (SO₄) aerosol column burden and surface concentration data as well as trends in both these quantities from MERRA-2 data over the Indian region during the period from 2005 to 2019.

Figure 3.9 shows the annual mean sulfate (SO₄) aerosol column burden (in Kg/m²) data from MERRA-2 for the years 2005 and 2019. MERRA-2 data suggests high sulfate (SO₄) aerosol column burden all along the Indo-Gangetic Plain starting from Punjab and continuing through Haryana, Uttar Pradesh, Bihar, Jharkhand, West Bengal, northern Odhisa, and up to northern Bay of Bengal. It is also evident from Figure 3.9 that there has been significant increases in annual mean sulfate (SO₄) aerosol column burden across most of the Indian region from the year 2005 to 2019. Anyway, in order to understand the changes in sulfate (SO₄) aerosol column burden across the Indian region based on the MERRA-2 data in a better way, we examined the trends in sulfate (SO₄) aerosol column burden from this dataset during the period 2005 to 2019.

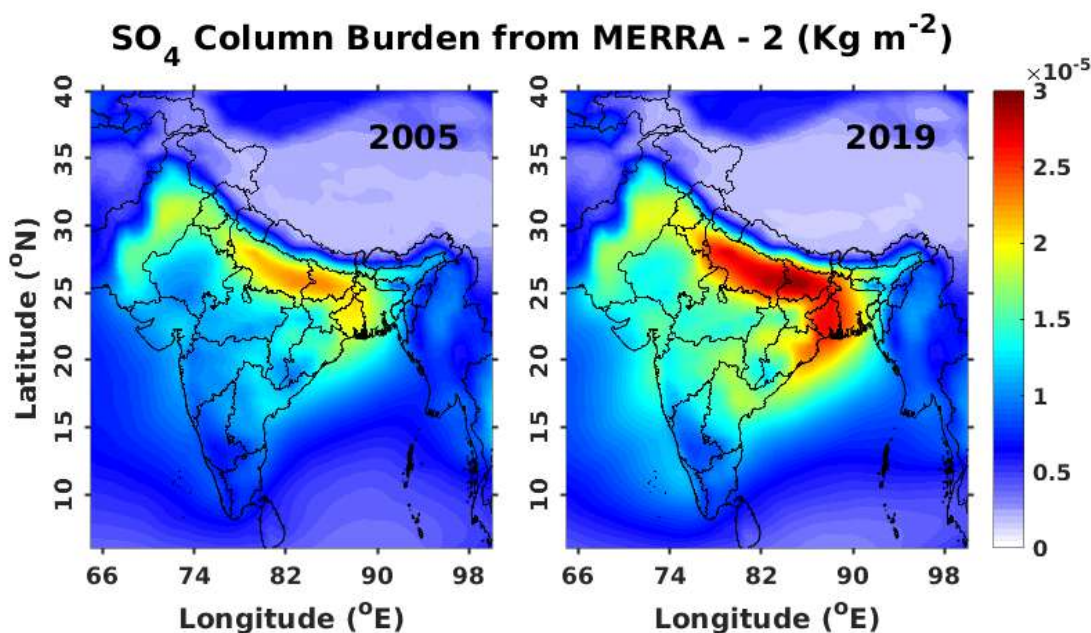


Figure 3.9: Annual mean sulfate (SO_4) aerosol column burden (in Kg/m^2) data from MERRA-2 for the years 2005 and 2019

Figure 3.10 shows the trend in annual mean sulfate (SO_4) aerosol column burden data from MERRA-2 during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in sulfate (SO_4) aerosol column burden helps us identify the potential areas where the changes in sulfate (SO_4) aerosol burden could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.10 that increasing trend in sulfate (SO_4) aerosol column burden are quite wide spread and noted not just over the land boundaries of India but also extends over vast areas over the Bay of Bengal and the Arabian Sea. It is well known that the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also depends on the concentrations of oxidants such as OH radical, hydrogen peroxide (H_2O_2), ozone (O_3), water vapor (H_2O), other reactive gases such as NH_3 , meteorological conditions such as wind speed, wind direction, relative humidity, sunlight, clouds etc. Although there is no doubt about the fact that one of the most important reasons for the noted positive trend in sulfate (SO_4) aerosol burden in MERRA2 data across the Indian region during the period 2005-2019 is due to increases in emissions of the precursor gas SO_2 from various sources including those from the coal based TPPs but, it seems that the changes in various other factors which influence the atmospheric chemistry involved in the formation of sulfate aerosols in the atmosphere must have also played a favourable role in resulting the noted positive trend in sulfate (SO_4) aerosol burden in most parts of the region. It requires a systematically designed model sensitivity simulations to be performed using any state-of-the-art chemistry-climate model to explain the sensitivity of sulfate aerosol concentrations/burden to each of these factors separately but that is beyond the scope of the present study and hence it can be taken up later as part of a separate study. Moreover, since the conversion from SO_2 to sulfate (SO_4) aerosol can occur at distances which are quite far away (hundreds of Km) from the source regions of SO_2 and also once the sulfate (SO_4) aerosol forms

in the atmosphere, it can further travel hundreds of kilometres through prevailing winds until it get scavenged from the atmosphere within a week of its formation, it is challenging to identify any particular TPP (source of SO_2) which may have maximum contribution towards the positive trend in sulfate (SO_4) aerosol burden over a particular region.

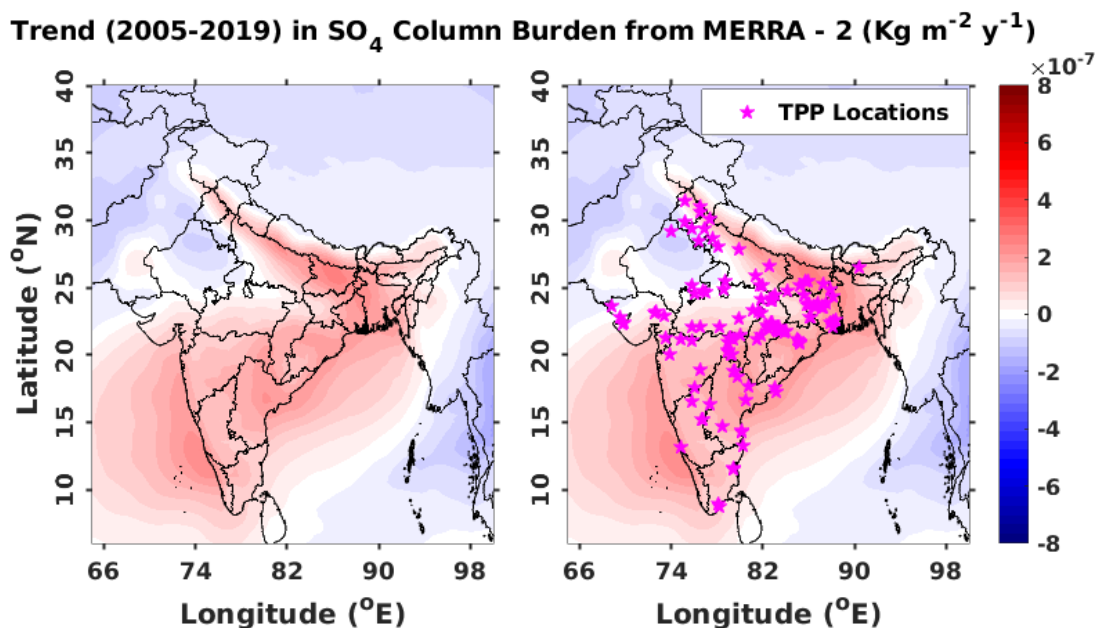


Figure 3.10: Trend in annual mean sulfate (SO_4) aerosol column burden (in $\text{Kg/m}^2/\text{year}$) data from MERRA-2 data during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in sulfate (SO_4) aerosol column burden in the right panel of the figure.

Figure 3.11 shows the annual mean sulfate (SO_4) aerosol surface concentration data from MERRA-2 for the years 2005 and 2019. As noted earlier in the case of SO_2 surface concentration data shown in figure 3.9, sulfate (SO_4) aerosol surface concentration data from MERRA-2 also identifies the Indo-Gangetic plain as a hot spot region with higher surface concentration of sulfate (SO_4) aerosols over this part of India. Some of the areas with high surface concentration of sulfate (SO_4) aerosol as noted MERRA-2 data include parts of western Uttar Pradesh, Vindhyaachal region in north eastern Madhya Pradesh and south-east Uttar Pradesh, parts of Bihar, Jharkhand, Odisha, West Bengal, and Chattishgarh. It is also evident from Figure 3.11 that there has been significant increases in annual mean sulfate (SO_4) aerosol surface concentrations almost across the Indian region from the year 2005 to 2019. In order to understand the changes in sulfate (SO_4) aerosol surface concentration across the Indian region based on the MERRA-2 data in a better way, we examined the trends in sulfate (SO_4) aerosol surface concentration during the period 2005 to 2019.

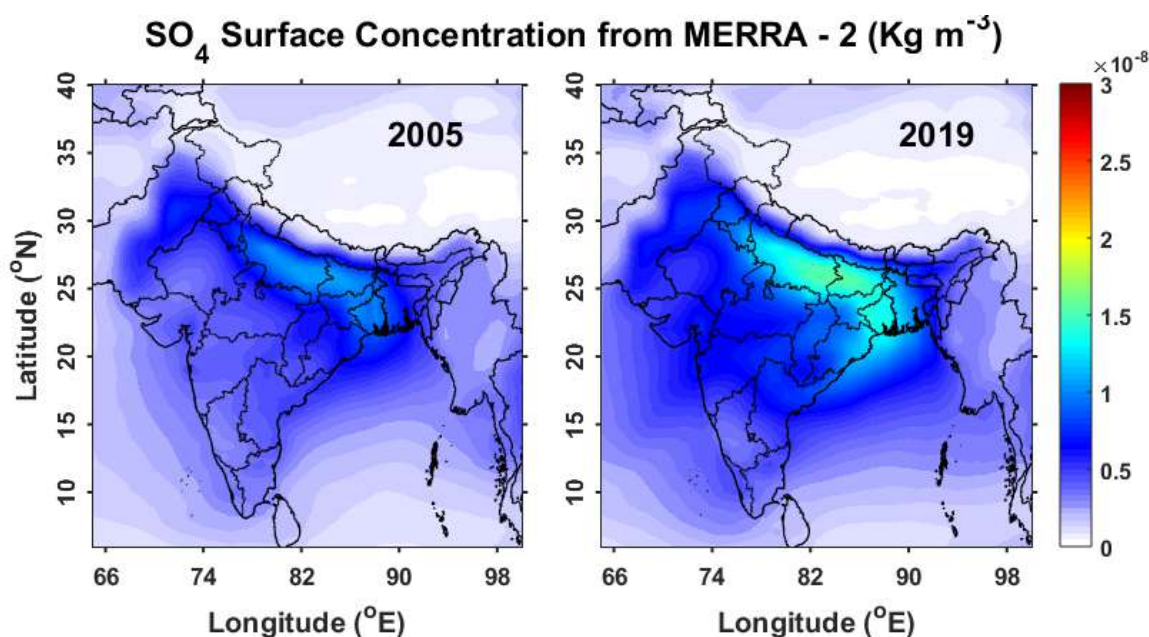


Figure 3.11: Annual mean sulfate (SO_4) aerosol surface concentration (in Kg/m^3) data from MERRA-2 for the years 2005 and 2019

Figure 3.12 shows the trend in annual mean sulfate (SO_4) aerosol surface concentration data from MERRA-2 during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in sulfate (SO_4) aerosol surface concentration helps us identify the potential areas where the changes in sulfate (SO_4) aerosol surface concentration could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.12 that increasing trend in sulfate (SO_4) aerosol surface concentration are quite wide spread across India except over parts of the Rajasthan state and increasing trend is noted not just over the land boundaries of India but also extends over vast areas over the Bay of Bengal and the Arabian Sea. Although there is no doubt about the fact that one of the most important reasons for the noted positive trend in sulfate (SO_4) aerosol surface concentration in MERRA2 data across the Indian region during the period 2005-2019 is due to increases in emissions of the precursor gas SO_2 from various sources including those from the coal based TPPs but, it seems that the changes in various other factors which influence the atmospheric chemistry involved in the formation of sulfate aerosols in the atmosphere must have also played a favourable role in resulting the noted positive trend in sulfate (SO_4) aerosol surface concentration in most parts of the region.

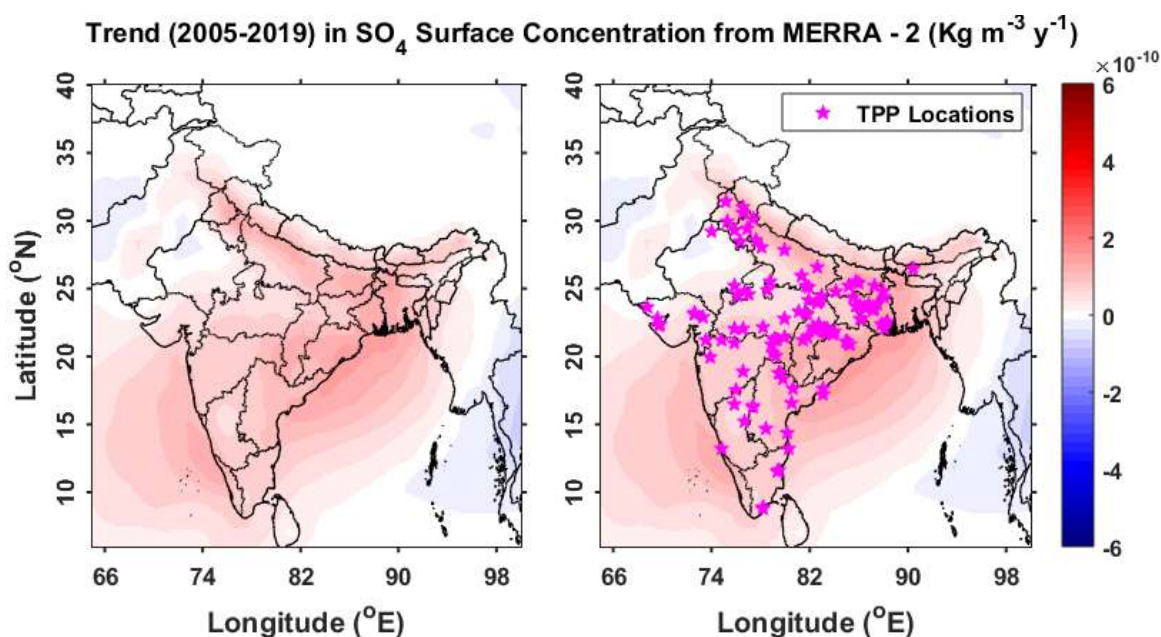


Figure 3.12: Trend in annual mean sulfate (SO_4) aerosol surface concentration (in $\text{Kg/m}^3/\text{year}$) data from MERRA-2 data during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in sulfate (SO_4) aerosol surface concentration in the right panel of the figure.

Although OMI/Aura observations provide SO_2 column burden (in Kg/m^2) data but assuming the same ratio for column burden to surface concentration of SO_2 in MERRA2 to be valid for OMI/Aura data, we derived the surface concentration of SO_2 from OMI data. Hence, we analyzed the SO_2 surface concentration data for different years as well as trend in derived SO_2 surface concentration data from OMI/Aura observations over the Indian region during the period from 2005 to 2019.

Figure 3.13 shows the annual mean SO_2 surface concentration data from OMI/Aura observations for the years 2005 and 2019. OMI/Aura observations data is able to identify several hot spot regions with higher surface concentration of SO_2 over parts of the states like Chattisgarh, Odisha, Maharashtra, Jharkhand, Tamil Nadu, Gujarat and West Bengal. It is also evident from Figure 3.13 that there has been significant increases in annual mean SO_2 surface concentration across most of the Indian region from the year 2005 to 2019. In order to understand the changes in SO_2 surface concentration across the Indian region in a better way, we examined the trends in SO_2 surface concentration based on OMI/Aura observations during the period 2005 to 2019.

Figure 3.14 shows the trend in annual mean SO_2 surface concentration data from OMI/Aura observations during the period 2005 to 2019. Overlaying the locations of all coal based TPPs across India on the spatial plot of trends in SO_2 surface concentration helps us identify the potential areas where the changes in SO_2 surface concentration could have happened due to changes in emissions from some of these TPPs. It is evident from figure 3.14 that some of the TPPs located in the states of Chattisgarh and Odisha could at least in part be responsible for the

noted positive trend in SO₂ surface concentration over this part of India based on OMI/Aura observations.

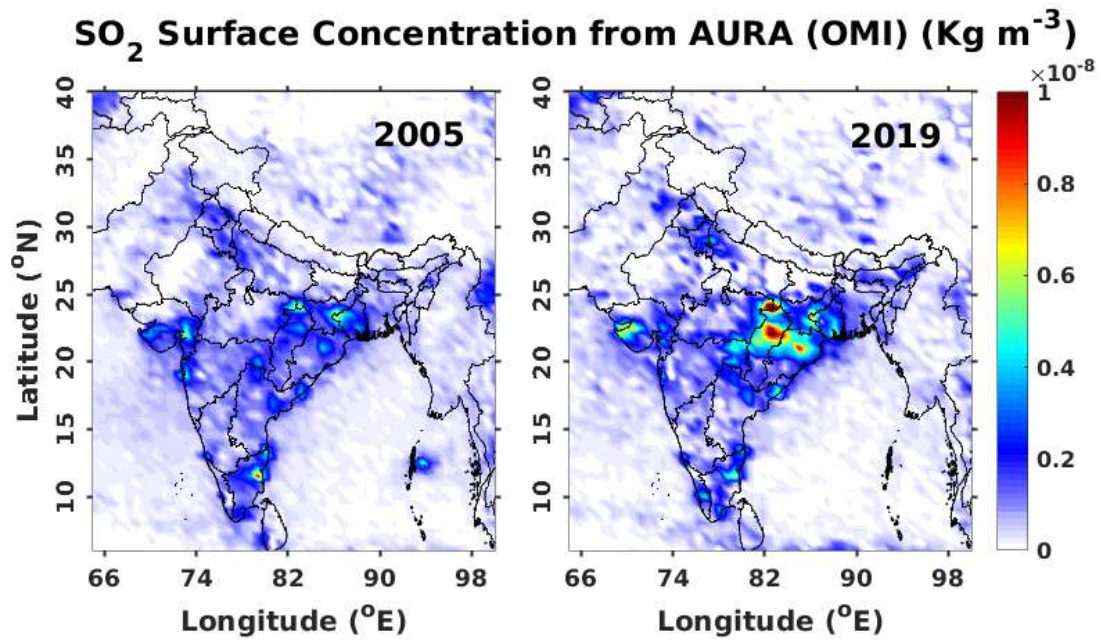


Figure 3.13: Annual mean SO₂ surface concentration (in Kg/m³) data from OMI/Aura observations for the years 2005 and 2019

Trend (2005-2019) in SO₂ Surface Concentration from AURA (OMI) (Kg m⁻³ y⁻¹)

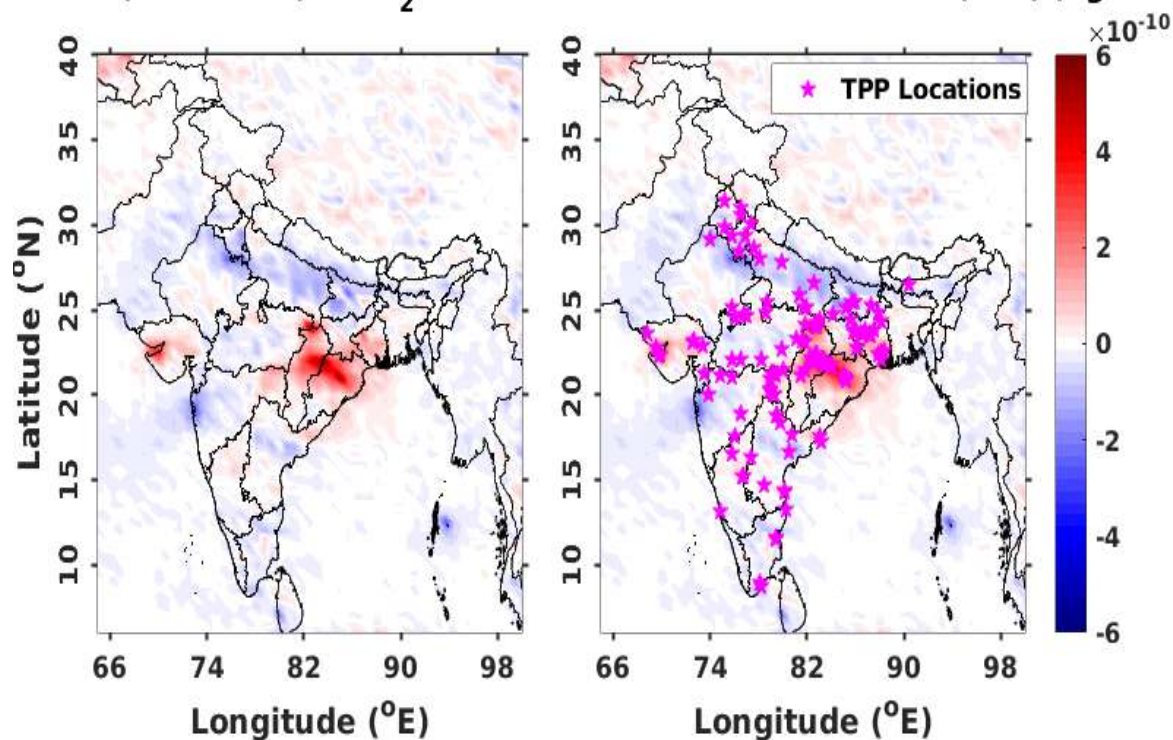


Figure 3.14: Trend in annual mean SO₂ surface concentration (in Kg/m³/year) data from OMI/Aura observations during the period 2005 to 2019. Locations of various coal based TPPs across India are overlayed on the trends in SO₂ surface concentration in the right panel of the figure.

CHAPTER 4: DISPERSION MODELLING OF AIR POLLUTANTS FROM SELECTED COAL BASED TPP's IN INDIA

AERMOD Dispersion Model Version 9 is used for understanding and the quantifying the dispersion of SO_2 from four different thermal plant plants (TPP) across the country based on their respective capacities and during four different months of the year 2019. Four coal based thermal power plants considered in this study include: Mundra UMTTP (Tata Power (CGPL)) and Mundra TPS (Adani Power Ltd), Gujarat, Vindhyachal Thermal Power Plant (Madhya Pradesh), Talcher Thermal Power Plant (Odisha) and Panipat Thermal Power Plant (Haryana). The horizontal resolution of the dispersion modeling simulations was kept as 500m x 500m and the simulations were performed over a model domain area of 200km x 200km by choosing the thermal power plant location as the center of the model domain in each simulation.

1. Mundra Thermal Power Plant:

The first coal based TPP considered for understanding and the quantifying the dispersion of SO_2 emissions from the stacks of the TPP into the ambient atmosphere over the surrounding region is the Mundra thermal power plant located in Mundra, Gujarat, India with approximate geographical co-ordinates of 22.82 °N, 69.55 °E. There are two separate coal based TPPs located very close to each other in Mundra. First one is the Tata Power plant named Mundra UMTTP having a capacity of 4000MW with five stacks of 800MW capacity each and the second one is Adani Power Ltd TPP named Mundra TPS has a capacity of 4620MW with nine stacks (four-330MW and five-660MW). The selection of these two Mundra TPPs for this study is because these are among the largest coal based TPPs in the state of Gujarat and these TPPs are in a completely different geographical region experiencing different meteorological variations as compared to other TPPs considered in this study. Since the Mundra UMTTP and Mundra TPS are located so close to each other, for the purposes of the present study, we have assumed them to be as one TPP. The terrain elevation around Mundra TPP is shown in Fig. 4.1.1.

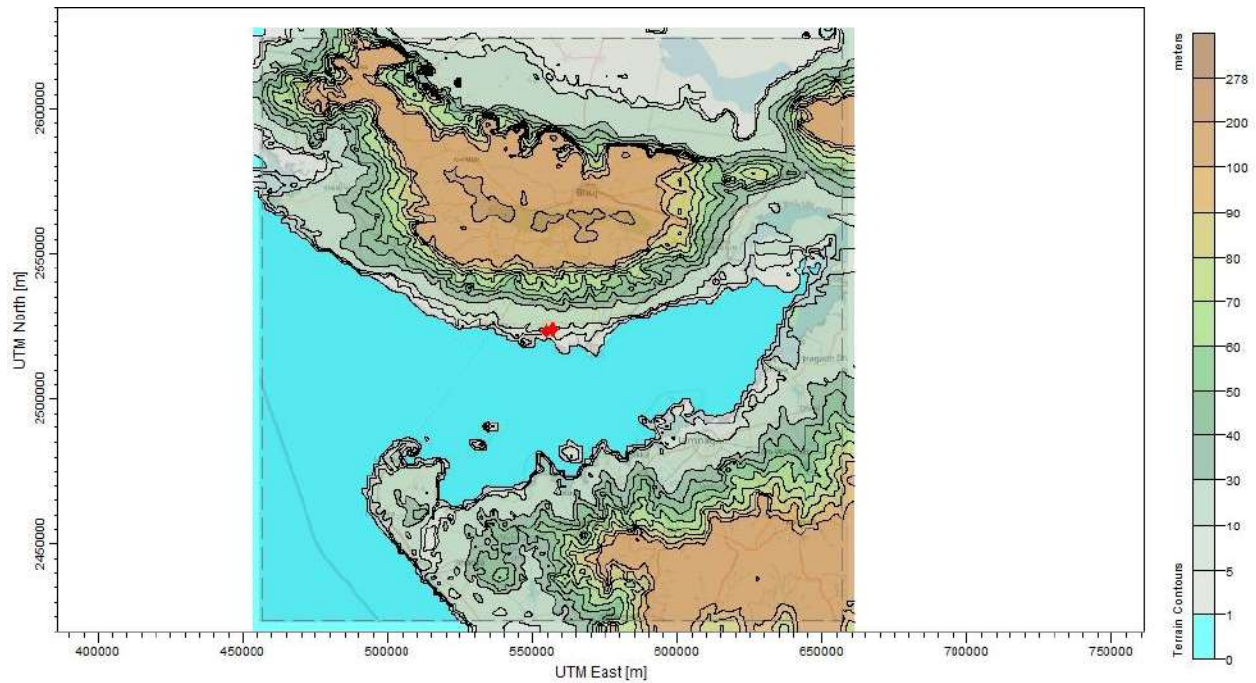


Figure 4.1.1: Terrain Elevations of Modeling Area (40000km²)

Meteorological Input

The atmospheric boundary layer meteorological data required as input for the AERMOD dispersion modeling for all the thermal power plants was generated using the Weather Research and Forecasting (WRF) model for the months of January, April, July, and October in the year 2019. The upper air meteorological data was generated using upper air estimator in-built in AERMET pre-processor.

The wind rose plots for the four months at Mundra Thermal Power Station (TPS) location are shown in Figure 4.1.2 to Figure 4.1.5.

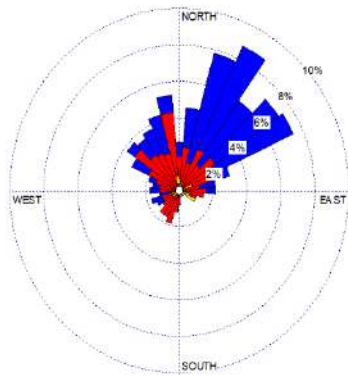


Fig 4.1.2 (a): Wind Rose Direction
(blowing from majorly N-E)

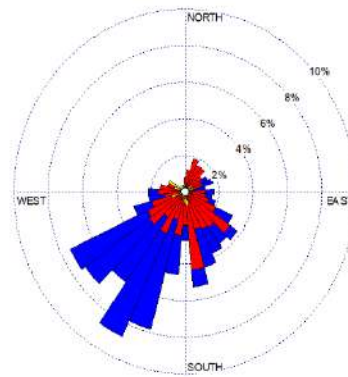


Fig 4.1.2 (b): Wind Rose Flow vector
(blowing to S-W)

Figure 4.1.2: Wind Rose plot for the month of January

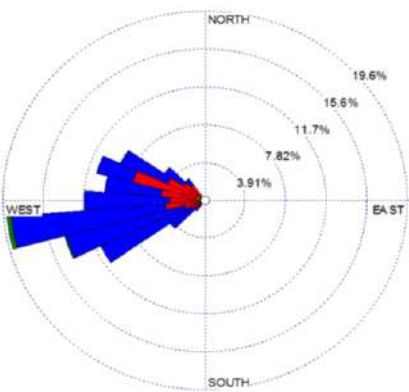


Fig 4.1.3 (a): Wind Rose Direction
(blowing from majorly West)

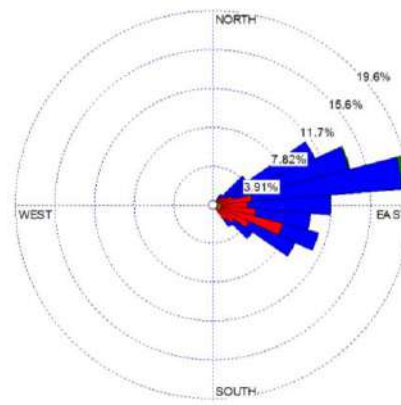


Fig 4.1.3 (b): Wind Rose Flow vector
(blowing to East)

Figure 4.1.3: Wind Rose plot for the month of April

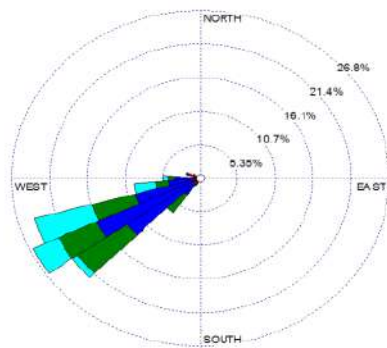


Fig 4.1.4(a): Wind Rose Direction (blowing from S-W)

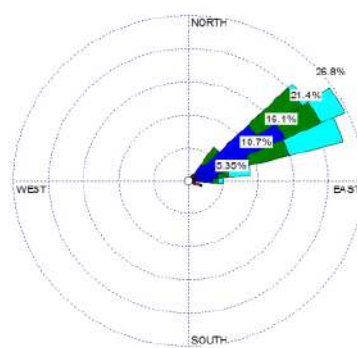


Fig 4.1.4(b): Wind Rose Flow vector (blowing to N-E)

Figure 4.1.4: Wind Rose plot for the month of July

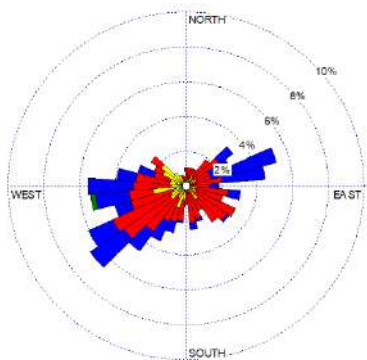


Fig 4.1.5(a): Wind Rose Direction (blowing from majorly S-W)

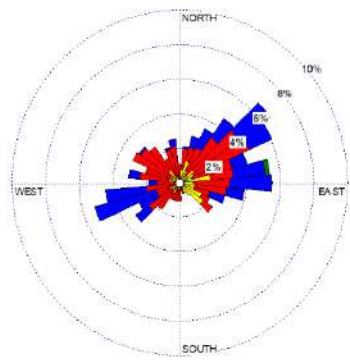


Fig 4.1.5(b): Wind Rose Flow vector (blowing to N-E)

Figure 4.1.5: Wind Rose plot for the month of October

Receptor Elevation

Receptor elevations were obtained from **GTOPO30/SRTM30** - Global digital elevation model files distributed by the USGS. The GTOPO30 data was processed with AERMAP, a pre-processor program which was developed to process terrain data (base elevation and hill height scale data) in conjunction with a layout of receptors and sources to be used in AERMOD.

Analysis of Dispersion Modeling Results

Air pollution dispersion modeling has been carried out using the surface elevation data for the entire domain area generated by the method discussed in the previous section. In this way, our simulations accounted for the actual surface elevations of the terrain inside the model domain, and thus our results on the dispersion of pollutants are more accurate as compared to simulations performed using only flat terrain. All SO₂ concentrations mentioned in this Chapter refer to their values at the surface level and these are presented as a function of distance from the TPS.

The air pollution dispersion modeling results for SO₂ surface concentration corresponding to the combination of Mundra UMTTP and Mundra TPS Power Plants considered as a single TPP is presented in Table 5.1.1.

In this study, for every TPS, additional dispersion modelling simulations are performed by assuming the installation of Flue-Gas Desulfurization (FGD) to cut down the emission of SO₂ from that TPS. The objective of performing this additional dispersion modeling simulation assuming FGD installed in the TPS is to understand the difference in dispersion of SO₂ from the TPS with and without FGD implementation. The efficiency of FGD in different units has been taken based on the date of installation and the electricity generation capacity of the units according to emission norms applicable to thermal power plants given in Environmental (Protection) Amendment rules, 2015. In the present case, we have assumed the following FGD efficiencies:

330MW units – 65% efficiency, 660MW- 92.5%, 800MW- 92.5%

As every TPS has multiple units of different age and capacity, we find that installation of FGD in all four TPS result in a reduction in the emission of SO₂ by about 80-85% in all four months considered in this study.

Table 4.1.1 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at any point within our AERMOD simulation domain and the locations as well as distances of these locations from the Centre of the simulation domain (location of the TPP) for both with and without FGD cases.

Table 4.1.1: SO₂ Dispersion Modeling results for MUNDRA POWER PLANTS in GUJARAT

Mon	Highest 1 hourly Conc. (µg m ⁻³)	Location of Highest 1 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 1 hourly Conc. from TPP (Km)	Highest 24 hourly Conc. (µg m ⁻³)	Location of Highest 24 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 24 hourly Conc. from TPP (Km)	Highest Monthly Average Conc. (µg m ⁻³)	Location of Highest Monthly Average Conc. (Lat °N, Lon °E)	Distance of Highest Monthly Average conc. from TPP (Km)
Without FGD									
JAN	9877	22.82, 69.56	1.03	1755	22.82, 69.56	1.03	534	22.82, 69.56	1.03
APR	4117	22.81, 69.56	1.51	1028	22.83, 69.56	1.51	805	22.83, 69.56	1.51
JUL	3218	22.83, 69.57	2.33	940	22.83, 69.57	2.33	687	22.83, 69.53	2.33
OCT	13568	22.85, 69.56	3.49	2345	22.83, 69.53	2.33	709	22.84, 69.56	2.45
With FGD									
JAN	1302	22.83, 69.55	1.11	252	22.82, 69.56	1.03	86	22.83, 69.55	1.11
APR	654	22.83, 69.56	1.51	159	22.83, 69.57	2.33	116	22.82, 69.56	1.03
JUL	504	22.82, 69.56	1.03	160	22.83, 69.59	4.25	111	22.80, 69.52	3.80
OCT	1504	22.81, 69.57	2.33	320	22.85, 69.56	3.49	118	22.83, 69.53	2.33

Table 4.1.2 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ within the AERMOD simulation domain at various distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion simulated by the model for both with and without FGD cases.

Table 4.1.2: SO₂ concentrations (µg/m³) at distances towards direction of maximum dispersion

MON	SO ₂	0km	3km	6km	8km	10km	13km	18km	25km	50km	75km	100km
Without FGD												
JAN	1 Hr	4483	2385	1853	1891	1710	1461	1390	1150	837	566	401
	24 Hr	738	833	505	433	405	357	276	189	75.2	42.5	26.9
	Mon	382	185	157	132	108	83.7	56.5	36.9	14.1	7.85	5.05
APR	1 Hr	2070	2120	2052	2001	1830	1691	1492	1180	837	571	418
	24 Hr	590	917	674	573	445	323	199	139	59.9	34.7	23.5
	Mon	174	659	303	184	147	109	76.5	49.7	18.6	10.5	7.1
JUL	1 Hr	1425	3033	1940	1910	1650	1250	997	1111	723	464	321
	24 Hr	548	892	431	341	302	248	182	125	49.9	28.1	19.1
	Mon	102	589	269	181	131	90.6	55.2	33.8	12.6	7.02	4.67
OCT	1 Hr	9680	13211	7659	1998	1660	1260	1060	1140	783	535	379
	24 Hr	1970	2185	602	476	394	299	208	165	84.5	50	33.5
	Mon	452	672	267	142	117	87.1	59.3	38.5	14.5	8.09	5.35
With FGD												
JAN	1 Hr	860	652	323	272	228	201	193	191	120	80.6	57.1
	24 Hr	107	105	66.7	60	52.7	43.1	30.9	21.2	9.91	5.89	4.1
	Mon	67.2	35.5	25.2	20.7	16.8	12.7	8.33	5.3	1.94	1.07	0.68
APR	1 Hr	402	471	349	315	298	270	228	196	120	78.1	55.7
	24 Hr	43.1	136	92.9	76.9	60.7	46.3	30.8	20.2	8.17	4.67	3.17
	Mon	22.4	64.1	39.5	34.8	27.7	20.4	13.3	8.5	2.96	1.56	0.98
JUL	1 Hr	261	313	295	242	240	199	183	177	101	62.1	42.9
	24 Hr	129	146	101	72.4	60.1	42.1	19.9	14.6	6.61	3.77	2.56
	Mon	20.2	88.4	51.4	28.5	20.6	13.8	8.25	4.97	1.75	0.98	0.63
OCT	1 Hr	1110	1321	355	301	258	203	199	188	113	71.5	67.2
	24 Hr	36.4	289	83.6	45	37	29.9	24.1	14.4	6.04	5.4	4.56
	Mon	56.5	96.2	77.3	48.6	14.4	11.7	7.67	5.12	1.97	1.12	0.74

1 Hr: Highest 1 hourly Conc., 24Hr: Highest 24-hourly Conc., Mon: Highest Monthly Average Conc.

Here it is worth mentioning that the highest 1-hourly and highest 24-hourly concentrations refer to highest concentration values of SO₂ estimated by the model at any height from the surface and at any distance from the TPP location within the simulation domain. Generally, these highest concentration values are obtained at the stack height level. Whereas the monthly mean concentration values refer to the surface level monthly

mean values of SO₂ concentration estimated by the model at all receptor points located at different distances from the TPP within the simulation domain.

Analysis of dispersion of SO₂ from the Mundra TPP for the month of January 2019

Figures 4.1.6 and 4.1.7 show combined dispersion of total SO₂ emission from all the stacks of both the TPPs located in Mundra for the month of January 2019 for cases with and without FGD respectively. It can be noted from figures 4.1.6 and 4.1.7 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of both these TPPs. Figures 4.1.6 and 4.1.7 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.1.8 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

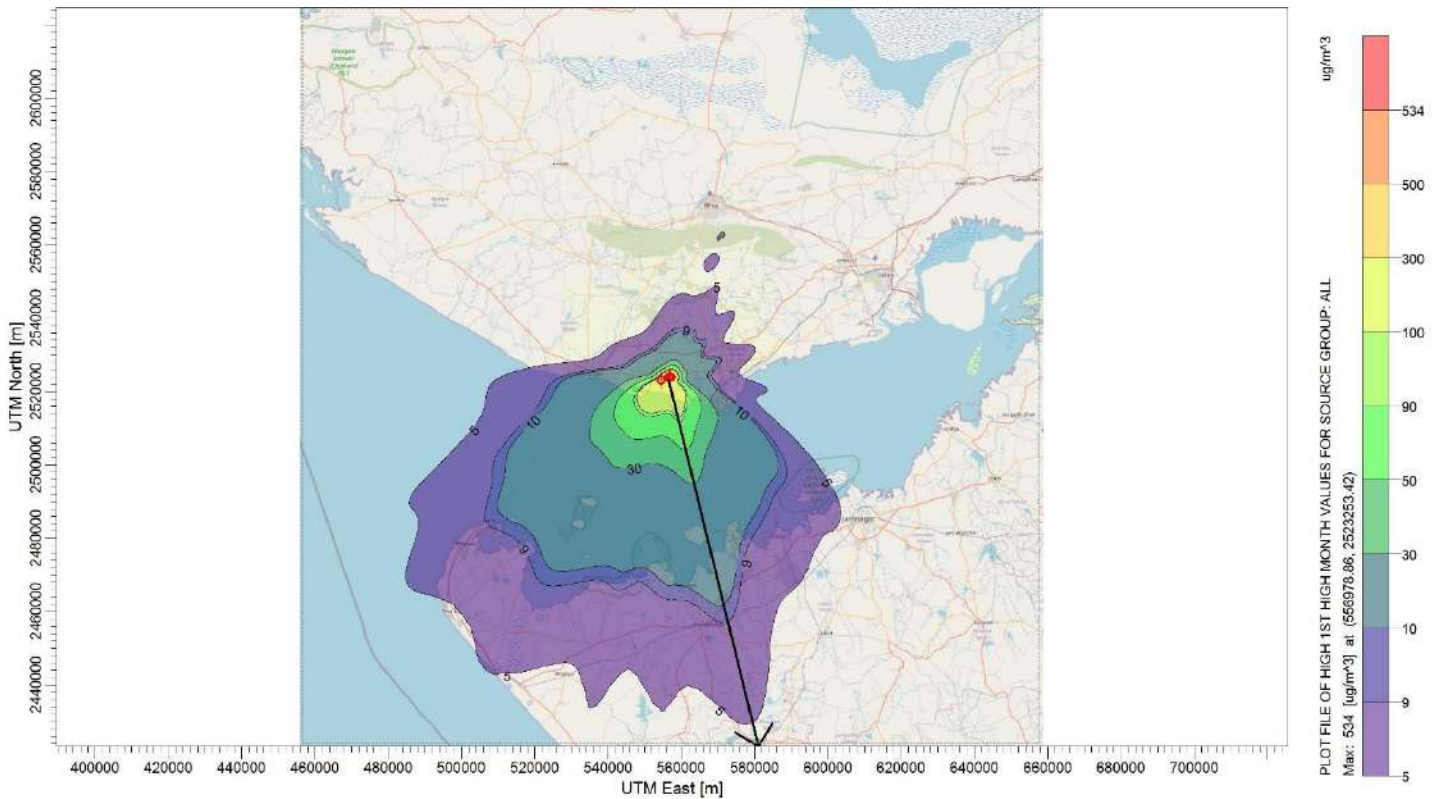


Figure 4.1.6: SO₂ Concentration for January Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

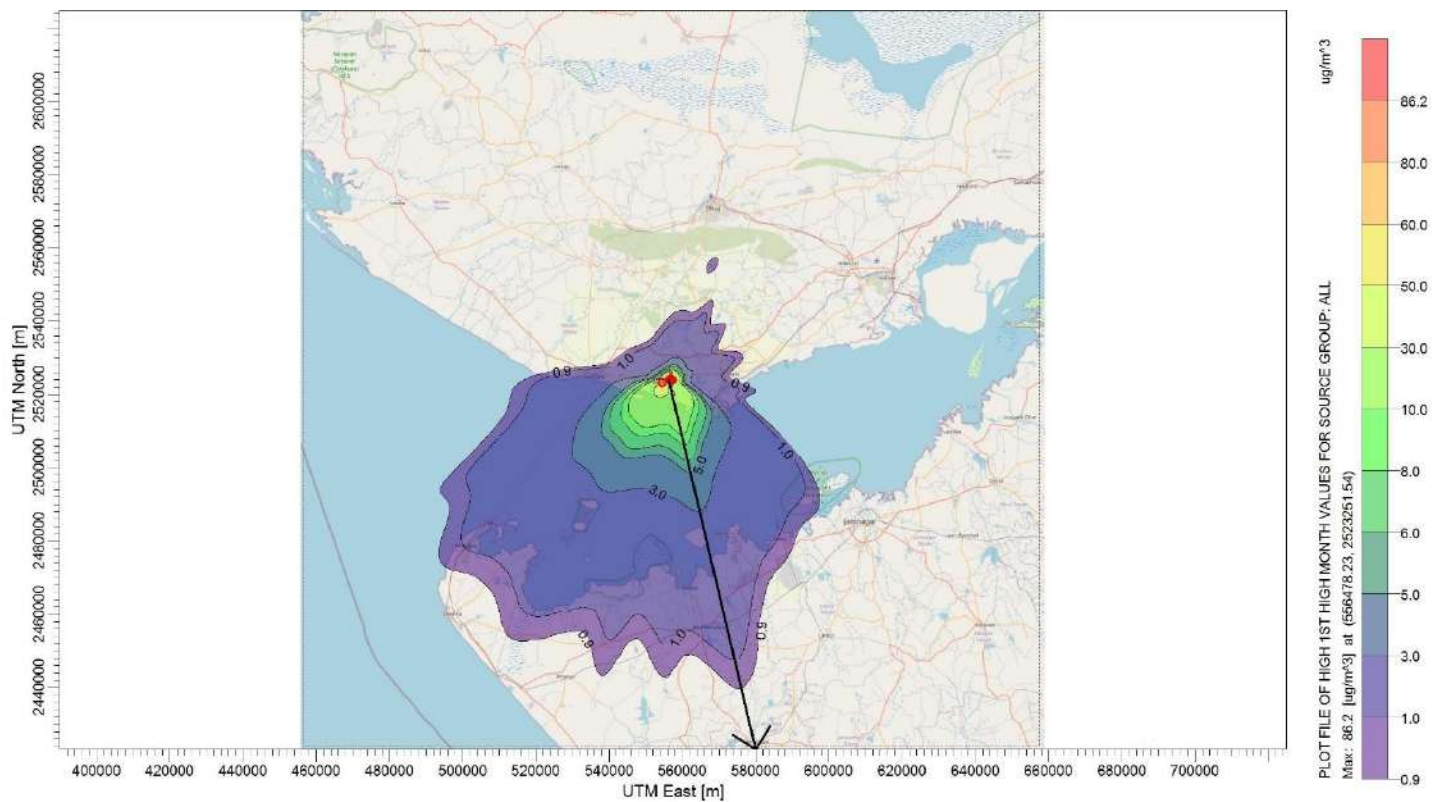


Figure 4.1.7: SO₂ Concentration for January Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

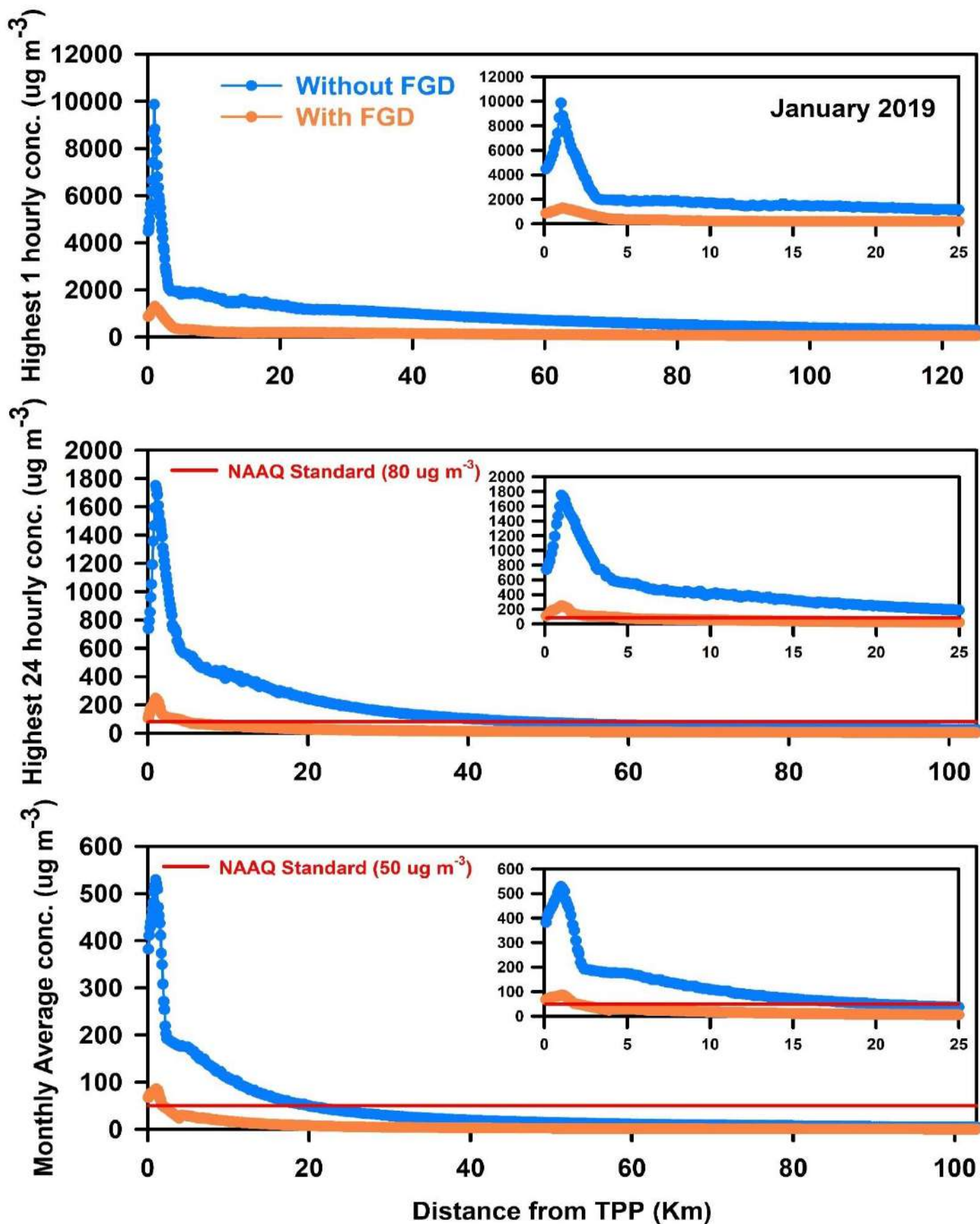


Figure 4.1.8: SO_2 concentration versus distance plot in the direction of maximum dispersion for January 2019

Analysis of dispersion of SO₂ from the Mundra TPP for the month of April 2019

Figures 4.1.9 and 4.1.10 show combined dispersion of total SO₂ emission from all the stacks of both the TPPs located in Mundra for the month of April 2019 for cases with and without FGD respectively. It can be noted from figures 4.1.9 and 4.1.10 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of both these TPPs. Figures 4.1.9 and 4.1.10 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.1.11 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ for the month of April 2019 at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

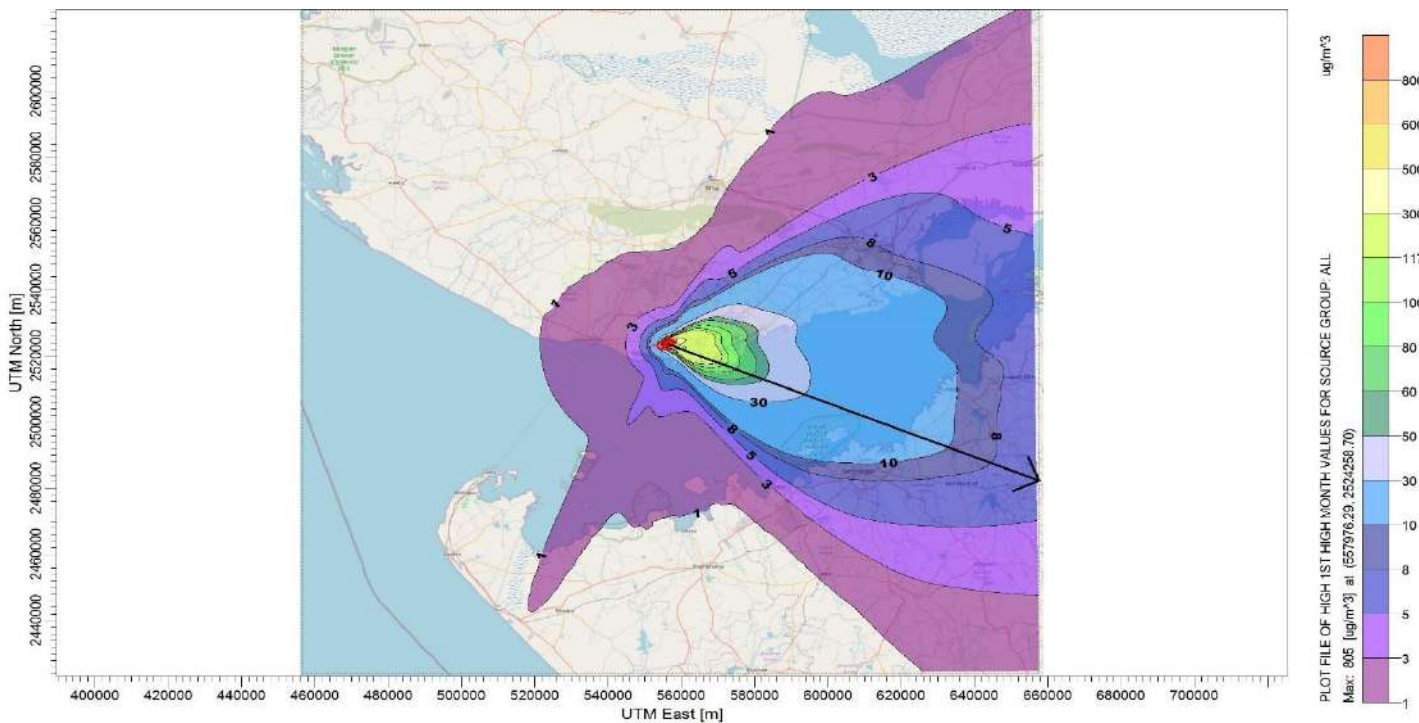


Figure 4.1.9: SO₂ Concentration for April Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

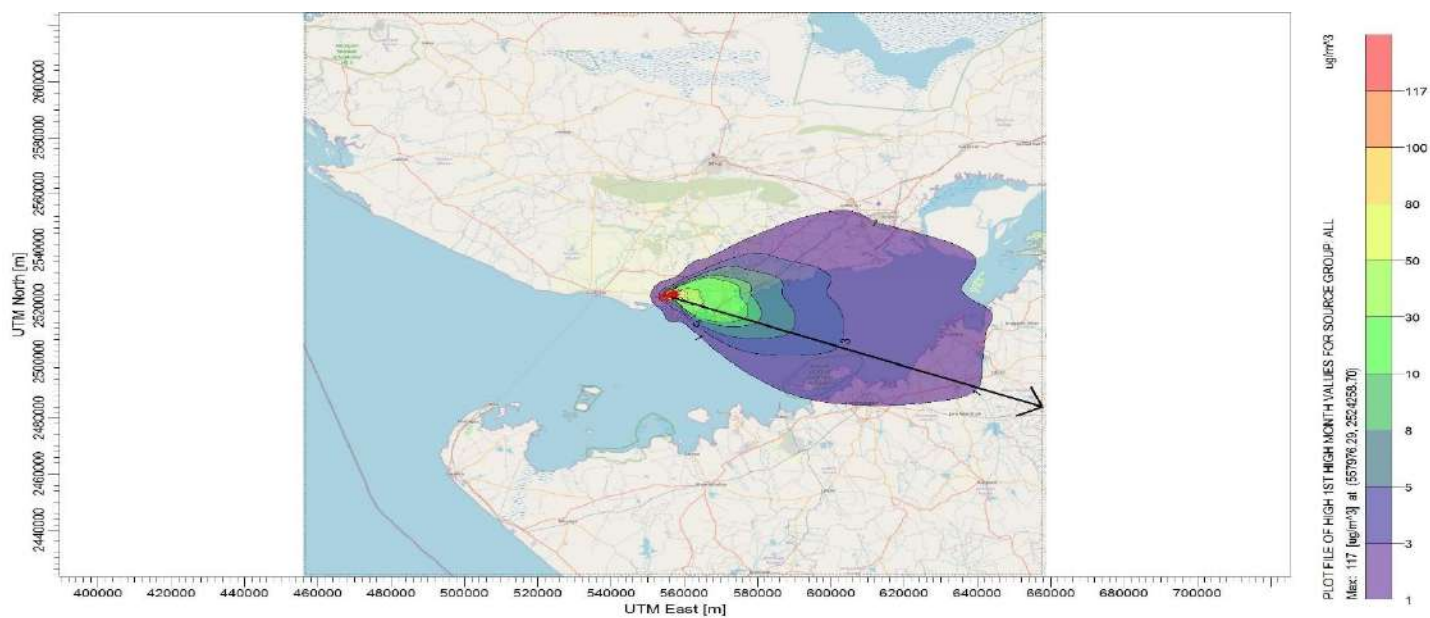


Figure 4.1.10: SO₂ Concentration for April Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

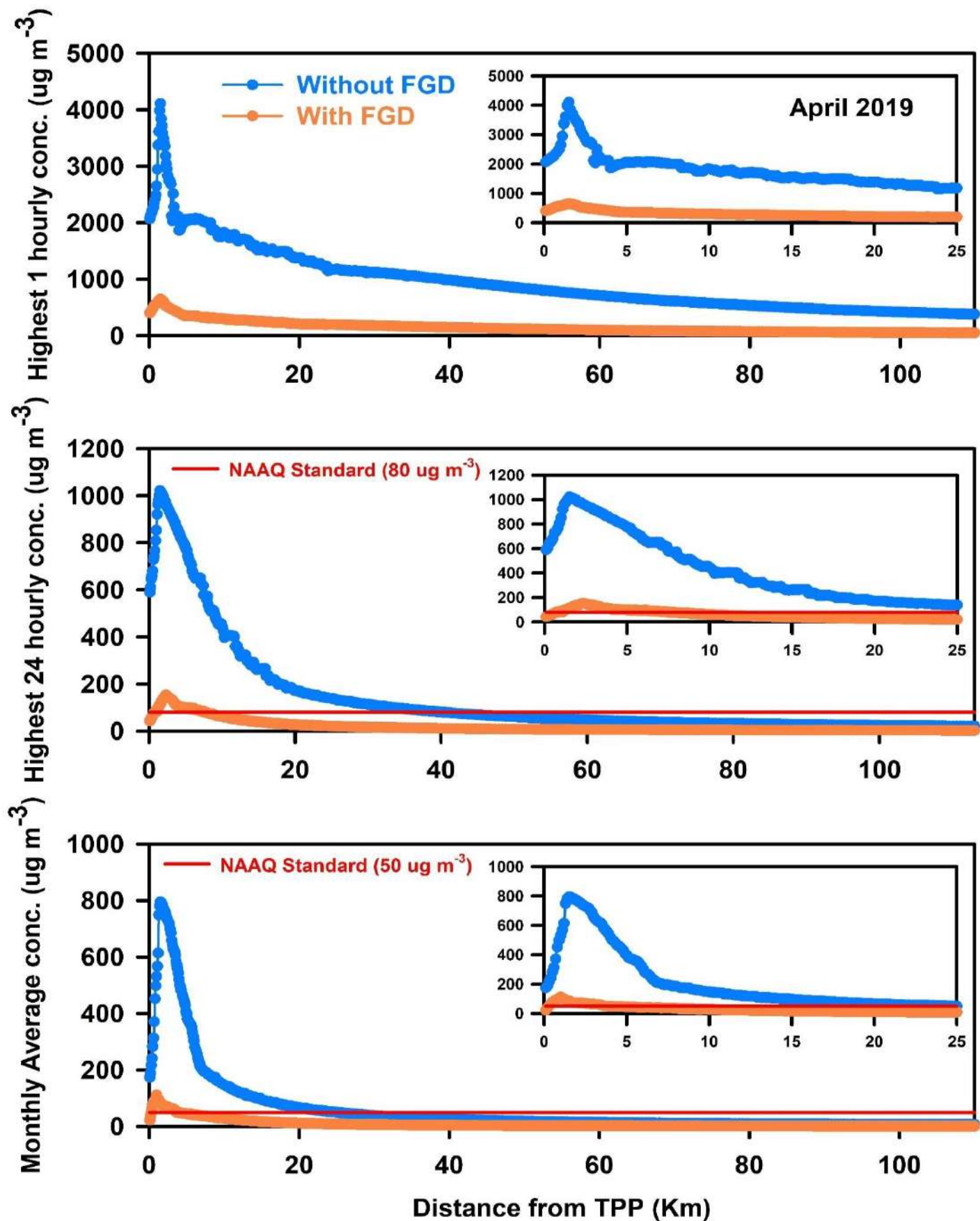


Figure 4.1.11: SO_2 concentration versus distance plot in the direction of maximum dispersion for April 2019

Analysis of dispersion of SO₂ from the Mundra TPP for the month of July 2019

Figures 4.1.12 and 4.1.13 show combined dispersion of total SO₂ emission from all the stacks of both the TPPs located in Mundra for the month of July 2019 for cases with and without FGD respectively. It can be noted from figures 4.1.12 and 4.1.13 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of both these TPPs. Figures 4.1.12 and 4.1.13 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.1.14 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ for the month of July 2019 at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

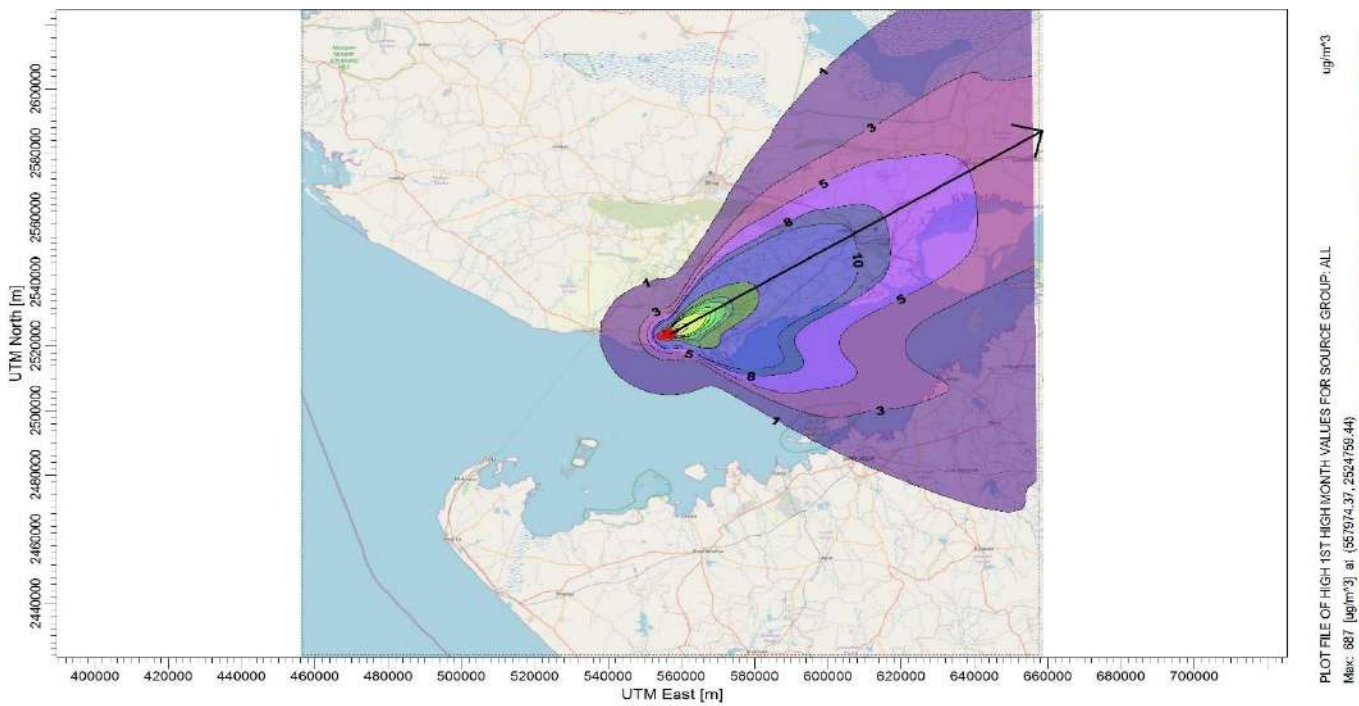


Figure 4.1.12: SO₂ Concentration for July Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

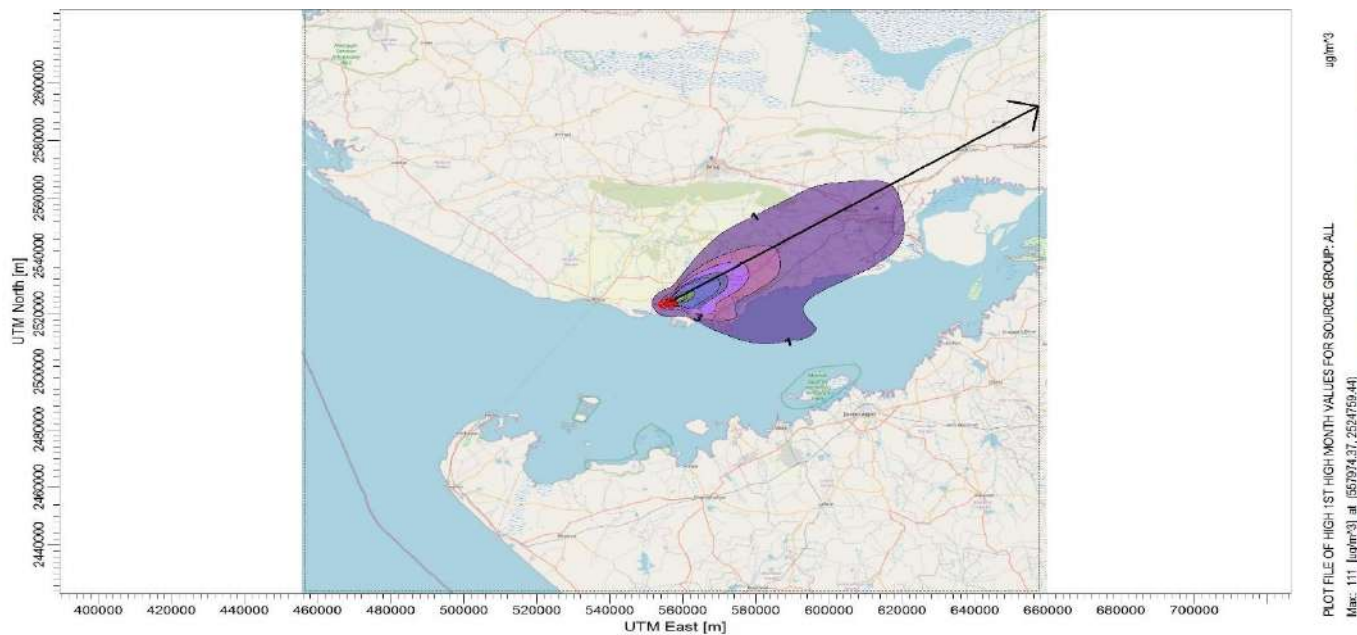


Figure 4.1.13: SO₂ Concentration for July Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

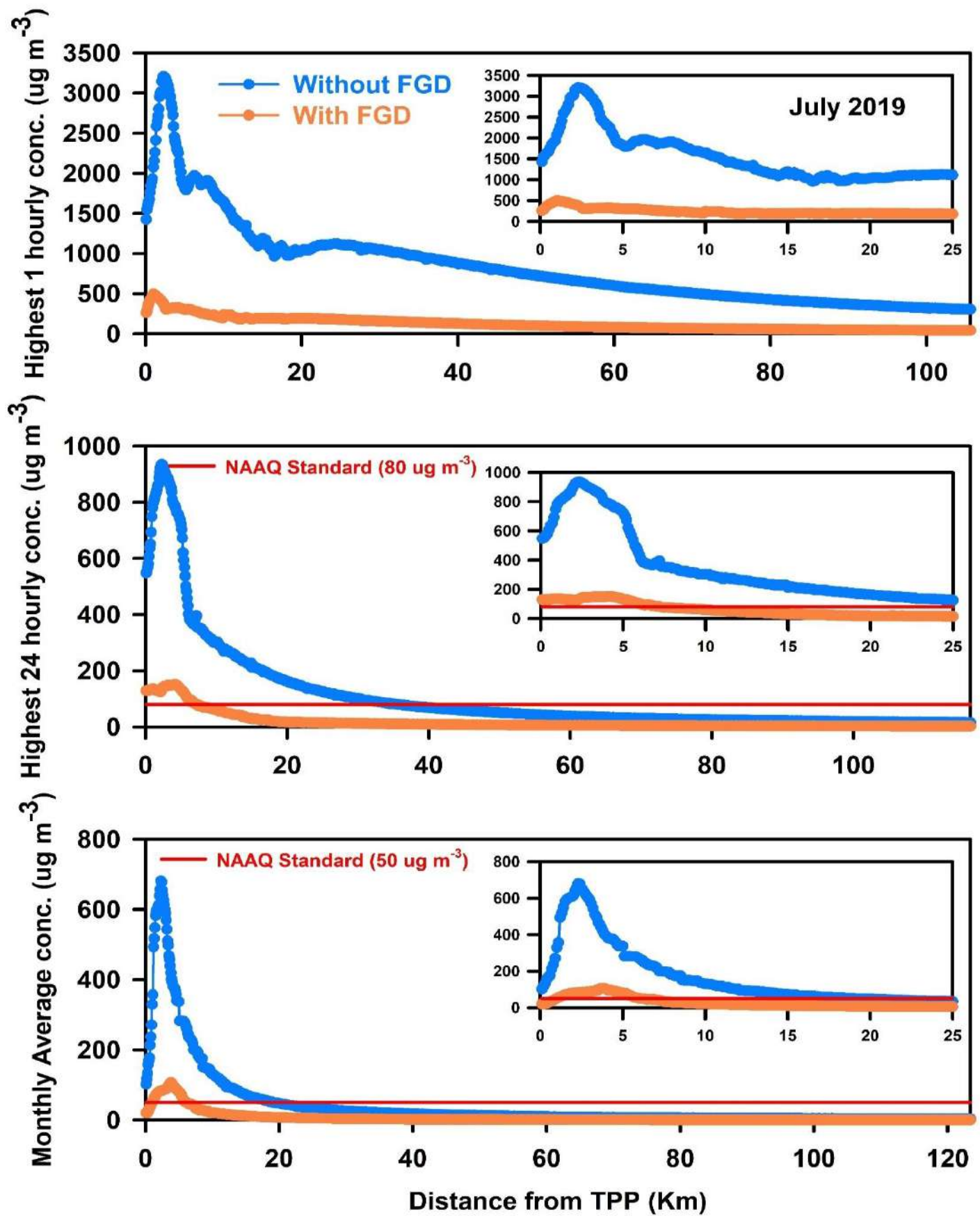


Figure 4.1.14: SO₂ concentration versus distance plot in the direction of maximum dispersion for July 2019

Analysis of dispersion of SO₂ from the Mundra TPP for the month of October 2019

Figures 4.1.15 and 4.1.16 show combined dispersion of total SO₂ emission from all the stacks of both the TPPs located in Mundra for the month of October 2019 for cases with and without FGD respectively. It can be noted from figures 4.1.15 and 4.1.16 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of both these TPPs. Figures 4.1.15 and 4.1.16 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.1.17 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ for the month of October 2019 at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

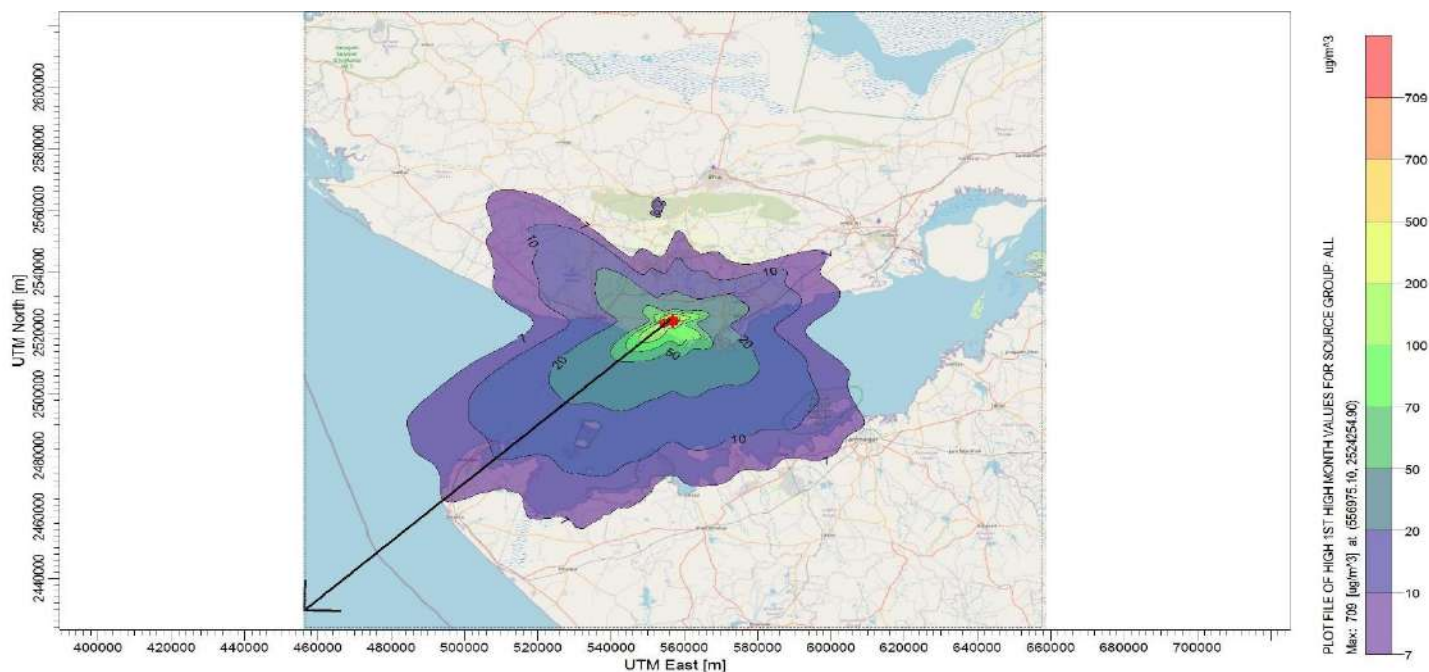


Figure 4.1.15: SO₂ Concentration for October Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

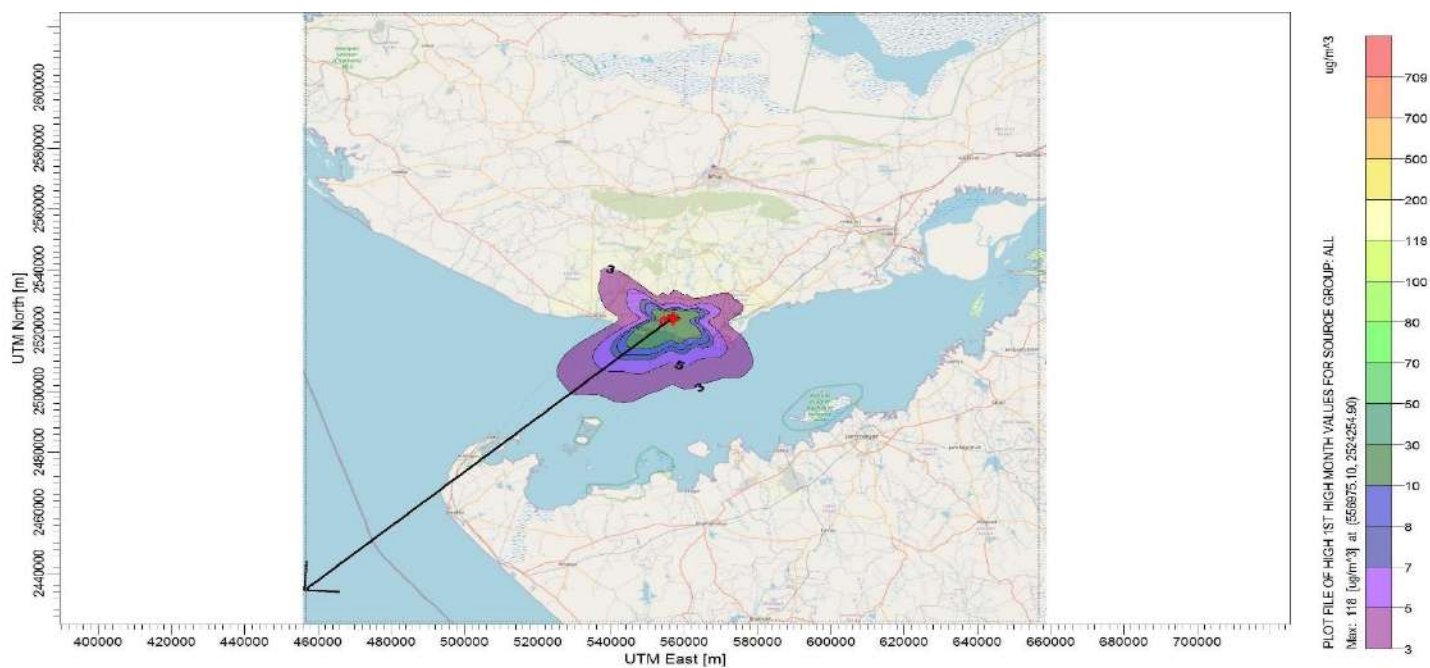


Figure 4.1.16: SO₂ Concentration for October Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

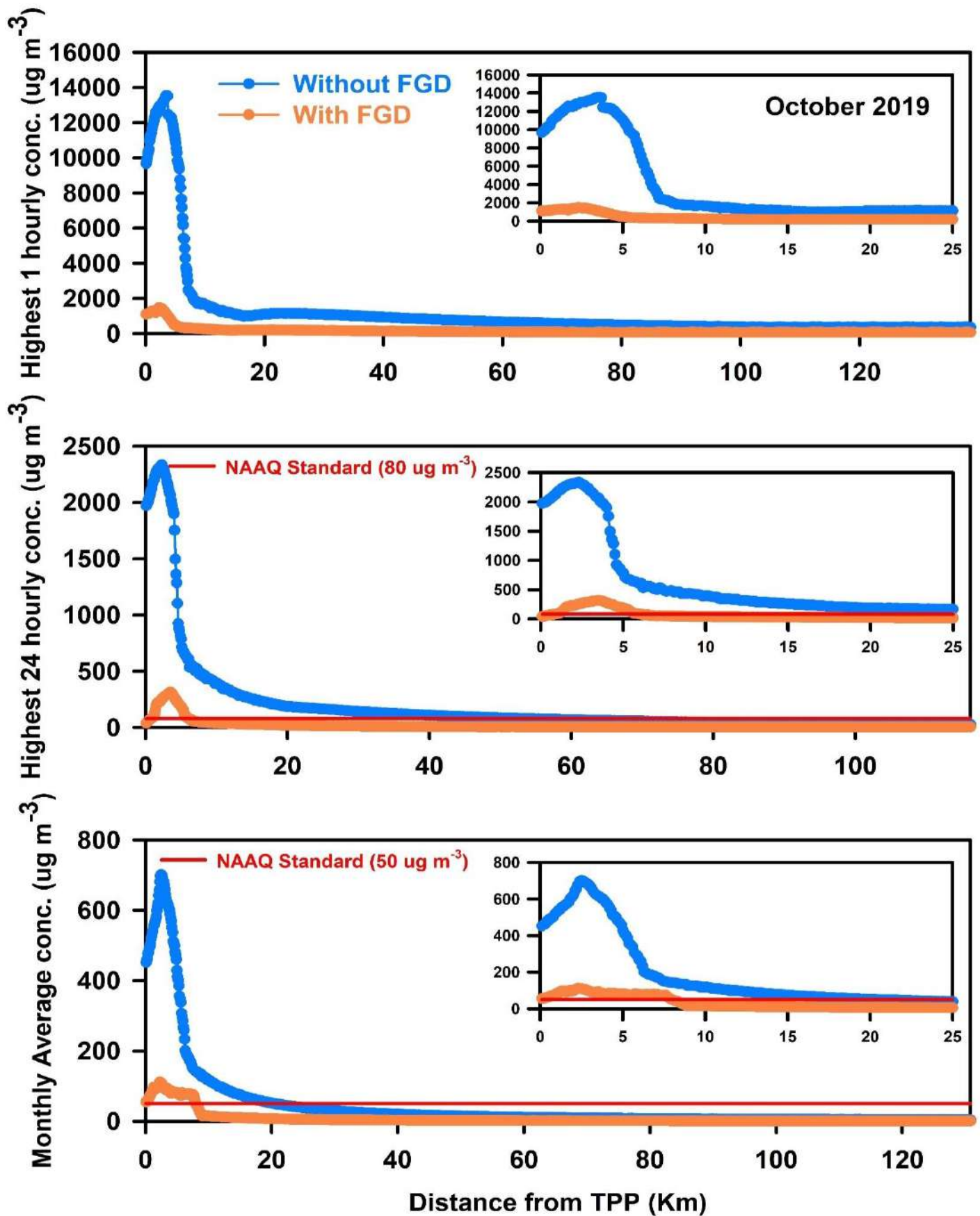


Figure 4.1.17: SO_2 concentration versus distance plot in the direction of maximum dispersion for October

2. Vindhyachal Thermal Power Plant:

The second coal based TPP considered for understanding and the quantifying the dispersion of SO₂ emissions from the stacks of the TPP into the ambient atmosphere over the surrounding region is the Vindhyachal thermal power plant located in Singrauli, Madhya Pradesh, India. This TPP has a total power production capacity of 4260 MW with seven stacks of 500MW capacity each and six stacks of 210MW capacity each and it has geographical co-ordinates of 24.089°N, 82.648°E. The selection of Vindhyachal TPP for this study is based on the fact that it is one of the largest coal based TPP in India and this TPP is located in a region with highest SO₂ atmospheric column burden over India (see Chapter 3) and this region also exhibits the highest increasing trend in SO₂. Moreover, this TPP is in a completely different geographical region experiencing different meteorological variations as compared to other TPPs considered in this study. The terrain elevation around Mundra TPP is shown in Figure 4.2.1. The horizontal resolution of the dispersion modeling simulations was kept as 500m x 500m and the simulations were performed over a model domain area of 200km x 200km by choosing the thermal power plant location as the center of the model domain in each simulation.

In this study, for every TPS, additional dispersion modelling simulations are performed by assuming the installation of Flue-Gas Desulfurization (FGD) to cut down the emission of SO₂ from that TPS. The objective of performing this additional dispersion modeling simulation assuming FGD installed in the TPS is to understand the difference in dispersion of SO₂ from the TPS with and without FGD implementation. The efficiency of FGD in different units has been taken based on the date of installation and the electricity generation capacity of the units according to emission norms applicable to thermal power plants given in Environmental (Protection) Amendment rules, 2015. In the present case, we have assumed the following FGD efficiencies:

210MW units – 65% efficiency, 500MW- 92.5%

With the installation of FGD in this power plant, we noted a reduction of about 83-85% in the emissions of SO₂ in all the four months.

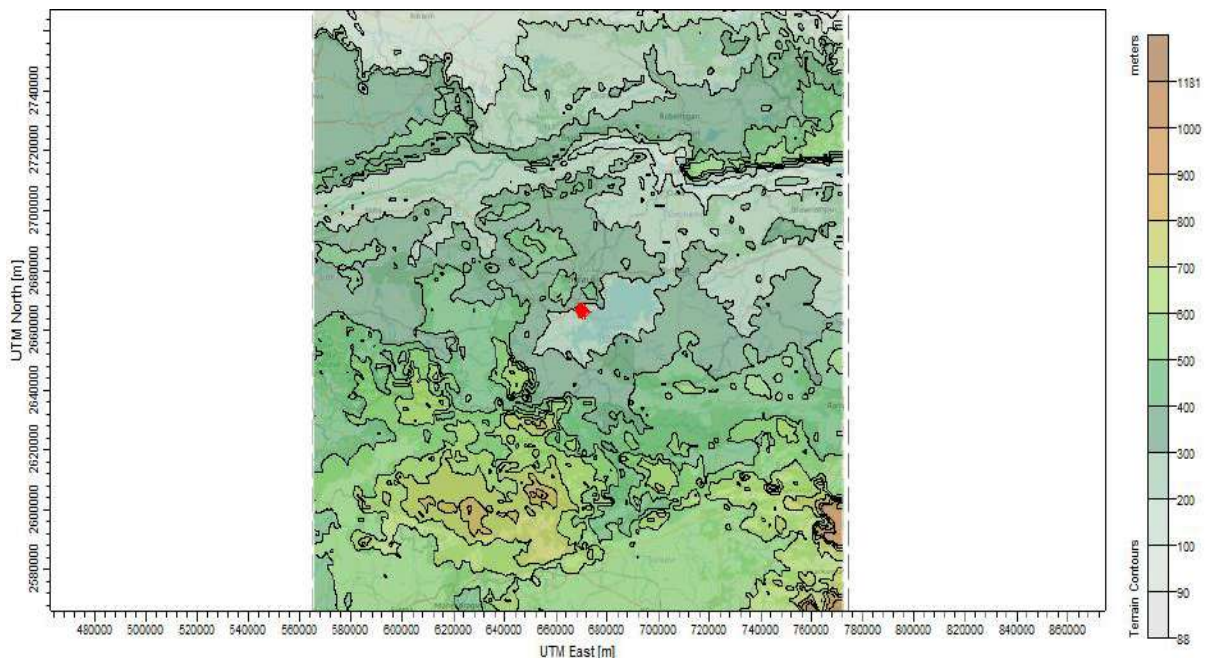


Figure 4.2.1: Terrain Elevation of Modelling Area (40000km²)

Meteorological Input The surface data was generated using the Weather Research and Forecasting model for the months of January, April, July and October in the year 2019. The upper air data was generated using upper air estimator in-built in AERMET pre-processor. The wind rose plots for different four months corresponding to the Vindhyachal Thermal Power Station (TPS) are shown in Figures 4.2.2 to 4.2.5.

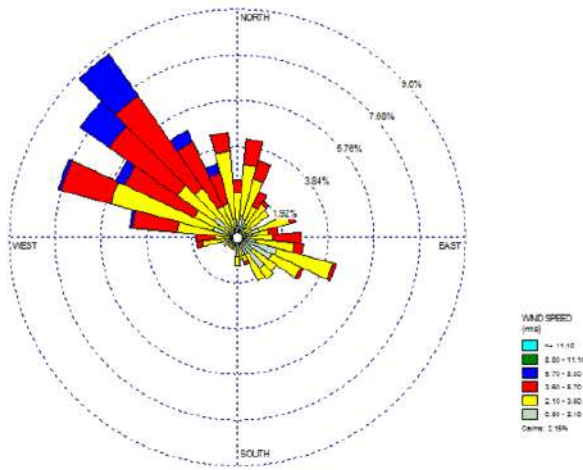


Fig 4.2.2 (a): Wind Rose Direction

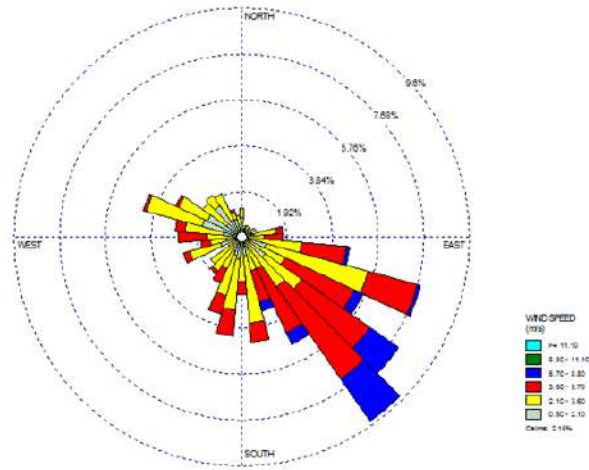


Fig 4.2.2 (b): Wind Rose Flow vector

Figure 4.2.2: Wind Rose plot for the month of January

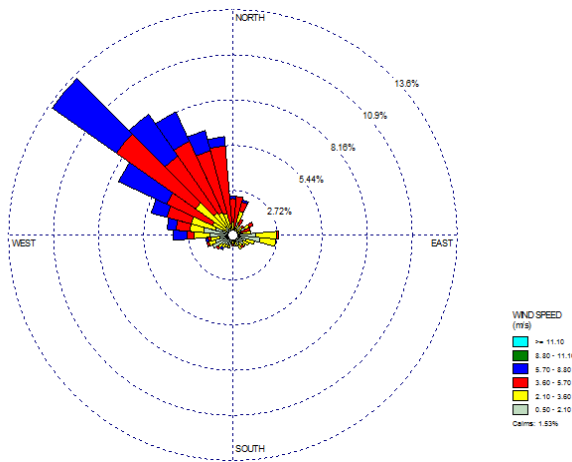


Fig 4.2.3 (a): Wind Rose Direction

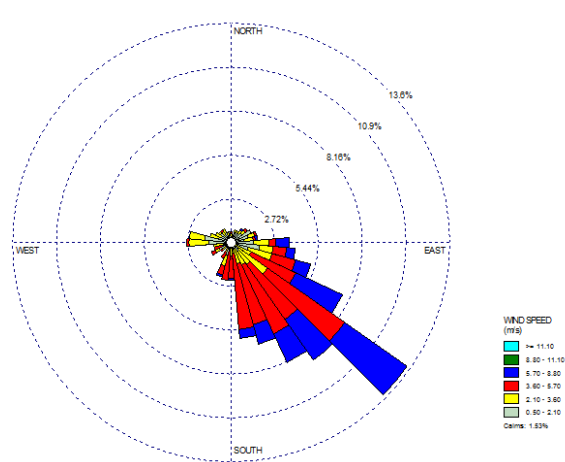


Fig 4.2.3 (b): Wind Rose Flow vector

Figure 4.2.3: Wind Rose plot for the month of April

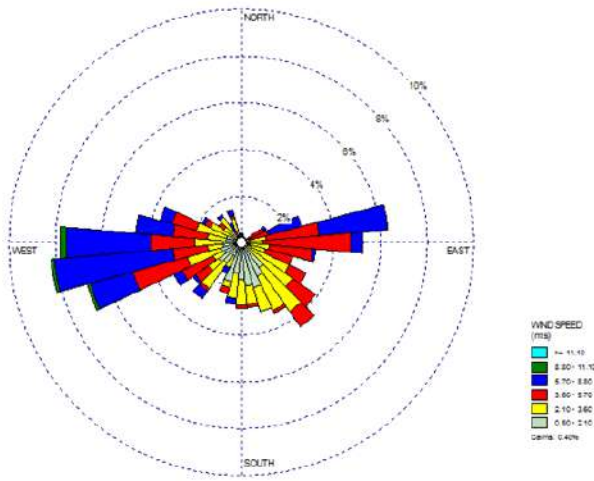


Fig 4.2.4 (a): Wind Rose Direction

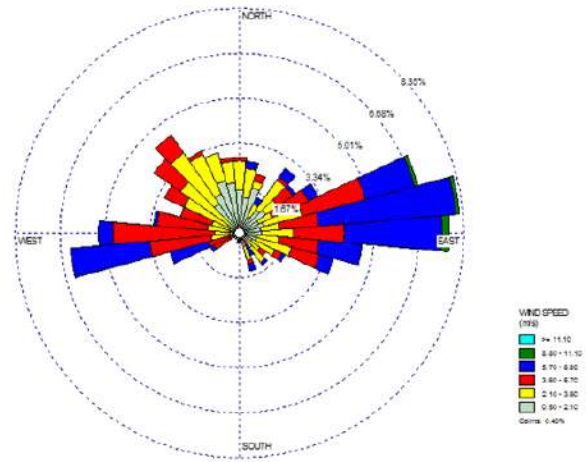


Fig 4.2.4 (b): Wind Rose Flow vector

Figure 4.2.4: Wind Rose plot for the month of July

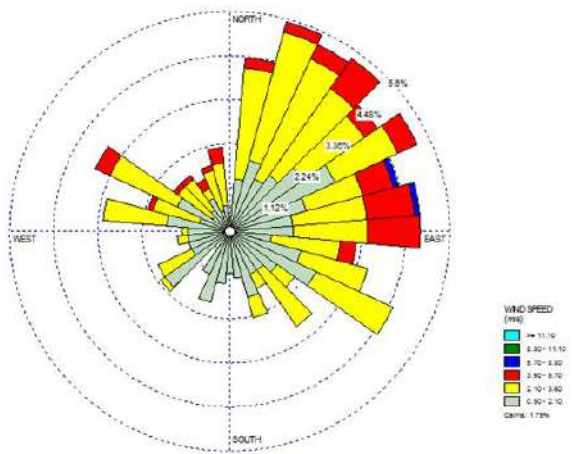


Fig 4.2.5 (a): Wind Rose Direction

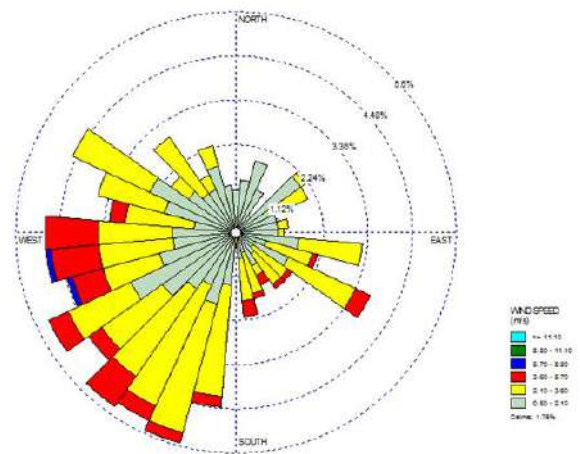


Fig 4.2.5 (b): Wind Rose Flow vector

Figure 4.2.5: Wind Rose plot for the month of October

Table 4.2.1 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at any point within our AERMOD simulation domain and the locations as well as distances of these locations from the Centre of the simulation domain (location of the TPP) for both with and without FGD cases.

Table 4.2.1: SO₂ Dispersion Modeling results for Vindhyachal Power Plant of Madhya Pradesh

Mon	Highest 1 hourly Conc. (µg m ⁻³)	Location of Highest 1 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 1 hourly Conc. from TPP (Km)	Highest 24 hourly Conc. (µg m ⁻³)	Location of Highest 24 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 24 hourly Conc. from TPP (Km)	Highest Monthly Average Conc. (µg m ⁻³)	Location of Highest Monthly Average Conc. (Lat °N, Lon °E)	Distance of Highest Monthly Average conc. from TPP (Km)
Without FGD									
JAN	7434	24.15, 82.60	8.38	620	24.08, 82.70	5.21	217	24.08, 82.68	3.24
APR	6636	24.12, 82.61	5.26	421	24.10, 82.68	3.24	149	24.12, 82.69	5.26
JUL	4836	24.10, 82.68	3.24	638	24.10, 82.65	1.11	221	24.13, 82.68	5.39
OCT	7021	24.14, 82.59	8.25	682	24.11, 82.63	3.01	322	24.10, 82.68	3.24
With FGD									
JAN	2217	24.15, 82.60	8.38	98	24.15, 82.60	8.32	35	24.12, 82.67	3.91
APR	1663	24.15, 82.59	9.03	99	24.14, 82.57	9.84	24	24.03, 82.63	6.97
JUL	878	24.11, 82.61	4.63	85	24.10, 82.67	2.32	35	24.15, 82.61	7.81
OCT	2094	24.14, 82.59	8.25	146	24.14, 82.59	8.25	51	24.09, 82.66	1.02

Table 4.2.2 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ within the AERMOD simulation domain at various distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion simulated by the model for both with and without FGD cases.

Table 4.2.2: SO₂ concentrations (µg/m³) at distances towards direction of maximum dispersion

MON	SO ₂	0km	2km	5km	7km	10km	12km	18km	25km	50km	75km	100km
Without FGD												
JAN	1 Hr	1609	843	684	3245	3284	352	260	227	174	119	82.3
	24 Hr	139	585	548	284	90.6	79.2	59	50.2	27.9	22.3	12.9
	Mon	150	129	28.8	29.2	26.2	23.2	16.5	11.5	6.56	4.18	3.03
APR	1 Hr	2210	1580	5741	2185	358	341	255	233	168	115	
	24 Hr	221	275	89.5	94.2	79.3	68.3	44.4	29.2	12.1	7.82	6.97
	Mon	121	87.5	133	20.5	15.5	13.5	9.64	7.24	4.21	3.85	1.79
JUL	1 Hr	1360	2383	1764	403	335	241	216	227	159	110	80.3
	24 Hr	243	197	81.1	76.2	88.8	84.2	67.2	53.8	25.6	15.5	10.4
	Mon	106	40.2	181	49.1	12.5	12.3	7.85	5.6	2.43	1.48	1.06
OCT	1 Hr	1934	1973	721	4268	968	262	179	218	163	108	73.6

	24 Hr	172	343	80	107	98.2	87.4	60.3	42.7	17.1	9.35	5.92
	Mon	115	213	103	9.35	7.73	7.21	6.38	5.73	3.06	6.28	1.68
With FGD												
JAN	1 Hr	255	307	109	1158	1267	56.1	46.9	44.4	28	18.1	12.2
	24 Hr	31.1	22.7	21.1	65.3	33.7	11.3	10.3	8.25	4.25	2.64	1.68
	Mon	32.2	26.5	9.83	3.6	3.05	2.59	1.94	1.32	0.53	0.31	0.23
APR	1 Hr	249	317	102	358	1143	57.9	43.5	43.3	26.5	23	
	24 Hr	27.2	21.5	15.6	14.1	87.3	9.86	6.57	4.33	1.77	1.24	1.06
	Mon	21.3	10.6	4.1	21.7	2.5	2.19	1.55	1.16	0.64	0.46	0.27
JUL	1 Hr	155	241	532	65.5	58	52.7	44.2	40.2	25.5	15.4	11.5
	24 Hr	60.2	67.4	17.9	16.5	16	15.2	11.4	8.67	3.91	2.33	1.55
	Mon	24.9	8.34	4.31	21.3	2.22	1.81	1.11	0.73	0.31	0.19	0.15
OCT	1 Hr	184	277	101	1368	93	38.3	41.8	41.4	25.8	16.5	12.3
	24 Hr	43.7	20.2	5.57	103	65.7	9.01	11	10.7	5.75	5.4	2.49
	Mon	29.9	26.5	2.79	2.62	2.14	1.92	1.34	0.98	0.55	0.29	0.23

1 Hr: Highest 1 hourly Conc., 24Hr: Highest 24-hourly Conc., Mon: Highest Monthly Average Conc.

Analysis of dispersion of SO₂ from the Vindhyachal TPP for the month of January 2019

Figures 4.2.6 and 4.2.7 show combined dispersion of total SO₂ emission from all the stacks of the Vindhyachal TPP for the month of January 2019 for cases with and without FGD respectively. It can be noted from figures 4.2.6 and 4.2.7 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.2.6 and 4.2.7 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.2.8 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

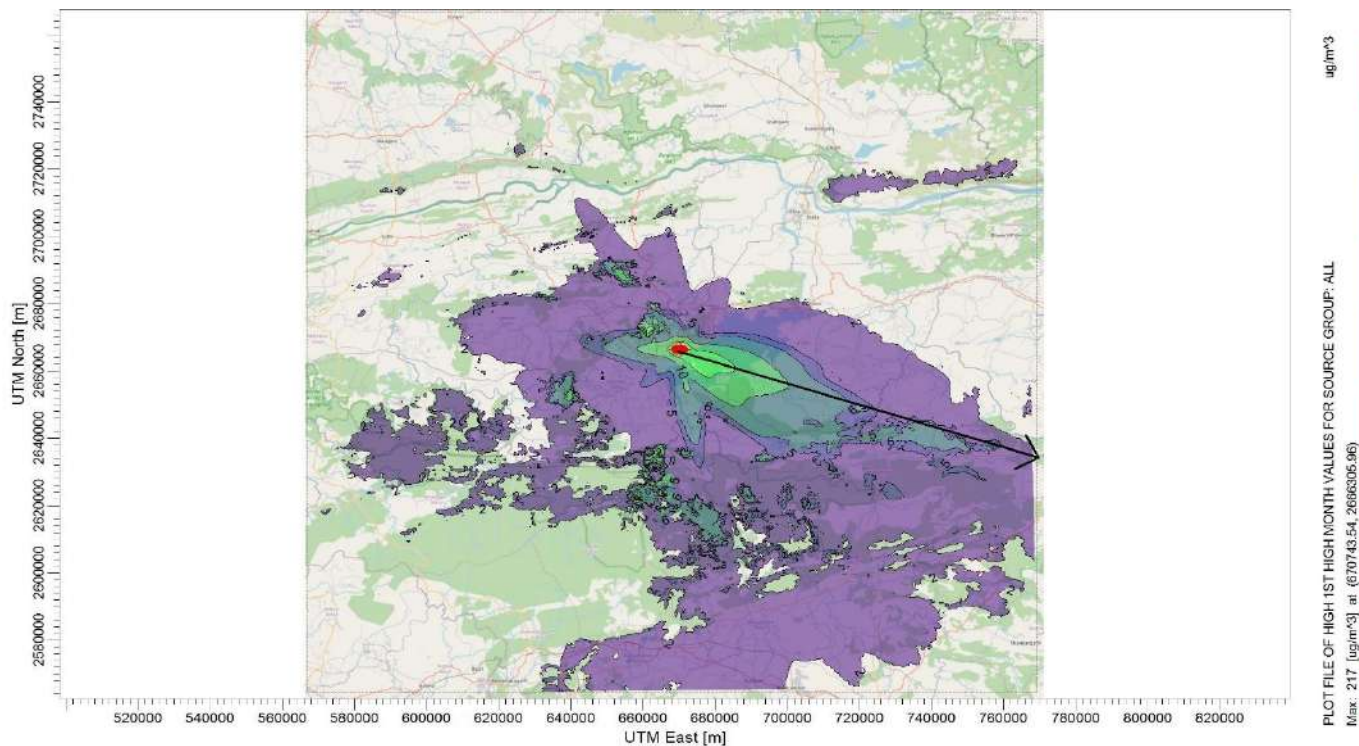


Figure 4.2.6: SO₂ Concentration. for January Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

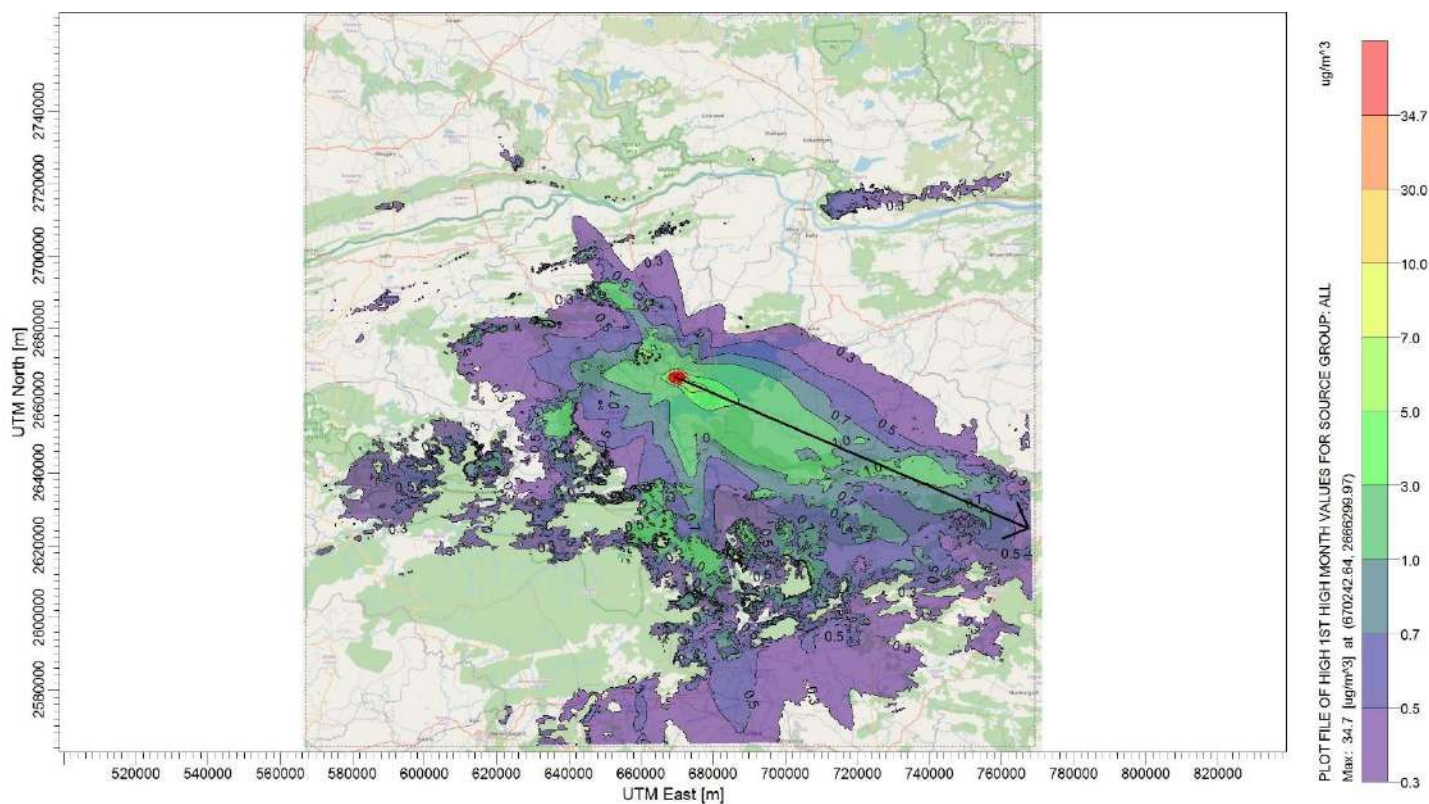


Figure 4.2.7: SO₂ Concentration for January Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

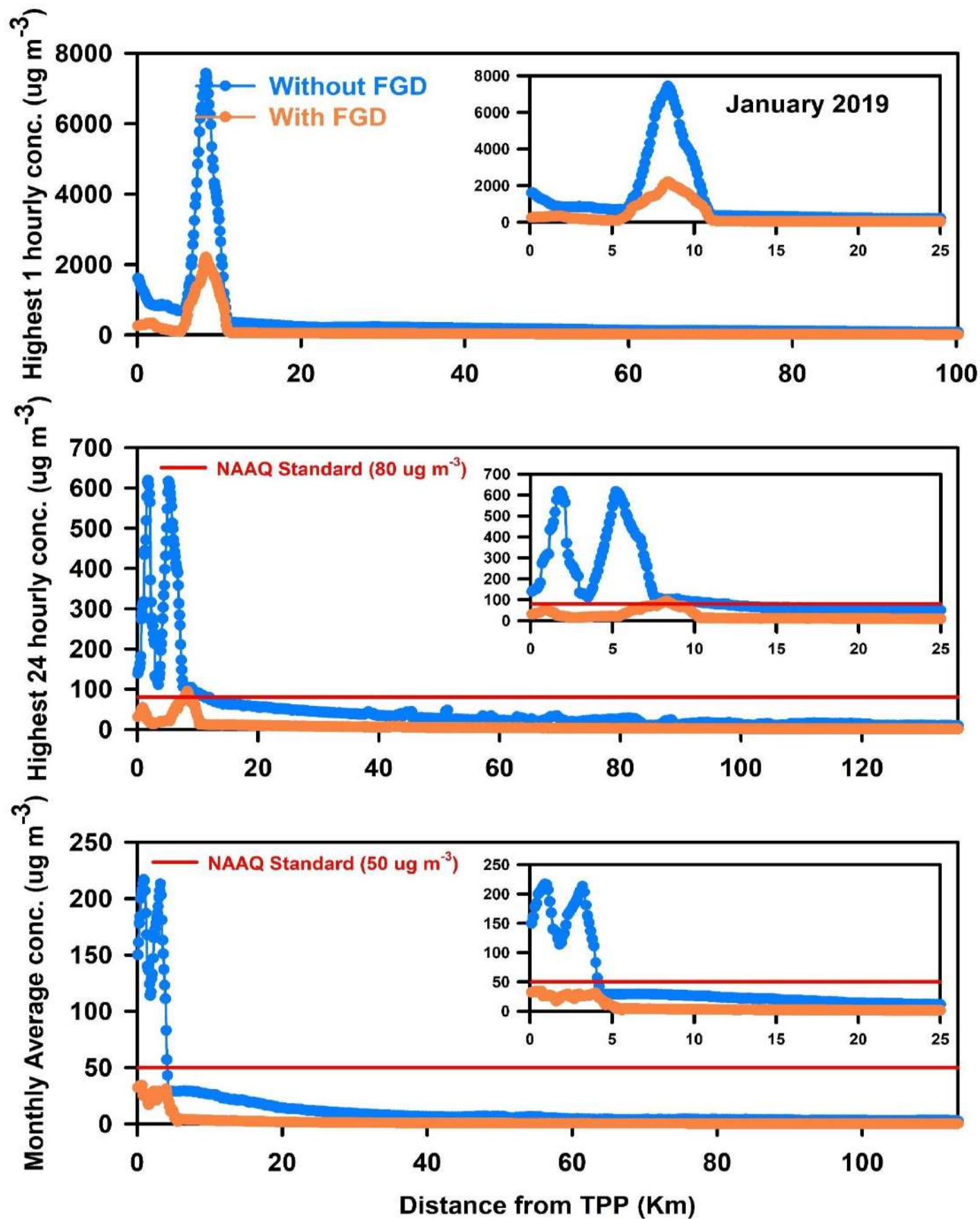


Figure 4.2.8: SO₂ concentration versus distance plot in the direction of maximum dispersion for January

Analysis of dispersion of SO₂ from the Vindhyachal TPP for the month of April 2019

Figures 4.2.9 and 4.2.10 show combined dispersion of total SO₂ emission from all the stacks of the Vindhyachal TPP for the month of April 2019 for cases with and without FGD respectively. It can be noted from figures 4.2.9 and 4.2.10 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.2.9 and 4.2.10 also show that the dispersion of SO₂ without FGD is in both S-E and N-E directions whereas with FGD it is majorly in S-E direction. Figure 4.2.11 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

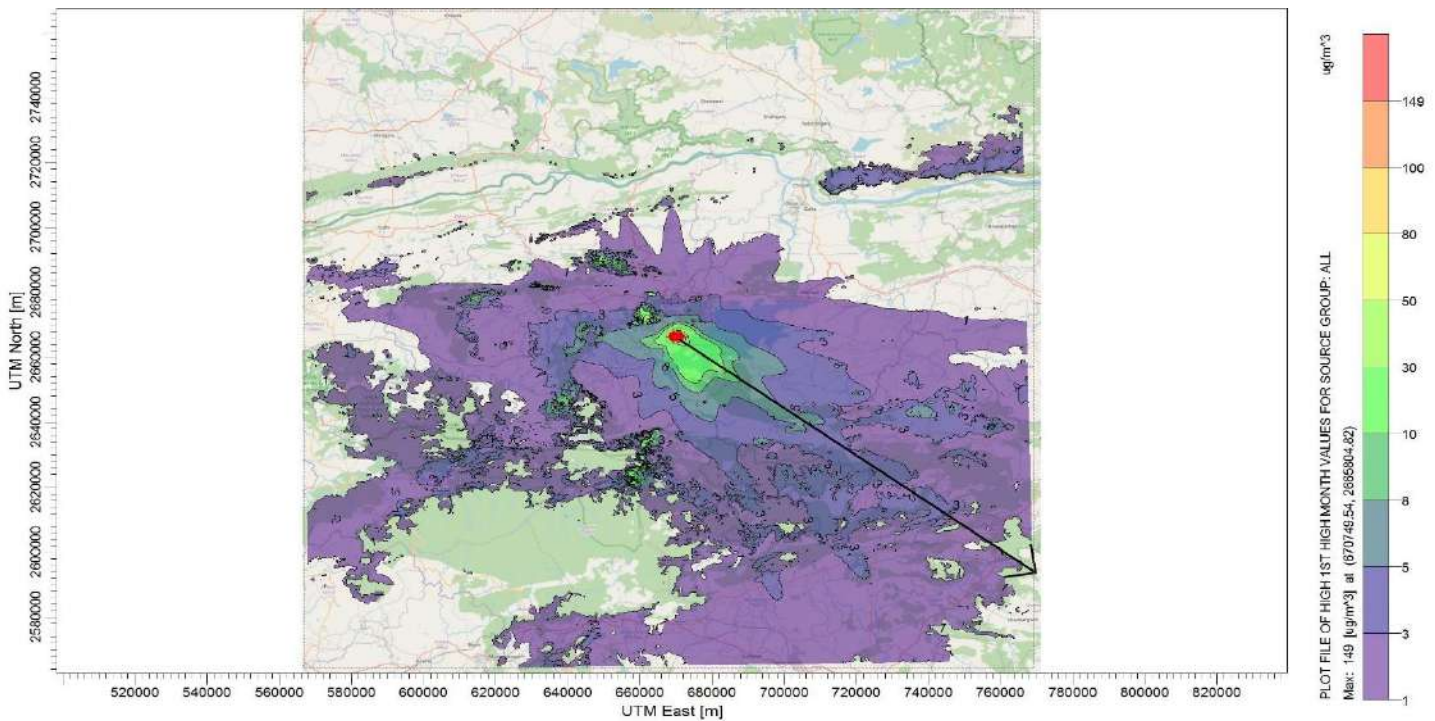


Figure 4.2.9: SO₂ Concentration for April Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

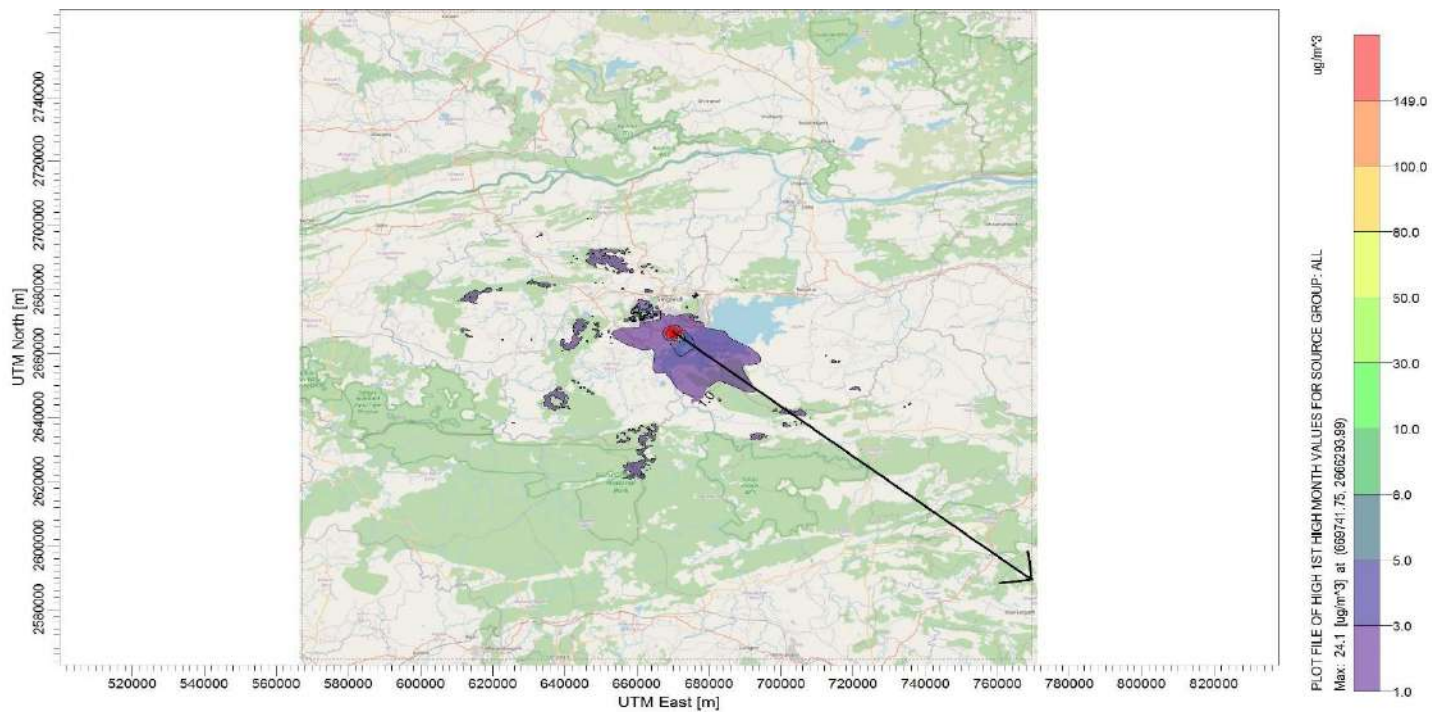


Figure 4.2.10: SO₂ Concentration for April Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

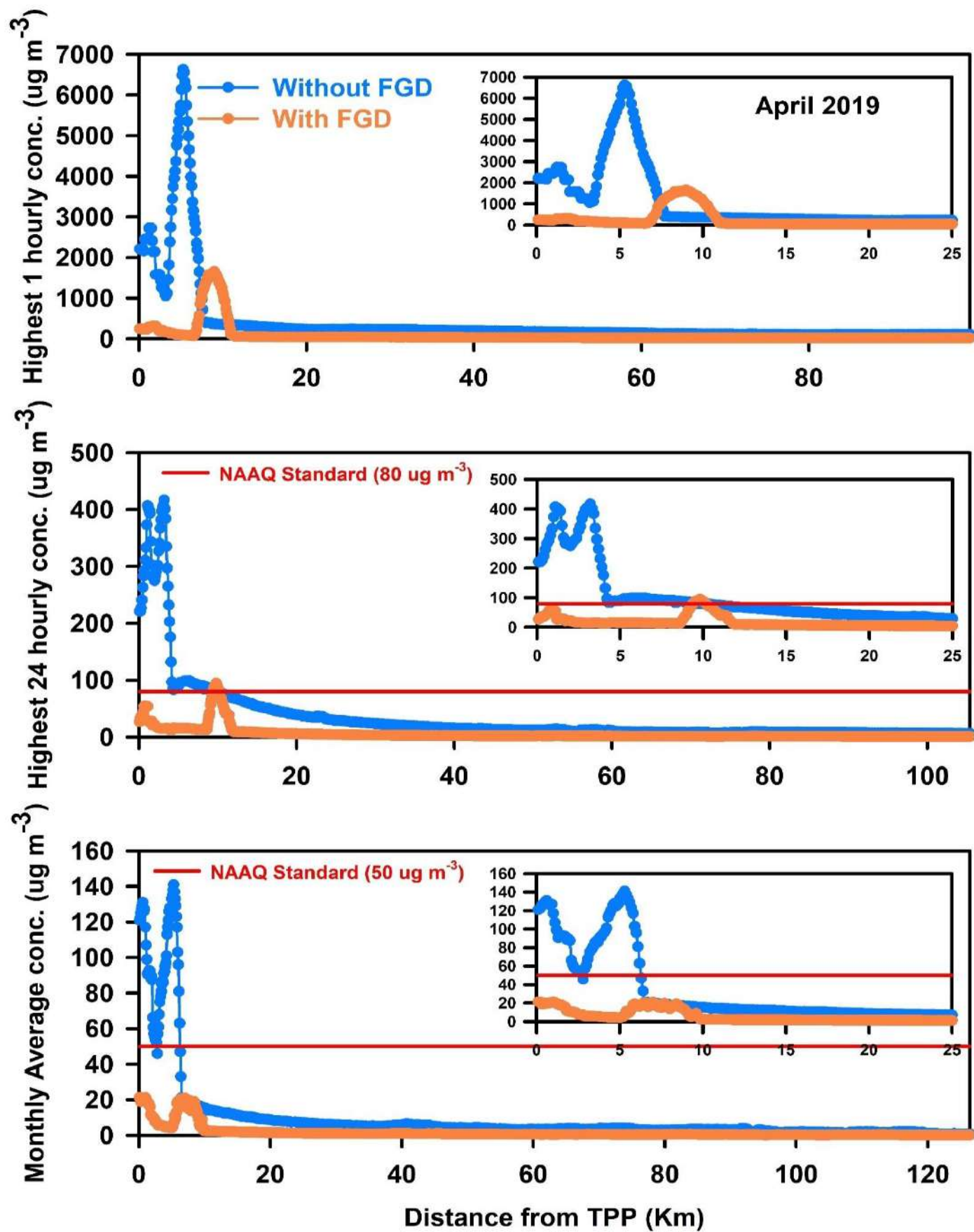


Figure 4.2.11: SO₂ concentration versus distance plot in the direction of maximum dispersion for April

Analysis of dispersion of SO₂ from the Vindhyachal TPP for the month of July 2019

Figures 4.2.12 and 4.2.13 show combined dispersion of total SO₂ emission from all the stacks of the Vindhyachal TPP for the month of July 2019 for cases with and without FGD respectively. It can be noted from figures 4.2.12 and 4.2.13 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figure 4.2.14 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

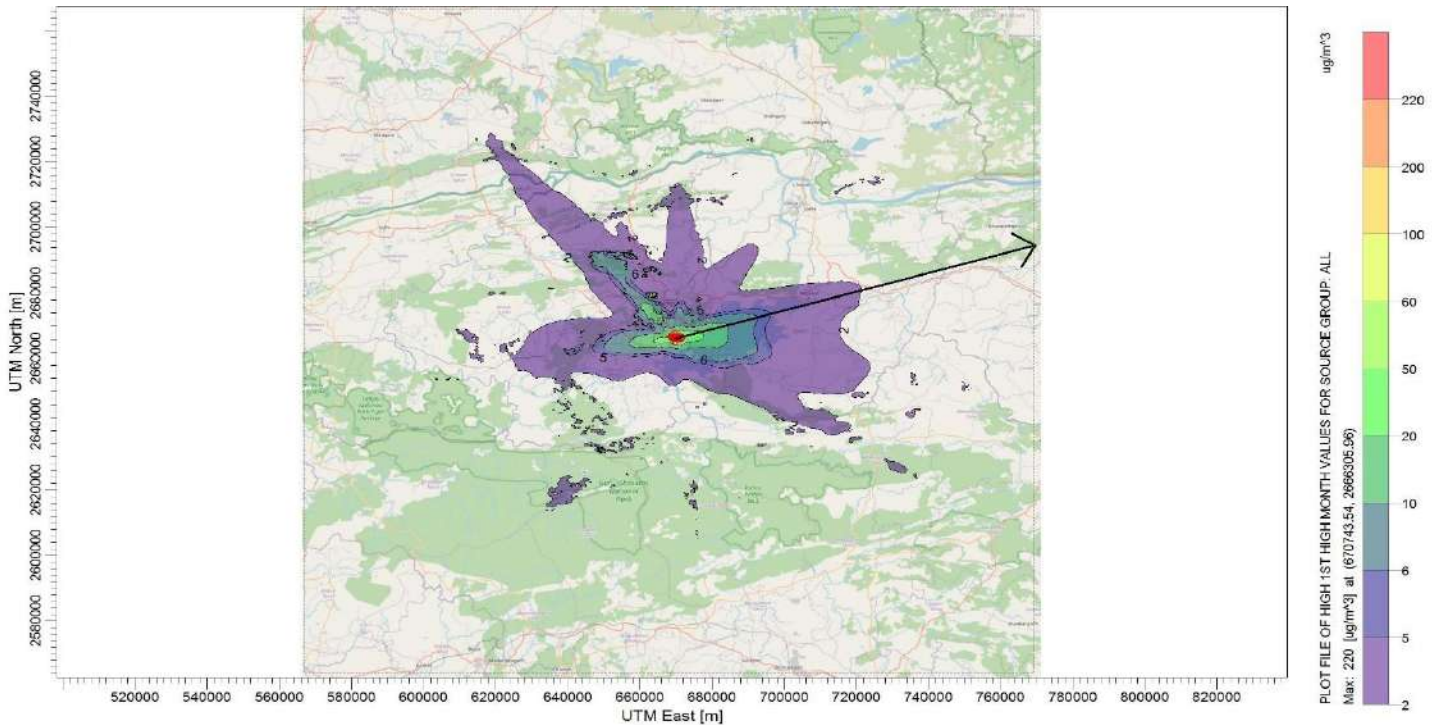


Figure 4.2.12: SO₂ Concentration for July Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

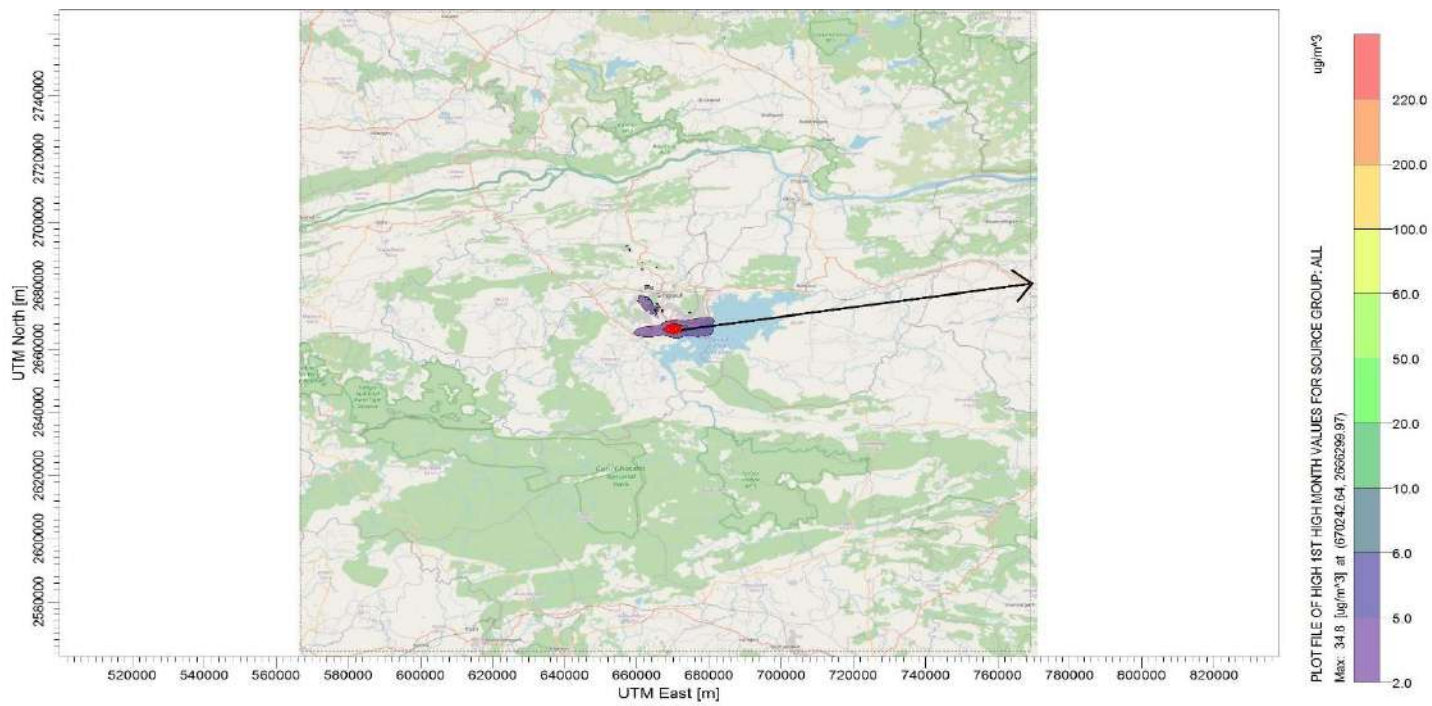


Figure 4.2.13: SO₂ Concentration for July Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

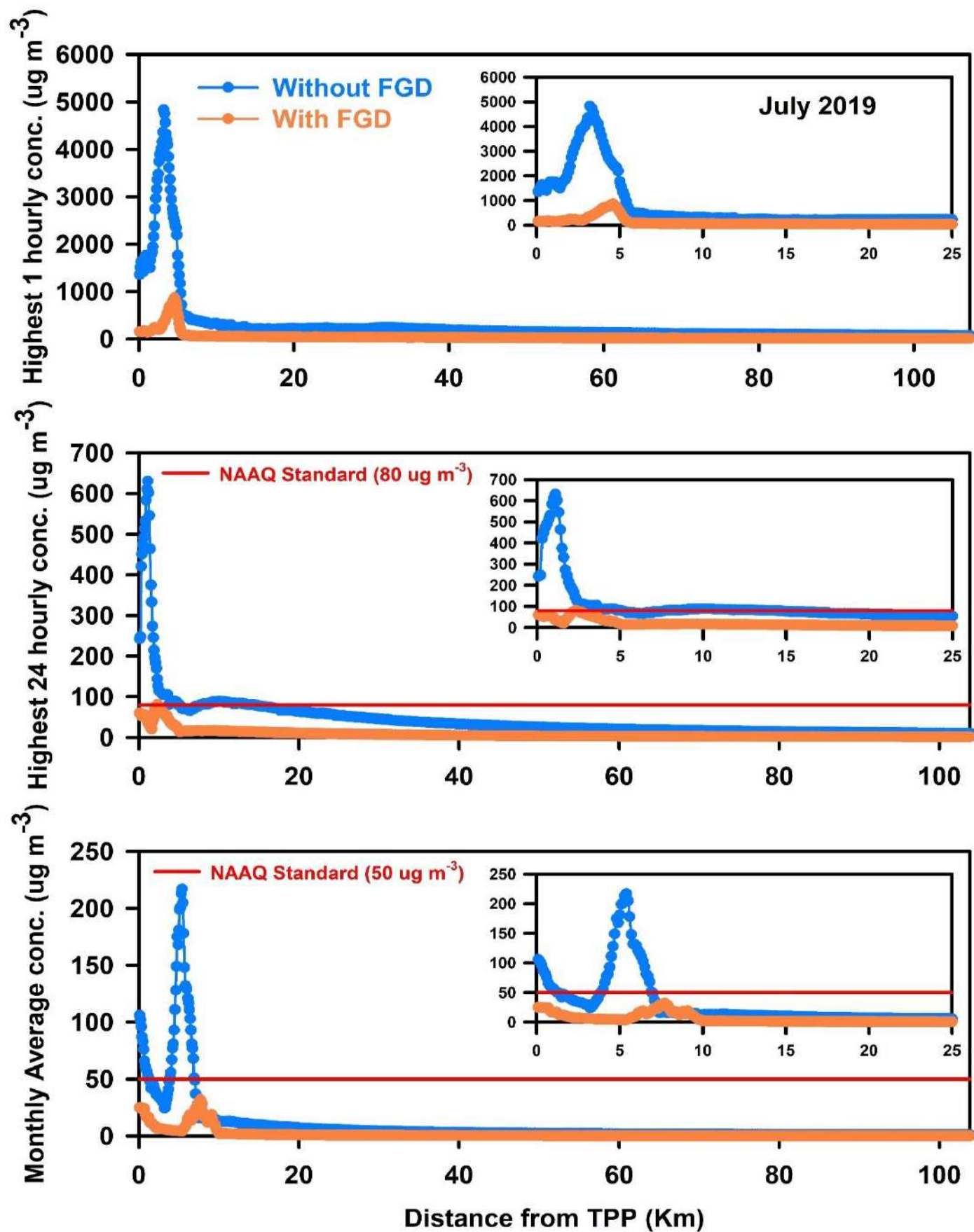


Figure 4.2.14: SO₂ concentration versus distance plot in the direction of maximum dispersion for July

Analysis of dispersion of SO₂ from the Vindhyachal TPP for the month of October 2019

Figures 4.2.15 and 4.2.16 show combined dispersion of total SO₂ emission from all the stacks of the Vindhyachal TPP for the month of October 2019 for cases with and without FGD respectively. It can be noted from figures 4.2.15 and 4.2.16 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figure 4.2.17 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

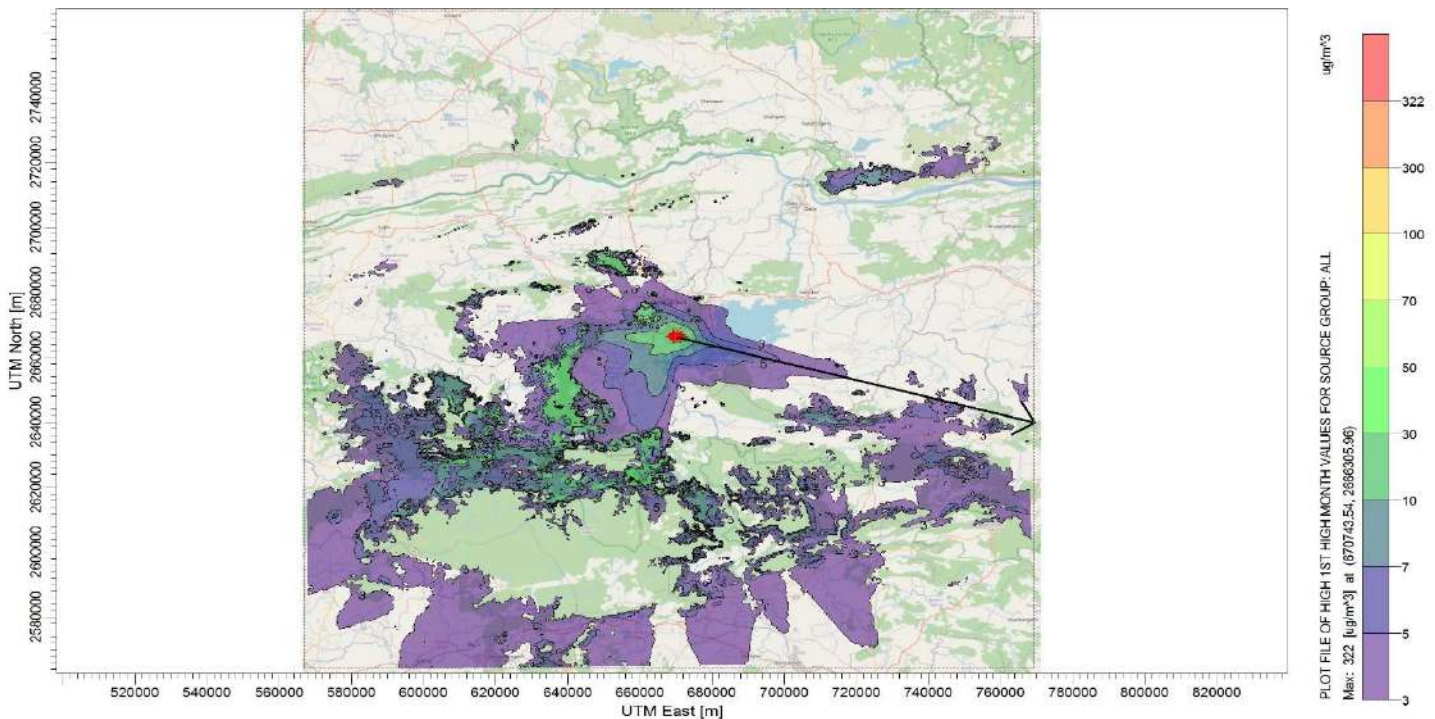


Figure 4.1.15: SO₂ Concentration for October Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

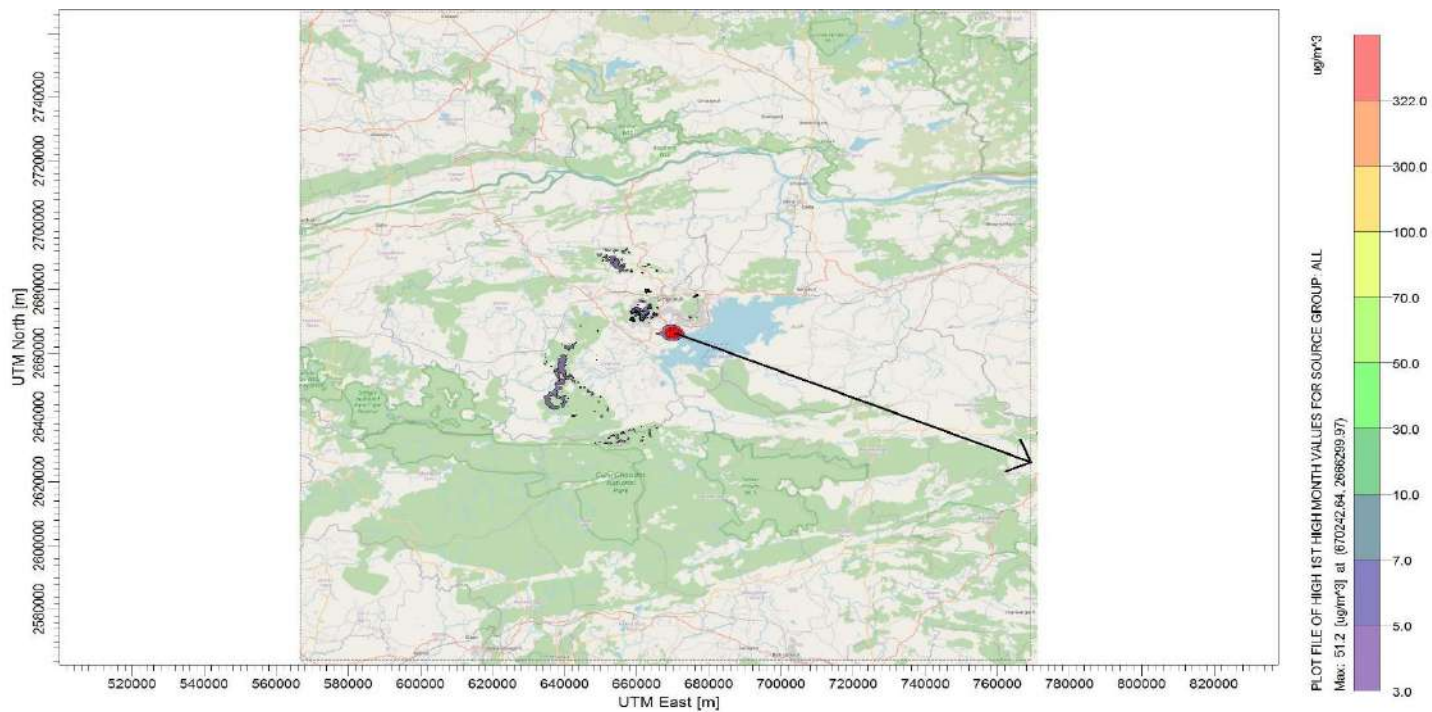


Figure 4.1.16: SO₂ Concentration for October Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

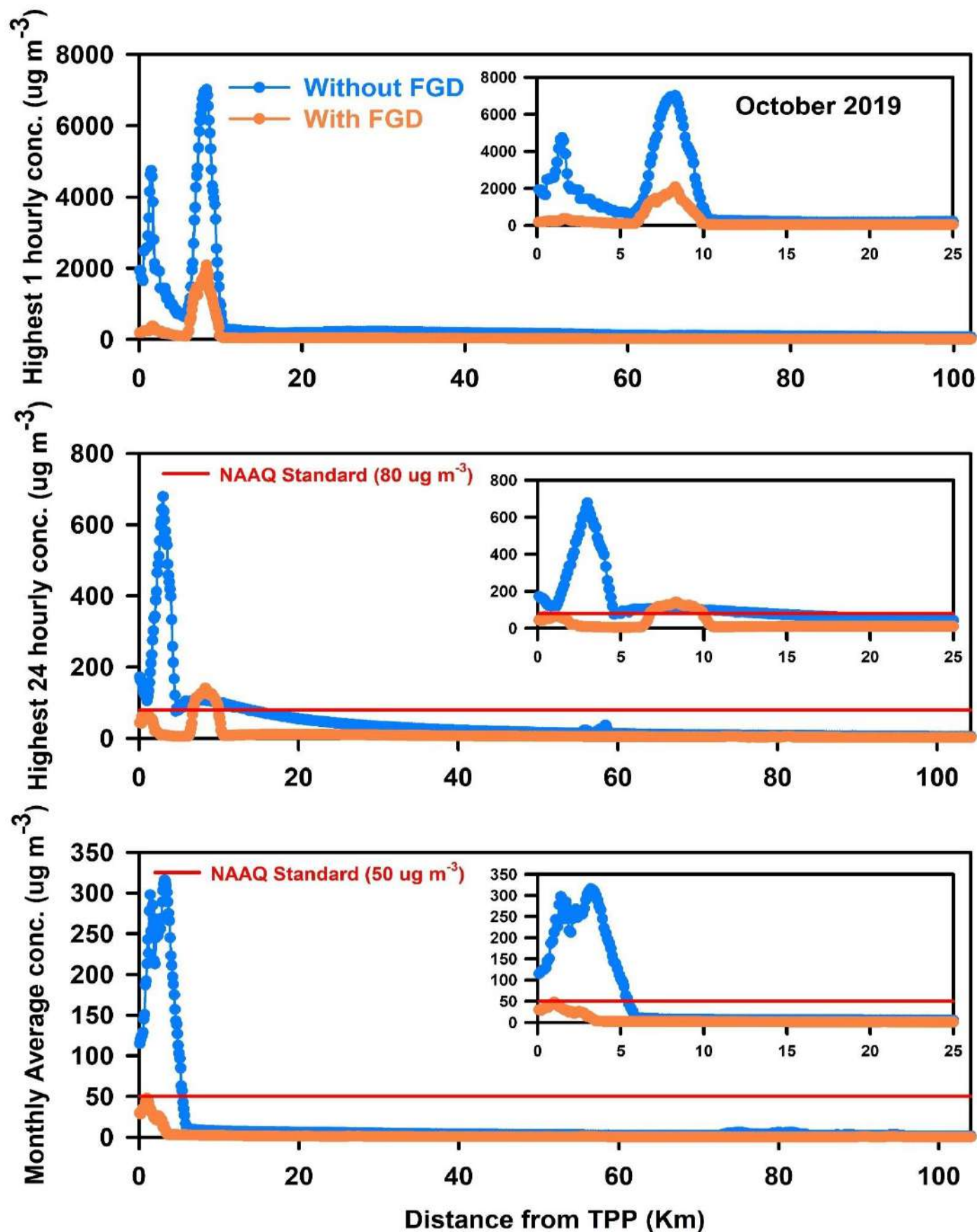


Figure 4.2.17: SO_2 concentration versus distance plot in the direction of maximum dispersion for October

3. Talcher Thermal Power Plant, Odisha

The third coal based TPP considered for understanding and the quantifying the dispersion of SO₂ emissions from the stacks of the TPP into the ambient atmosphere over the surrounding region is the Talcher thermal power plant in Odisha, India. Talcher thermal power plant has a total capacity of 3660MW with six stacks of 500MW capacity each, two stacks of 210MW capacity each and four stacks of 60MW capacity each. However, the Talcher thermal power plant in Odisha consists of 2 phases of power generation units. Phase 1 considers four 500MW power generation units, four 60MW power generation units, and two 110MW power generation units. Phase 2 considers two 500MW power generation units. Phase-1 and Phase-2 power generating units are separated by approximately 25km distance from each other. The terrain elevation around the Talcher TPP is shown in Figure 4.3.1. The horizontal resolution of the dispersion modeling simulations was kept as 500m x 500m and the simulations were performed over a model domain area of 200km x 200km by choosing the Phase-1 power generating units of the Talcher TPP as the center of the model domain in each simulation.

In this study, for every TPS, additional dispersion modelling simulations are performed by assuming the installation of Flue-Gas Desulfurization (FGD) to cut down the emission of SO₂ from that TPS. The objective of performing this additional dispersion modeling simulation assuming FGD installed in the TPS is to understand the difference in dispersion of SO₂ from the TPS with and without FGD implementation. The efficiency of FGD in different units has been taken based on the date of installation and the electricity generation capacity of the units according to emission norms applicable to thermal power plants given in Environmental (Protection) Amendment rules, 2015. In the present case, we have assumed the following FGD efficiencies:

60MW units- 65% efficiency, 210MW units – 65% efficiency, and 500MW- 92.5%

With the installation of FGD in this power plant, we noted a reduction of about 83-85% in the emissions of SO₂ in all the four months.

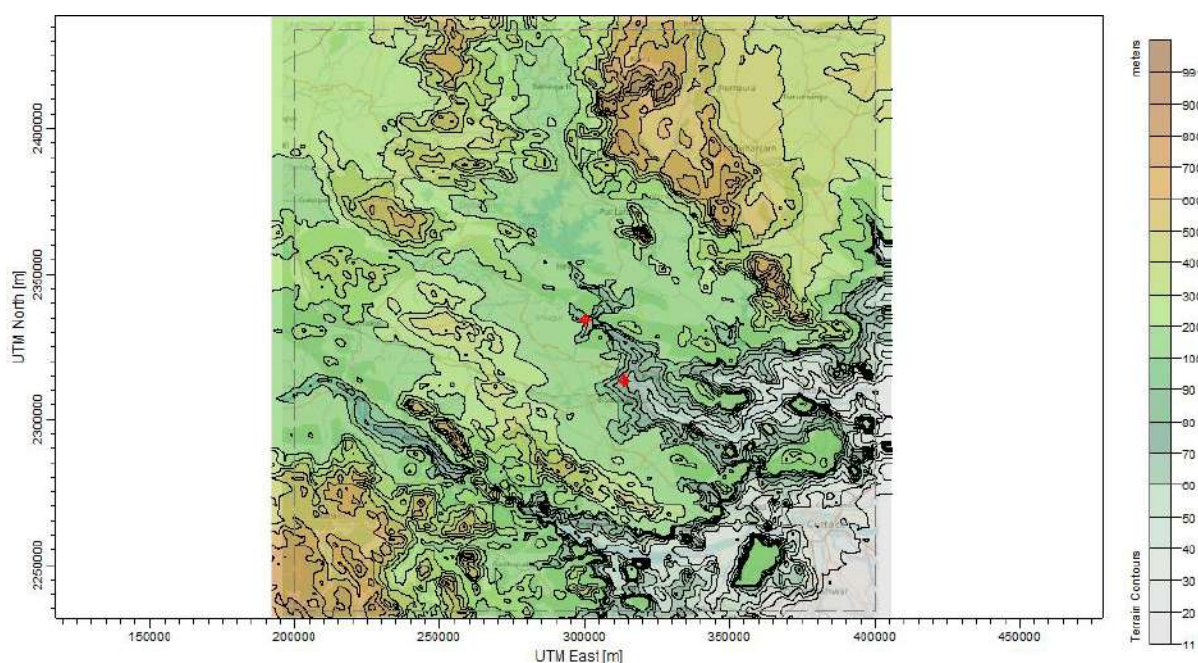


Figure 4.3.1: Terrain Elevation of Modelling Area (40000km²)

Meteorological Input: The surface meteorological data was generated using the Weather Research and Forecasting model for the months of January, April, July and October in the year 2019. The upper air data was generated using upper air estimator in-built in AERMET pre-processor. The wind rose plots for different four months corresponding to the Talcher Thermal Power Station (TPS) are shown in Figures 4.3.2 to 4.3.5.

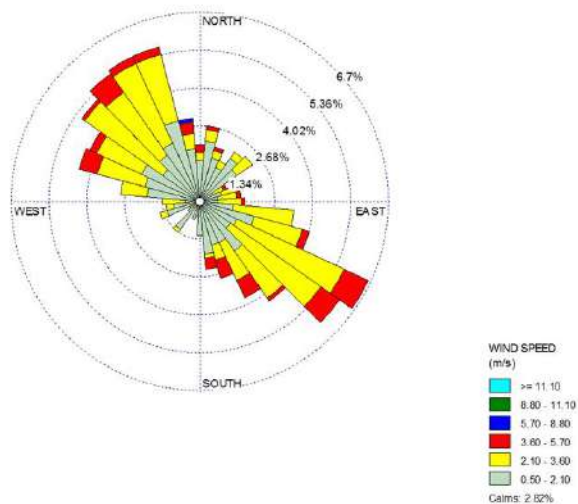


Fig 4.3.2 (a): Wind Rose Direction

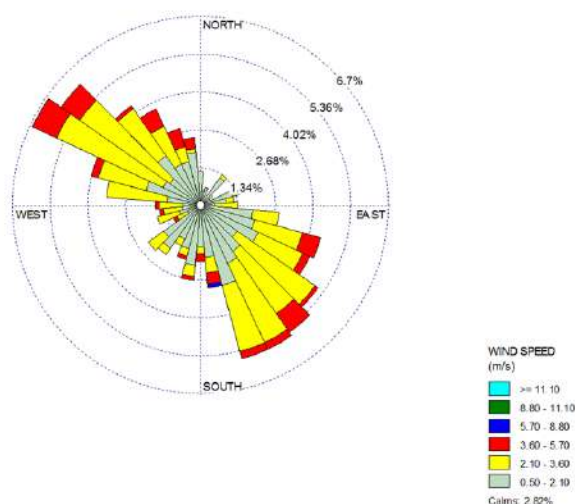


Fig 4.3.2 (b): Wind Rose Flow vector

Figure 4.3.2: Wind Rose plot for the month of January

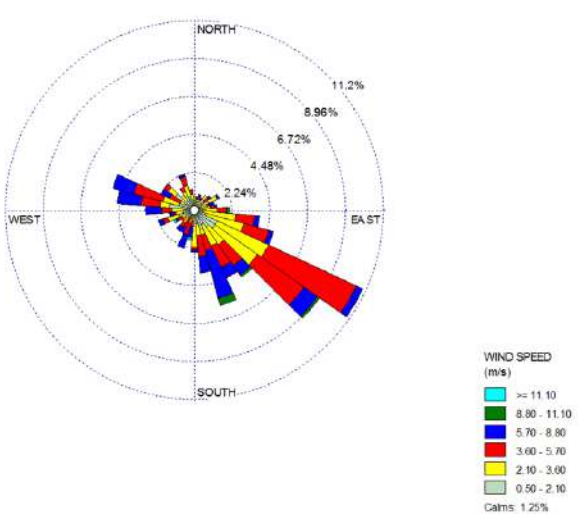


Fig 4.3.3 (a): Wind Rose Direction

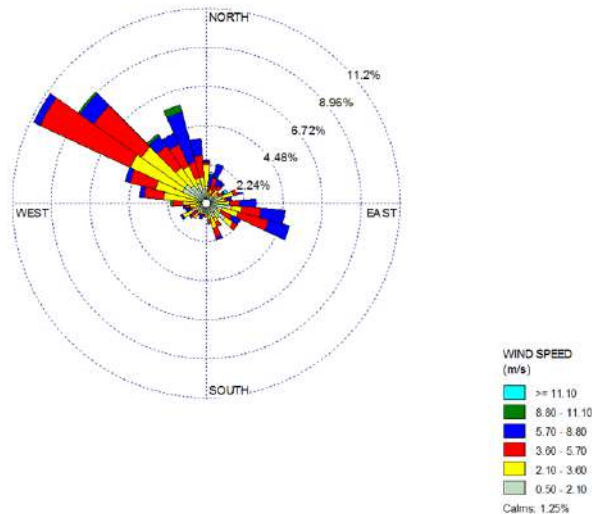


Fig 4.3.3 (b): Wind Rose Flow vector

Figure 4.3.3: Wind Rose plot for the month of April

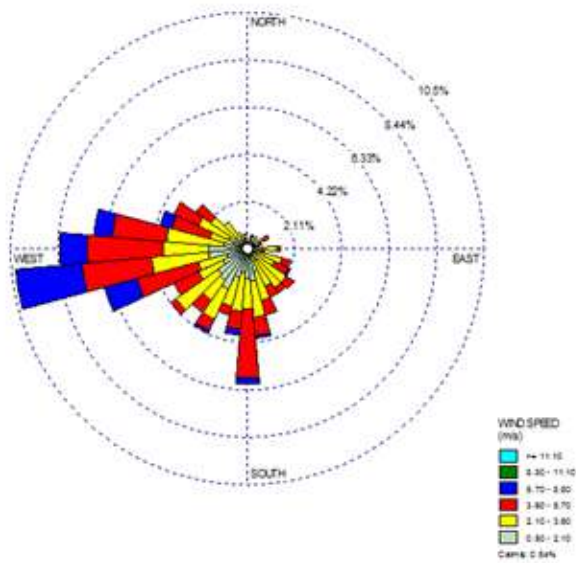


Fig 4.3.4 (a): Wind Rose Direction

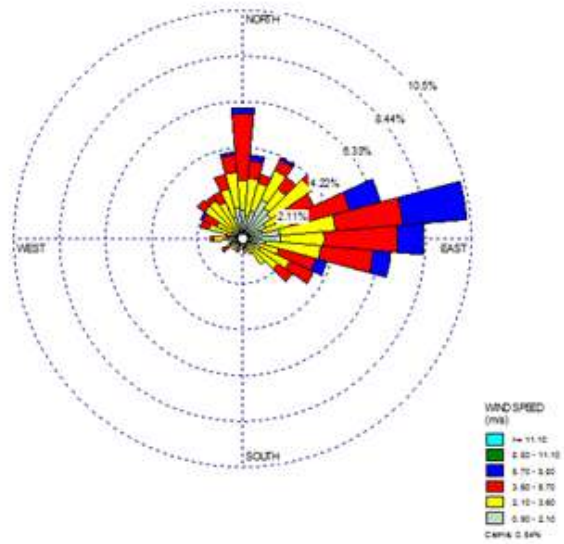


Fig 4.3.4 (b): Wind Rose Flow vector

Figure 4.3.4: Wind Rose plot for the month of July

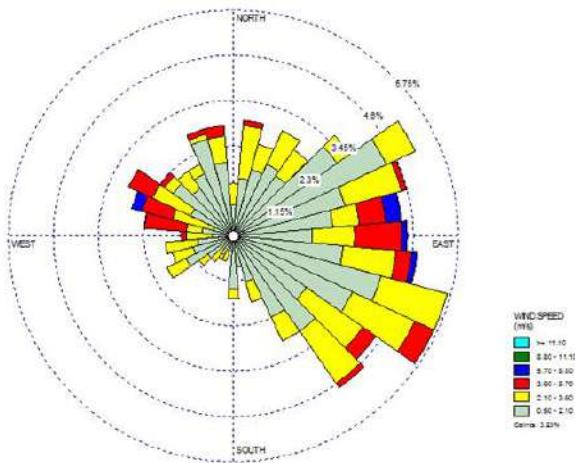


Fig 4.3.5 (a): Wind Rose Direction

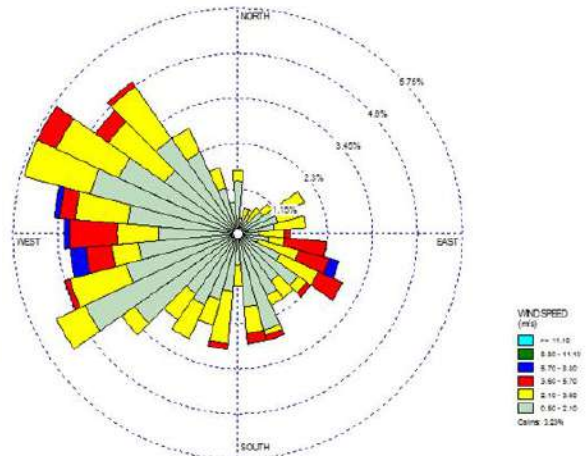


Fig 4.3.5 (b): Wind Rose Flow vector

Figure 4.3.5: Wind Rose plot for the month of October

Table 4.3.1 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at any point within our AERMOD simulation domain and the locations as well as distances of these locations from the Centre of the simulation domain (location of the TPP) for both with and without FGD cases.

Table 4.3.1: SO₂ Dispersion Modeling results for Talcher Power Plant of Odisha

Mon	Highest 1 hourly Conc. (µg m ⁻³)	Location of Highest 1 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 1 hourly Conc. from TPP (Km)	Highest 24 hourly Conc. (µg m ⁻³)	Location of Highest 24 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 24 hourly Conc. from TPP (Km)	Highest Monthly Average Conc. (µg m ⁻³)	Location of Highest Monthly Average Conc. (Lat °N, Lon °E)	Distance of Highest Monthly Average conc. from TPP (Km)
Without FGD									
JAN	17812	20.91, 85.21	23.84	3783	20.89, 85.21	25.64	1001	20.91, 85.21	23.84
APR	19294	20.94, 85.22	22.02	3746	20.91, 85.17	21.57	803	20.91, 85.20	23.23
JUL	21072	30.91, 85.23	23.16	5407	20.94, 85.21	21.31	1033	20.96, 85.21	19.73
OCT	16158	20.91, 85.22	24.49	3739	20.91, 85.20	23.23	714	20.91, 85.20	23.23
With FGD									
JAN	6234	20.91, 85.15	20.65	1320	20.86, 85.21	28.46	349	20.91, 85.21	23.84
APR	6753	20.84, 85.06	26.71	1311	20.91, 85.24	25.86	281	20.91, 85.20	23.23
JUL	7375	20.86, 85.17	26.58	1892	20.91, 85.21	23.84	362	20.95, 85.21	20.50
OCT	5655	20.91, 85.21	23.84	1309	20.92, 85.20	22.33	251	20.91, 85.13	19.91

Table 4.3.2 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ within the AERMOD simulation domain at various distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion simulated by the model for both with and without FGD cases.

Table 4.3.2: SO₂ concentrations (µg/m³) at distances towards direction of maximum dispersion

MON	SO ₂	0km	2km	4km	6km	10km	13km	18km	25km	50km	75km	100km
Without FGD												
JAN	1 Hr	12008	8641	5650	3791	2630	2273	1570	8321	530	338	81.8
	24 Hr	3043	699	294	149	159	125	94.7	3297	23.6	22.4	18.8
	Mon	726	206	81.3	50.3	32.4	25.5	17.5	651	14.2	7.14	5.35
APR	1 Hr	18600	10810	5663	4590	2923	2543	1480	2854	425	310	420
	24 Hr	3540	340	189	128	140	160	134	112	22	25.6	
	Mon	768	217	64.9	35.7	16.9	11.5	7.76	97.3	15.6	6.28	3.46
JUL	1 Hr	15100	8920	7490	5070	2790	1853	1110	6845	264	248	220
	24 Hr	1670	997	542	317	158	134	109	90.2	57.4	29.2	20.9
	Mon	77.4	385	162	94.6	47.2	34.3	211	13.3	5.01	1.73	2.68
OCT	1 Hr	11600	5543	6390	4320	3100	3180	1770	14315	955	212	
	24 Hr	2061	680	352	306	252	206	149	1023	64.5	22.7	16.1
	Mon	511	307	131	71.2	48.1	35.7	24	329	10.3	9.4	5.46
With FGD												
JAN	1 Hr	5434	3240	2730	1830	1311	1040	1270	427	275	123	27.4
	24 Hr	1070	288	157	104	55.1	44.3	32.2	19	8.61	3.27	2.02
	Mon	314	61.4	33.5	22.3	12.8	9.43	6.43	209	1.43	0.26	0.78
APR	1 Hr	5600	2682	1674	1080	1060	1353	1080	1553	179	217	61.7
	24 Hr	853	162	97.7	94.4	45.9	43.3	28.9	1083	6.46	3.55	
	Mon	264	81.3	26.7	13.9	8.43	6.09	3.71	57.8	1.51	0.78	0.36
JUL	1 Hr	5480	2510	2271	3262	2134	1470	1104	1745	351	141	21.2
	24 Hr	516	308	275	188	90	69.4	19	1218	3.25	0.97	1.16
	Mon	86.8	142	59.7	28.7	15.4	11.4	11.2	3.45	0.85	0.26	0.34
OCT	1 Hr	4972	4010	2181	1394	1150	1030	866	2084	161	65	
	24 Hr	722	220	112	73.4	69.5	68.5	50	31.6	5.36	4.02	3.27
	Mon	83.5	105	60.2	27.5	16.8	12.5	117	5.02	1.88	0.86	0.17

1 Hr: Highest 1 hourly Conc., 24Hr: Highest 24-hourly Conc., Mon: Highest Monthly Average Conc.

Analysis of dispersion of SO₂ from the Talcher TPP for the month of January 2019

Figures 4.3.6 and 4.3.7 show combined dispersion of total SO₂ emission from all the stacks of the Talcher TPP for the month of January 2019 for cases with and without FGD respectively. It can be noted from figures 4.3.6 and 4.3.7 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.3.6 and 4.3.7 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.3.8 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

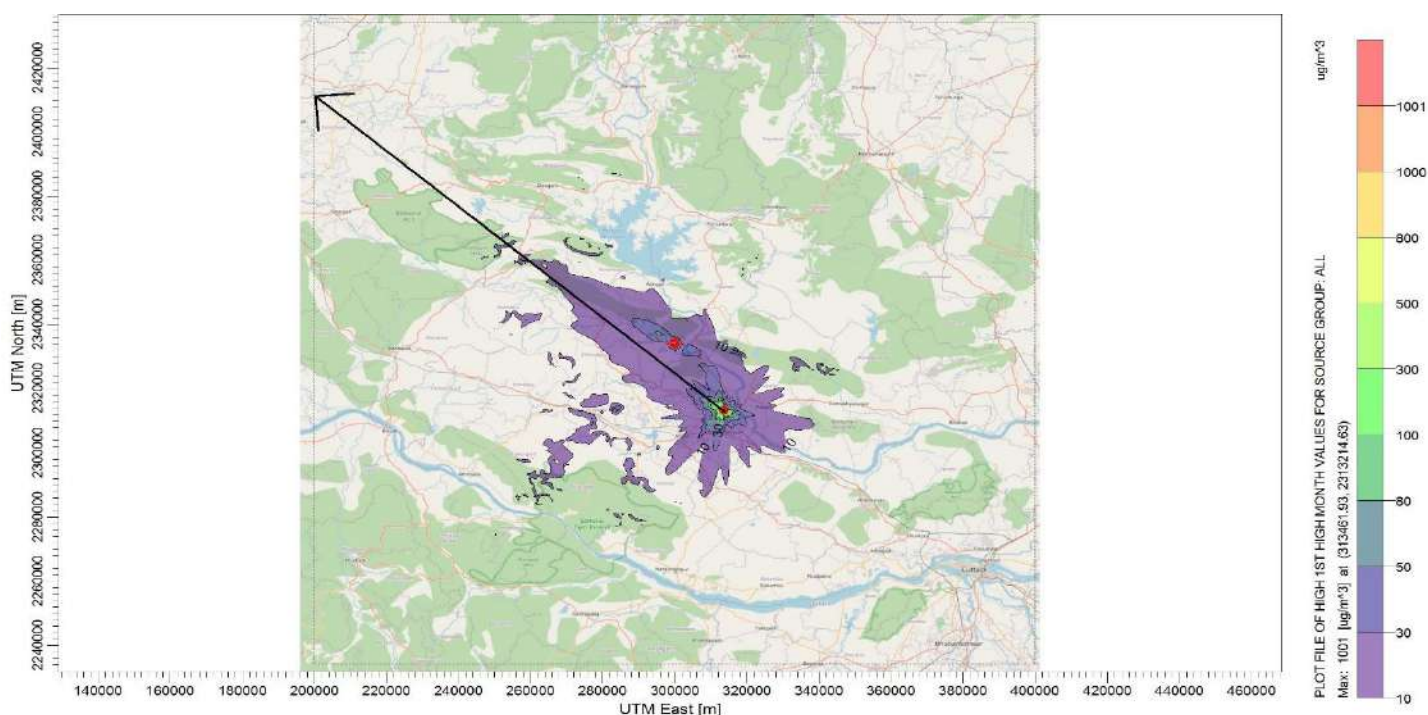


Figure 4.3.6: SO₂ Concentration for January Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

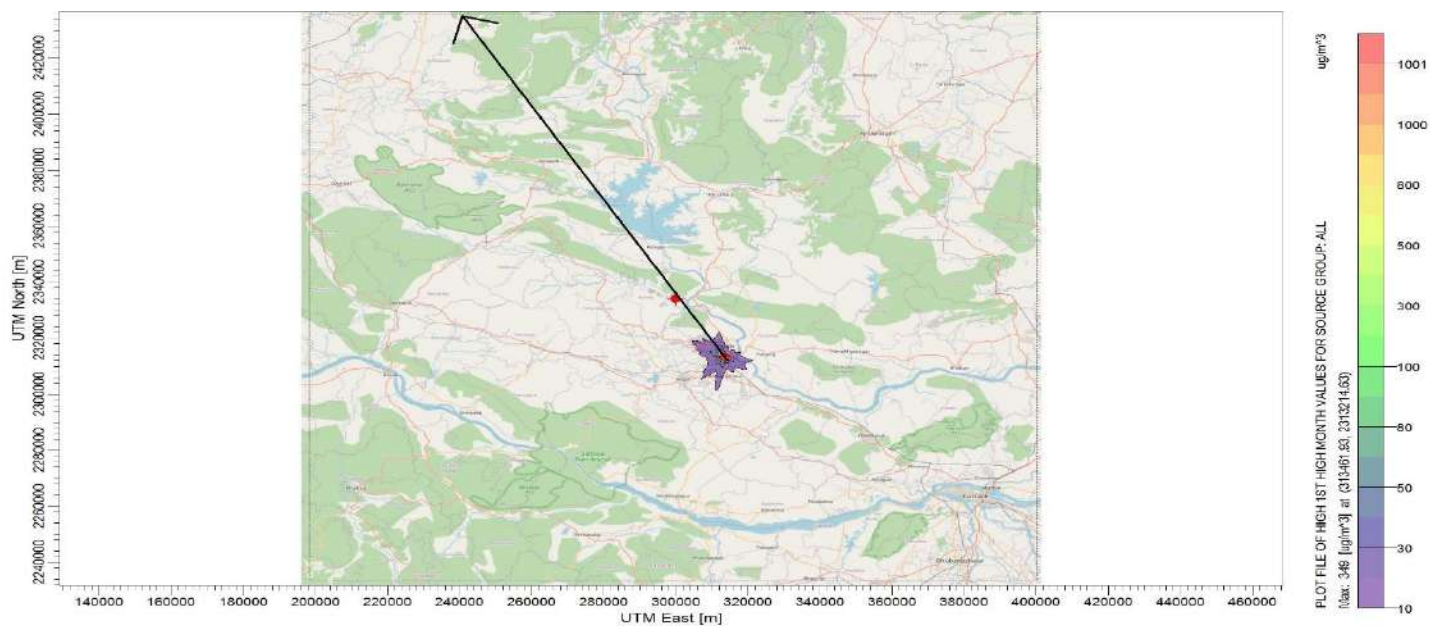


Figure 4.3.7: SO_2 Concentration for January Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

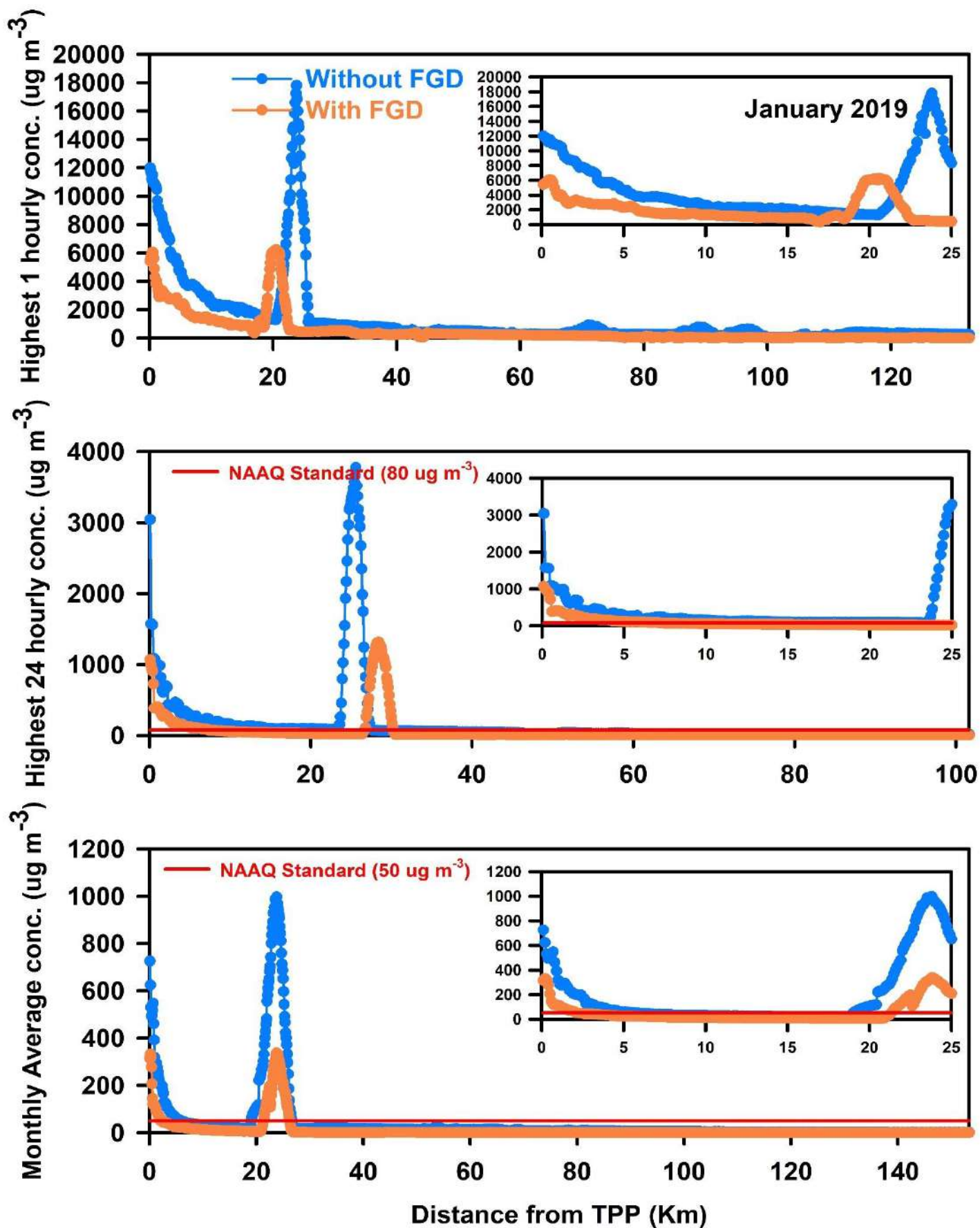


Figure 4.3.8: SO_2 concentration versus distance plot in the direction of maximum dispersion for January

Analysis of dispersion of SO₂ from the Talcher TPP for the month of April 2019

Figures 4.3.9 and 4.3.10 show combined dispersion of total SO₂ emission from all the stacks of the Talcher TPP for the month of April 2019 for cases with and without FGD respectively. It can be noted from figures 4.3.9 and 4.3.10 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.3.9 and 4.3.10 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.3.11 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

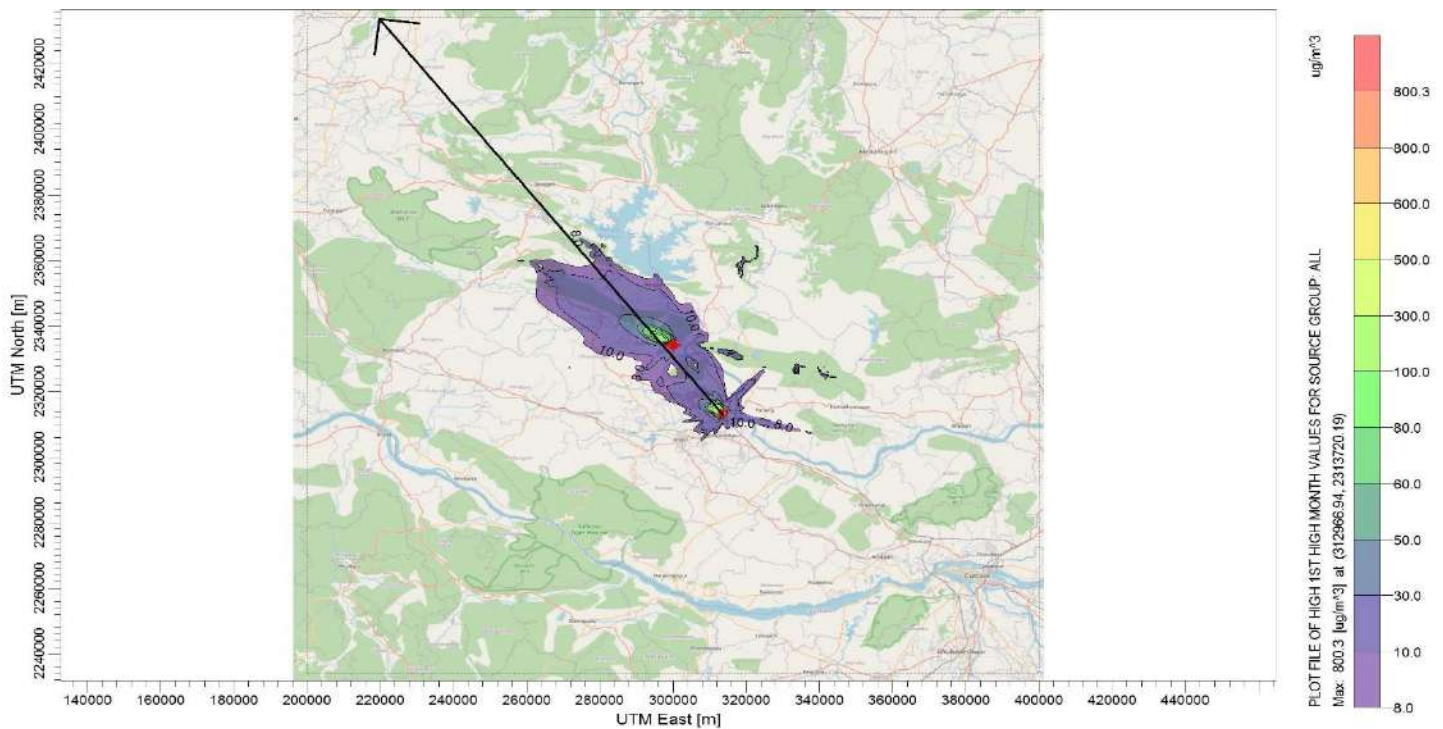


Figure 4.3.9: SO₂ Concentration for April Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

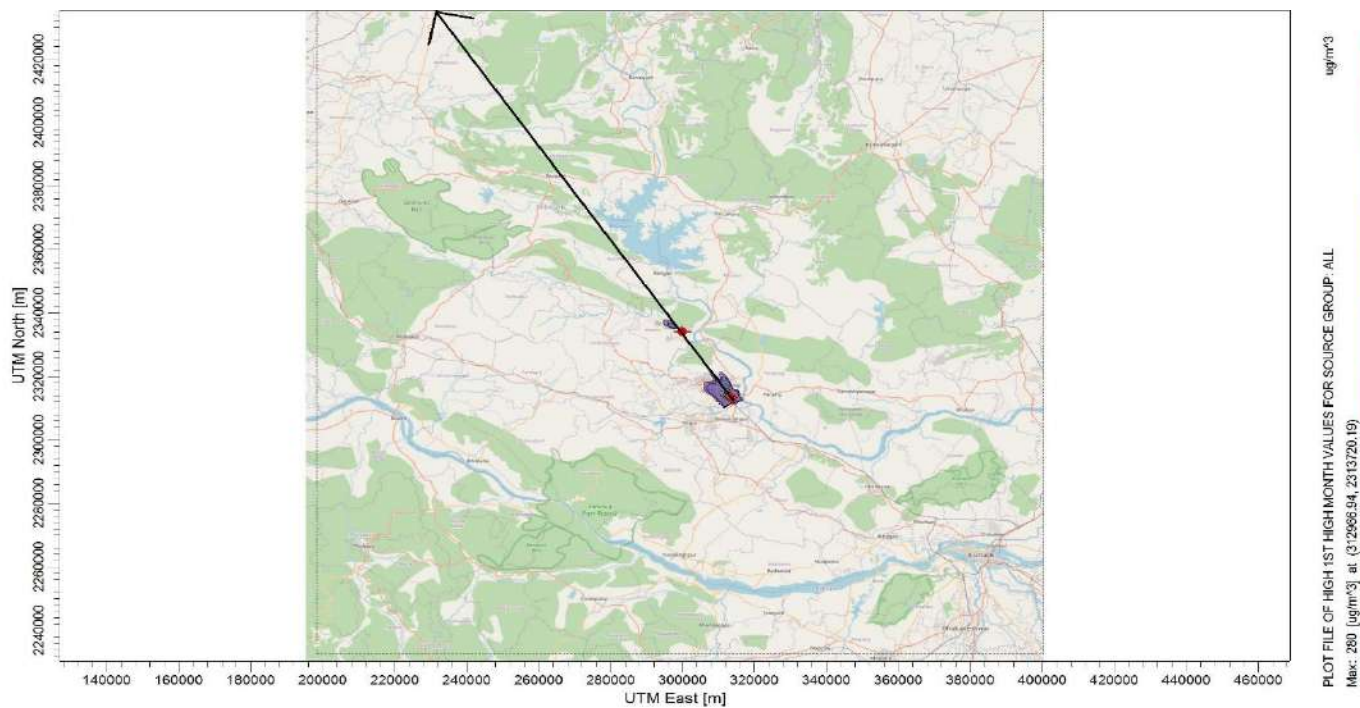


Figure 4.3.10: SO_2 Concentration for April Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

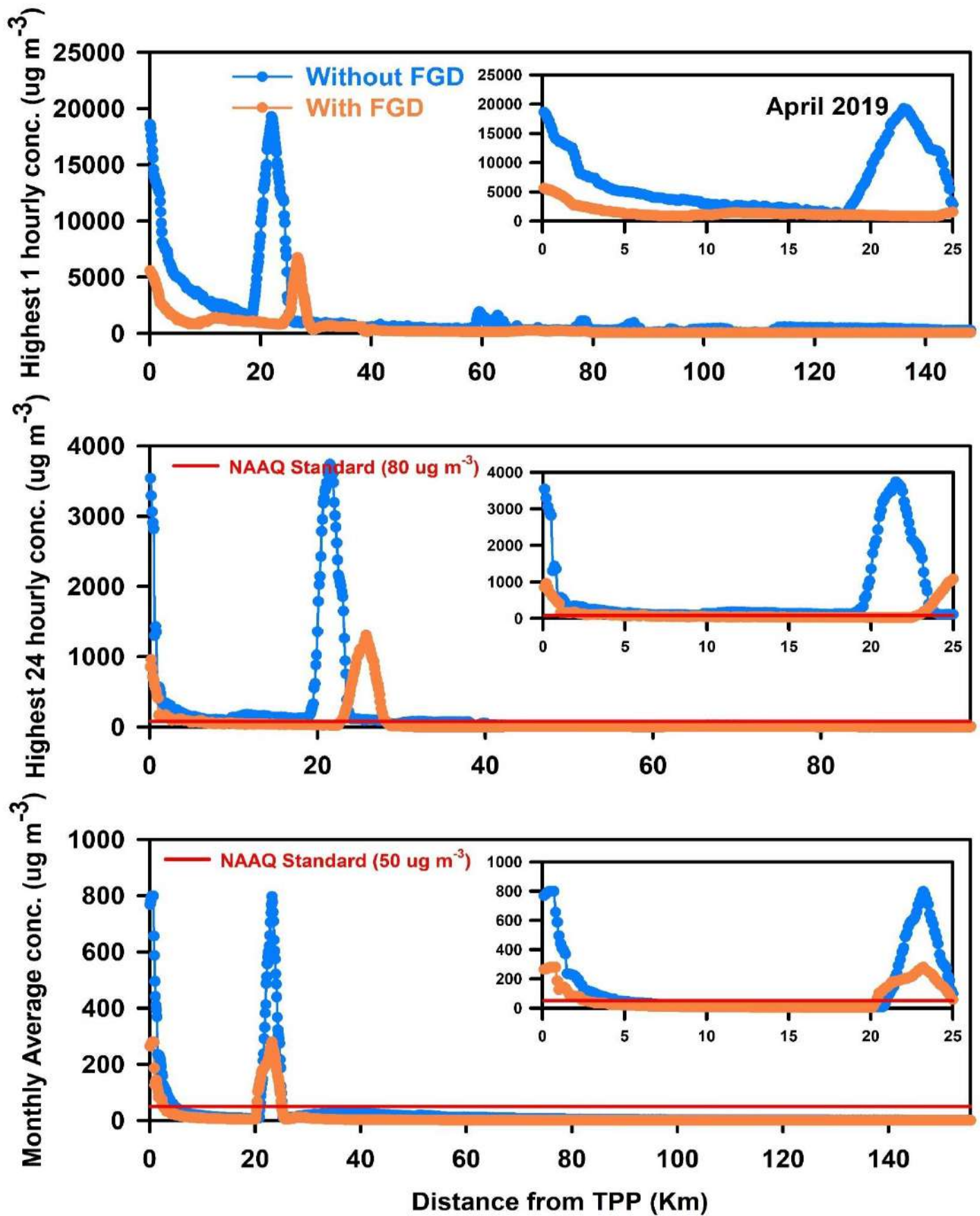


Figure 4.3.11: SO₂ concentration versus distance plot in the direction of maximum dispersion for April

Analysis of dispersion of SO₂ from the Talcher TPP for the month of July 2019

Figures 4.3.12 and 4.3.13 show combined dispersion of total SO₂ emission from all the stacks of the Talcher TPP for the month of July 2019 for cases with and without FGD respectively. It can be noted from figures 4.3.12 and 4.3.13 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.3.12 and 4.3.13 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.3.14 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

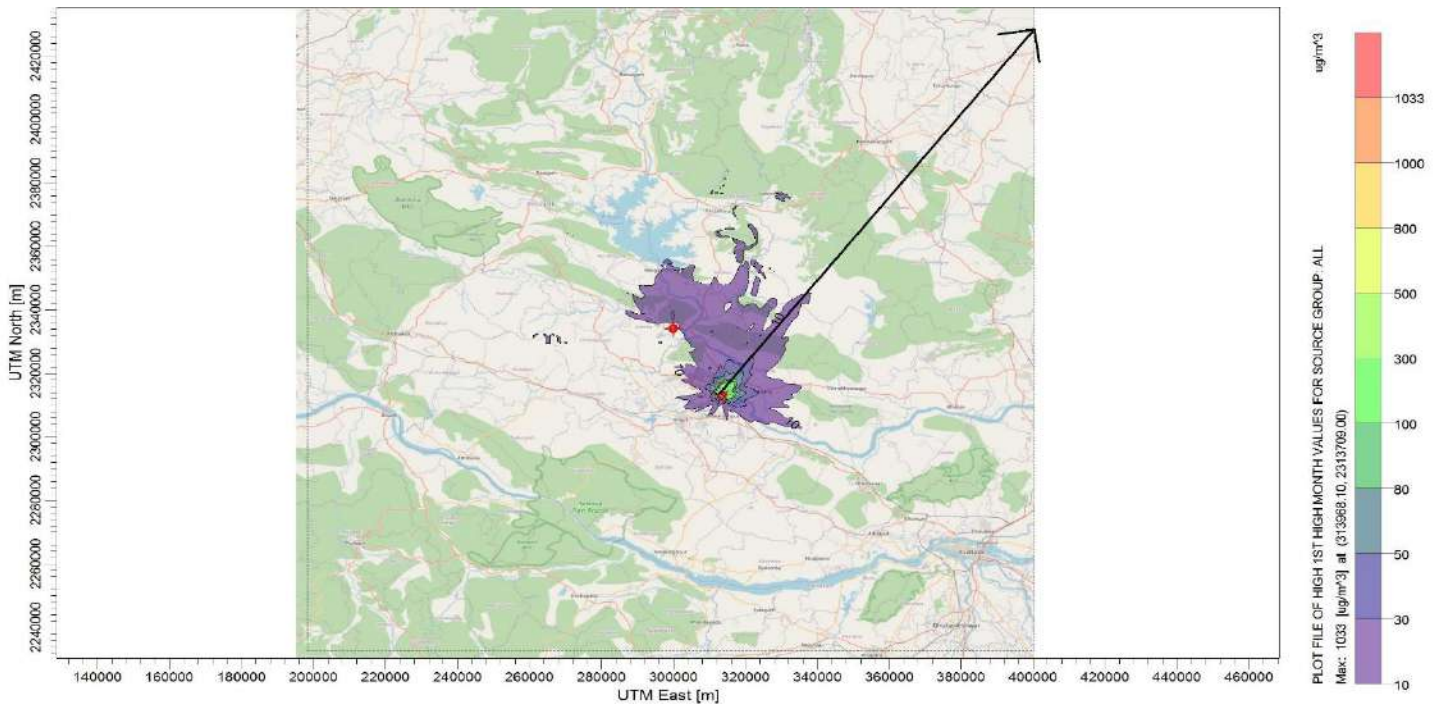


Figure 4.3.12: SO₂ Concentration for July Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

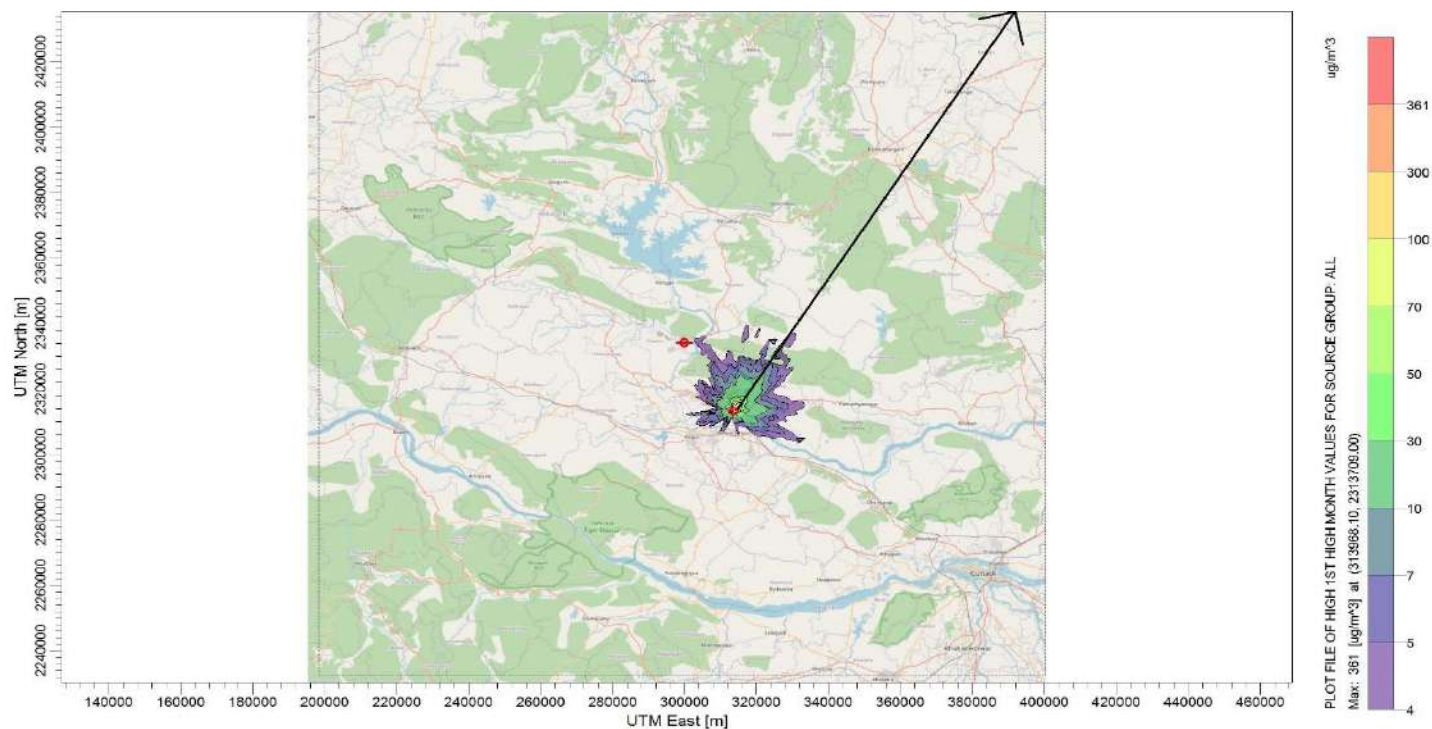


Figure 4.3.13: SO_2 Concentration for July Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

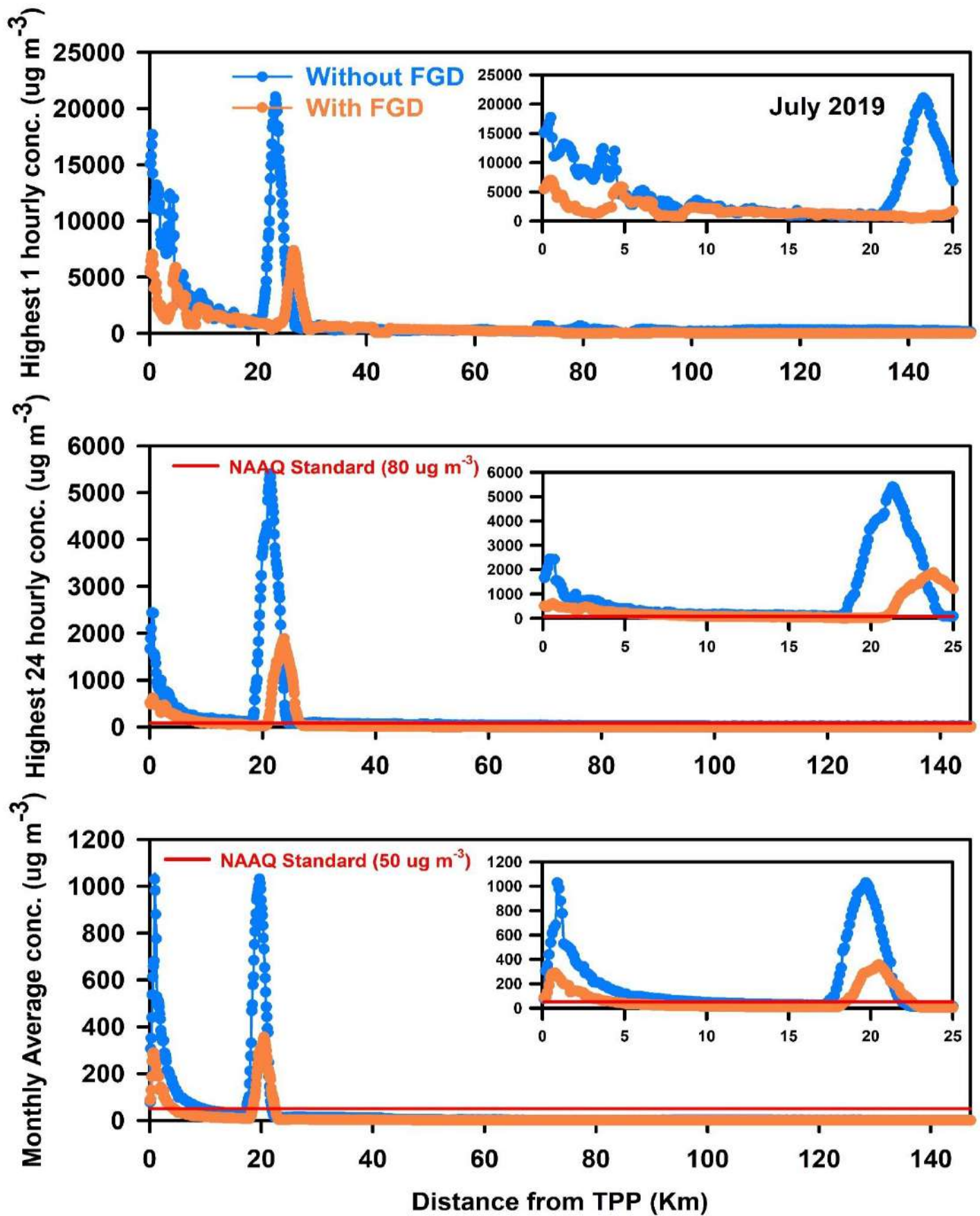


Figure 4.3.14: SO₂ concentration versus distance plot in the direction of maximum dispersion for July

Analysis of dispersion of SO₂ from the Talcher TPP for the month of October 2019

Figures 4.3.15 and 4.3.16 show combined dispersion of total SO₂ emission from all the stacks of the Talcher TPP for the month of October 2019 for cases with and without FGD respectively. It can be noted from figures 4.3.15 and 4.3.16 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.3.15 and 4.3.16 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.3.17 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

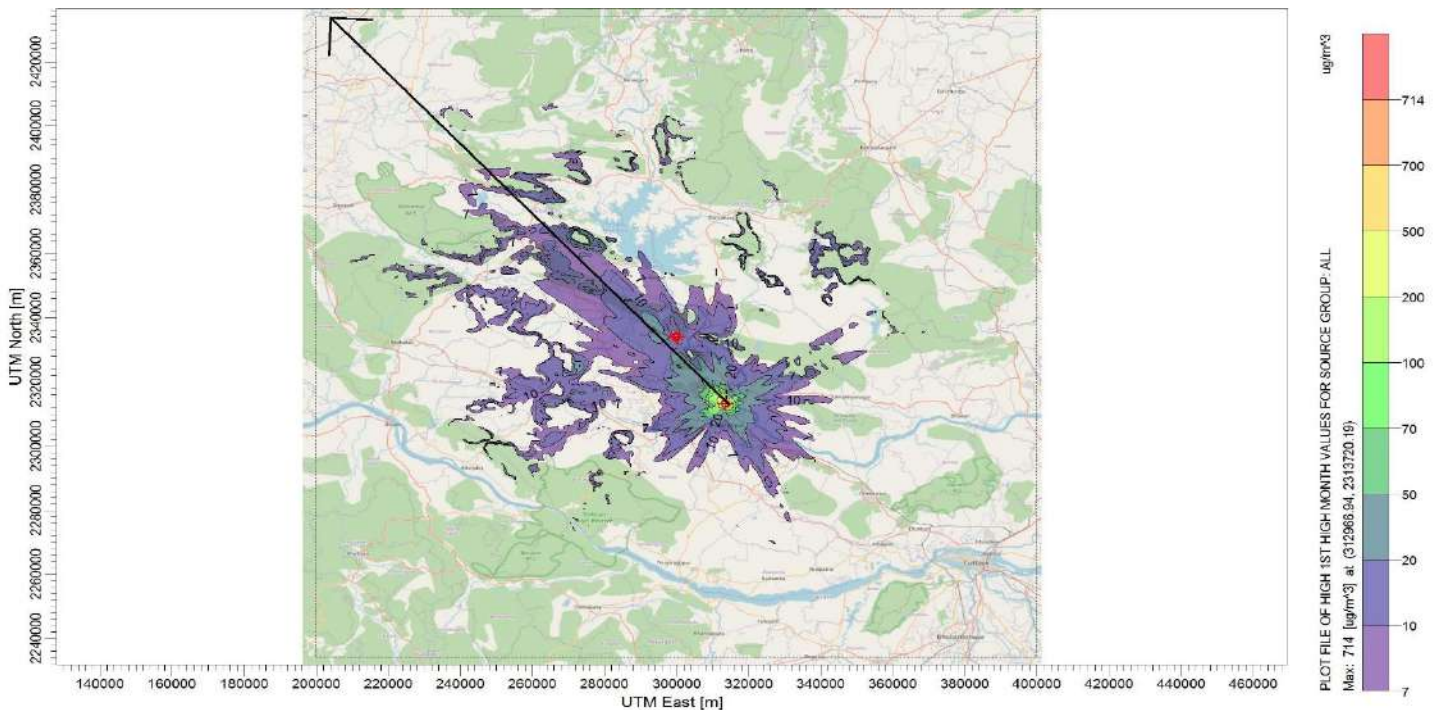


Figure 4.3.15: SO₂ Concentration for October Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

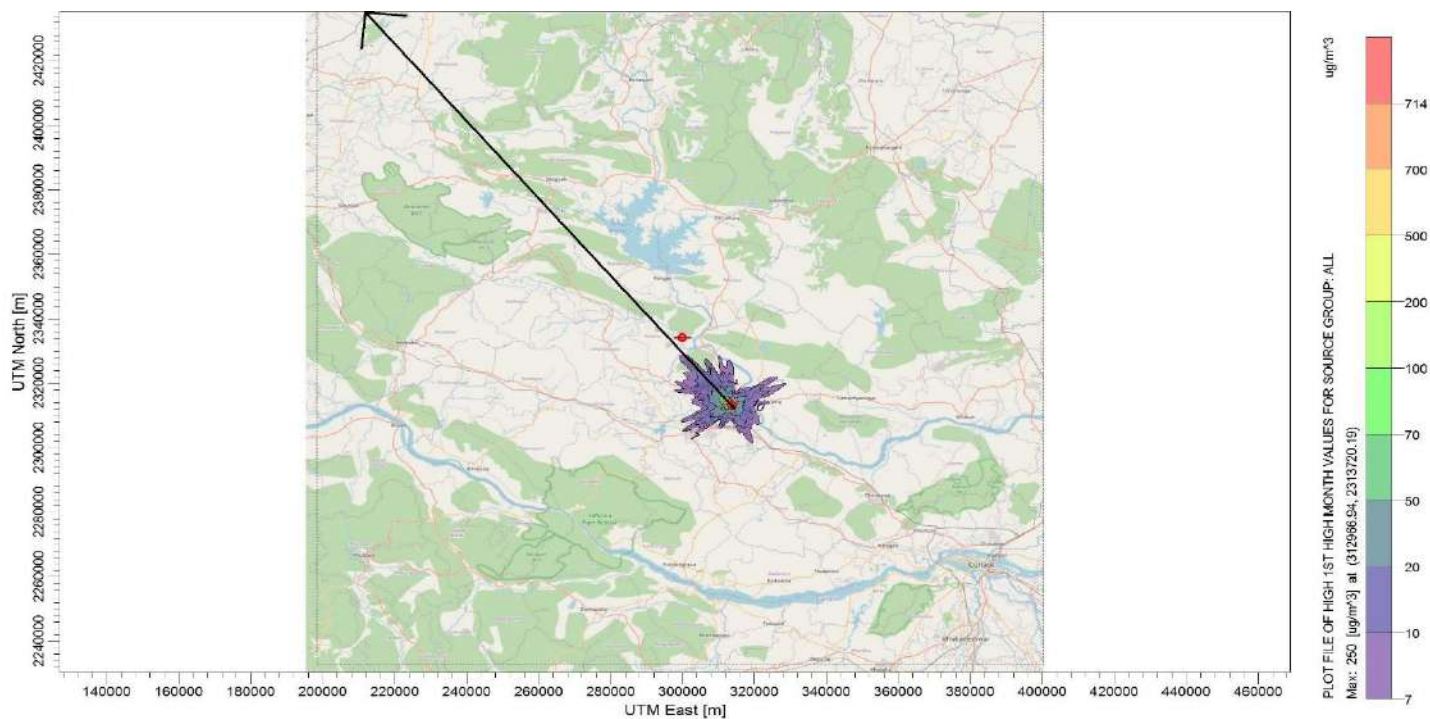


Figure 4.3.16: SO₂ Concentration for October Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

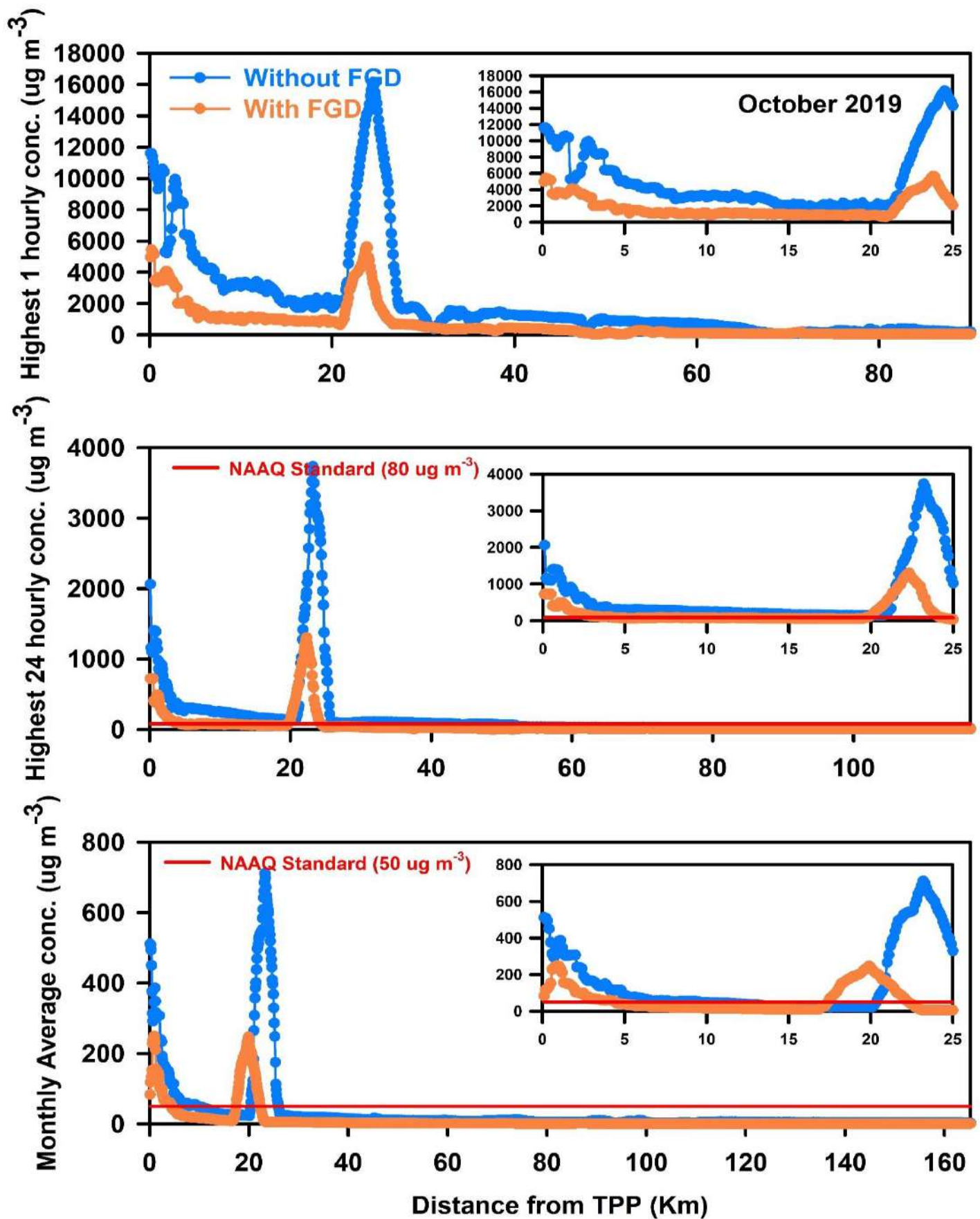


Figure 4.3.17: SO₂ concentration versus distance plot in the direction of maximum dispersion for October

4. Panipat Thermal Power Plant, Haryana

The fourth coal based TPP considered for understanding and the quantifying the dispersion of SO₂ emissions from the stacks of the TPP into the ambient atmosphere over the surrounding region is the Panipat thermal power plant located in Panipat, Haryana, India. This TPP has a total power production capacity of 710MW with two stacks of 250MW capacity each and one stack of 210MW capacity. This TPP is in a completely different geographical region experiencing different meteorological variations as compared to other TPPs considered in this study. The terrain elevation around Panipat TPP is shown in Figure 4.4.1. The horizontal resolution of the dispersion modeling simulations was kept as 500m x 500m and the simulations were performed over a model domain area of 200km x 200km by choosing the thermal power plant location as the center of the model domain in each simulation.

In this study, for every TPS, additional dispersion modelling simulations are performed by assuming the installation of Flue-Gas Desulfurization (FGD) to cut down the emission of SO₂ from that TPS. The objective of performing this additional dispersion modeling simulation assuming FGD installed in the TPS is to understand the difference in dispersion of SO₂ from the TPS with and without FGD implementation. The efficiency of FGD in different units has been taken based on the date of installation and the electricity generation capacity of the units according to emission norms applicable to thermal power plants given in Environmental (Protection) Amendment rules, 2015. In the present case, we have assumed the following FGD efficiencies:

250MW units- 65% efficiency, 210MW unit– 65% efficiency

With the installation of FGD in this power plant, we noted a reduction of about 65% in the emissions of SO₂ in all the four months.

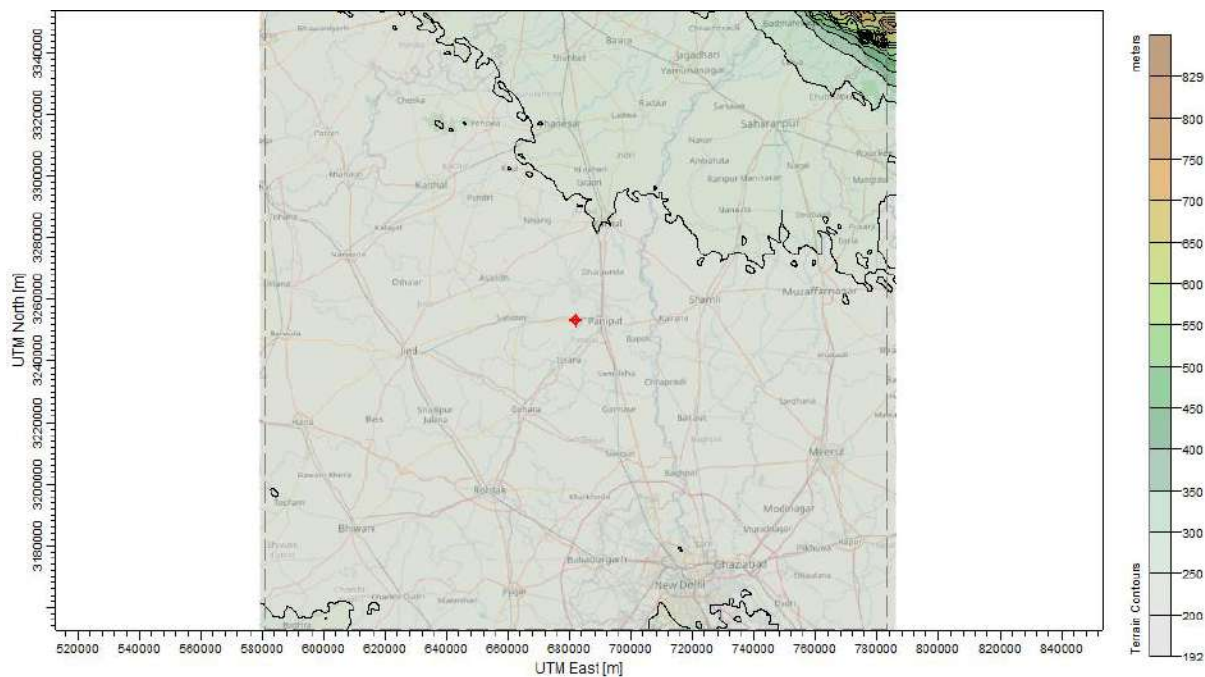


Figure 4.4.1: Terrain Elevation of Modelling Area

Meteorological Input: The surface meteorological data was generated using the Weather Research and Forecasting model for the months of January, April, July and October in the year 2019. The upper air data was generated using upper air estimator in-built in AERMET pre-processor. The wind rose plots for different four months corresponding to the Panipat Thermal Power Station (TPS) are shown in Figures 4.4.2 to 4.4.5.

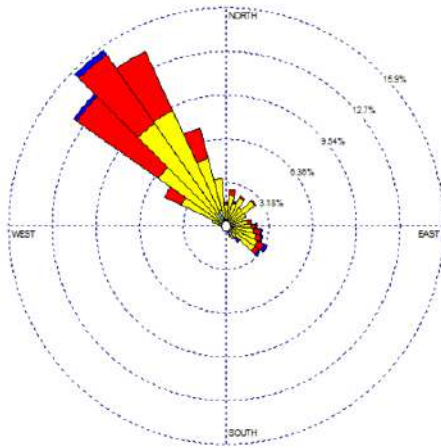


Fig 4.4.2 (a): Wind Rose Direction

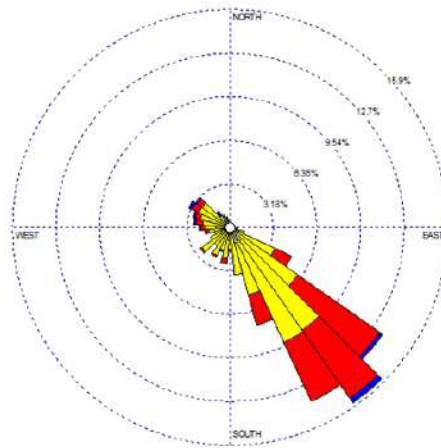


Fig 4.4.2 (b): Wind Rose Flow vector

Figure 4.4.2: Wind Rose plot for the month of January

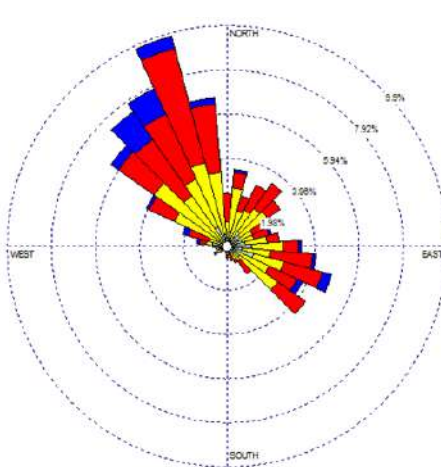


Fig 4.4.3 (a): Wind Rose Direction

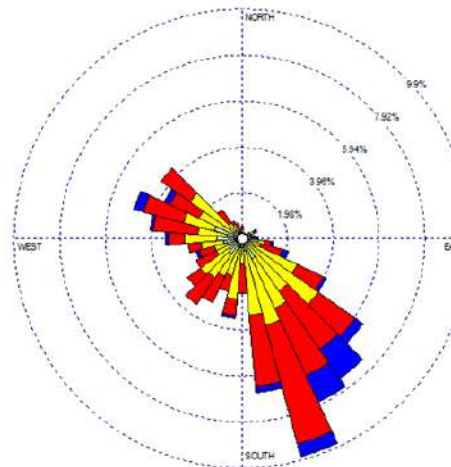


Fig 4.4.3 (b): Wind Rose Flow vector

Figure 4.4.3: Wind Rose plot for the month of April

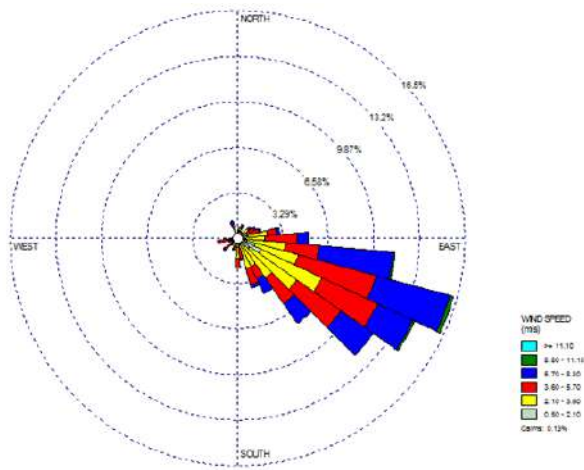


Fig 4.4.4 (a): Wind Rose Direction

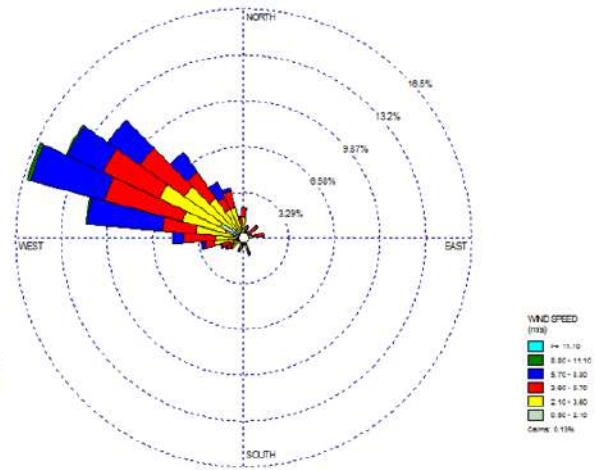


Fig 4.4.4 (b): Wind Rose Flow vector

Figure 4.4.4: Wind Rose plot for the month of July

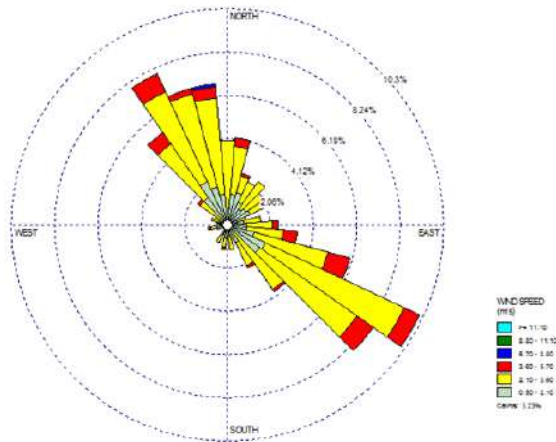


Fig 4.4.5 (a): Wind Rose Direction

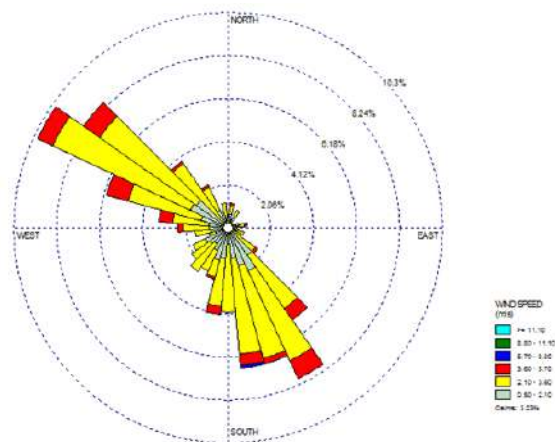


Fig 4.4.5 (b): Wind Rose Flow vector

Figure 4.4.5: Wind Rose plot for the month of October

Table 4.4.1 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at any point within our AERMOD simulation domain and the locations as well as distances of these locations from the Centre of the simulation domain (location of the TPP) for both with and without FGD cases.

Table 4.4.1: SO₂ Dispersion Modeling results for Panipat Power Plant of Haryana

Mon	Highest 1 hourly Conc. ($\mu\text{g m}^{-3}$)	Location of Highest 1 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 1 hourly Conc. from TPP (Km)	Highest 24 hourly Conc. ($\mu\text{g m}^{-3}$)	Location of Highest 24 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 24 hourly Conc. from TPP (Km)	Highest Monthly Average Conc. ($\mu\text{g m}^{-3}$)	Location of Highest Monthly Average Conc. (Lat °N, Lon °E)	Distance of Highest Monthly Average conc. from TPP (Km)
Without FGD									
JAN	96	29.41, 76.87	1.11	34	29.37, 76.87	3.34	14	29.38, 76.83	4.47
APR	101	29.40, 76.86	0.97	33	29.35, 76.88	5.64	11	29.42, 76.84	3.66
JUL	14	29.42, 76.85	2.95	5.46	29.40, 76.85	1.94	1.84	29.41, 76.84	3.11
OCT	68	29.41, 76.83	4.03	26	29.41, 76.87	1.11	17	29.42, 76.89	2.95
With FGD									
JAN	34	29.44, 76.87	4.45	12	29.44, 76.87	4.45	4.71	29.34, 76.87	6.67
APR	35	29.40, 76.82	4.84	13	29.34, 76.85	6.95	3.78	29.37, 76.87	3.34
JUL	5.02	29.42, 76.85	2.95	1.91	29.40, 76.85	1.94	0.64	29.41, 76.84	3.11
OCT	25	29.34, 76.87	6.67	9.45	29.48, 76.91	9.70	5.77	29.40, 76.77	9.69

Table 4.4.2 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ within the AERMOD simulation domain at various distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion simulated by the model for both with and without FGD cases.

Table 4.4.2: SO₂ concentrations (µg/m³) at distances towards direction of maximum dispersion

MON	SO ₂	0km	2km	4km	5km	7km	10km	18km	25km	50km	75km	100km
Without FGD												
JAN	1 Hr	19.8	53.3	17.3	15.2	12.6	15.2	11.3	9.73	5.98	5.1	4
	24 Hr	22.2	7	18.4	11.2	6.02	4.99	3.02	2.09	0.81	0.59	0.44
	Mon	13	3.12	11.5	9.24	2.31	1.88	1.05	0.69	0.25	0.13	0.09
APR	1 Hr	13.2	59.5	19.9	20.1	18.4	15.8	12.7	10.8	5.48	4.17	4.05
	24 Hr	2.99	3.48	5.05	25.3	7.84	5.39	2.8	1.86	0.84	0.57	0.47
	Mon	10.5	0.84	9.47	5.62	1.44	1.16	0.61	0.41	0.17	0.11	0.07
JUL	1 Hr	1.6	9.78	14.6	13.7	12.4	10.9	7.56	5.96	4.47	3.96	3.2
	24 Hr	0.32	5.54	4.18	4.52	4.76	4.12	2.31	1.54	0.58	0.31	0.29
	Mon	0.08	0.93	1.46	1.37	1.31	1.01	0.56	0.37	0.15	0.08	0.05
OCT	1 Hr	37.3	46.8	66.2	48.1	13.3	12.1	9.11	7.73	4.88	4.25	3.31
	24 Hr	19.1	16.2	1.75	2.43	2.97	2.59	1.57	1.06	0.48	0.34	0.26
	Mon	9.28	14.9	13.6	8.71	5.37	0.86	0.53	0.36	0.14	0.08	0.05
With FGD												
JAN	1 Hr	12.6	1.32	26.3	23.1	5.93	5.32	3.87	3.42	2.05	1.72	1.37
	24 Hr	1.68	0.35	9.15	9.65	5.88	1.66	1.07	0.73	2.82	0.21	0.15
	Mon	3.2	0.35	0.56	1.78	4.82	0.67	0.37	0.24	0.09	0.05	0.03
APR	1 Hr	7.71	2.5	15.4	28.9	6.81	5.57	4.47	3.85	1.97	1.45	1.43
	24 Hr	0.48	9.07	0.98	3.35	12.6	1.68	1.11	0.82	0.34	0.19	0.12
	Mon	1.64	2.49	2.97	1.56	0.54	0.43	0.23	0.14	0.05	0.02	0.01
JUL	1 Hr	1.11	3.13	4.31	4.74	4.29	3.93	2.75	2.23	1.57	1.4	1.13
	24 Hr	0.17	1.86	1.27	1.54	1.59	1.45	0.82	0.55	0.21	0.11	0.09
	Mon	0.03	0.38	0.56	0.61	0.49	0.38	0.21	0.14	0.05	0.03	0.02
OCT	1 Hr	2.22	1.16	8.17	11.8	15.6	3.99	3.03	2.58	1.35	1.18	1.05
	24 Hr	2.58	0.48	0.59	0.78	1.15	9.06	0.53	0.36	0.14	0.08	0.05
	Mon	3.37	0.31	0.21	0.27	0.34	5.31	0.19	0.13	0.05	0.02	0.01

1 Hr: Highest 1 hourly Conc., 24Hr: Highest 24-hourly Conc., Mon: Highest Monthly Average Conc.

Analysis of dispersion of SO₂ from the Panipat TPP for the month of January 2019

Figures 4.4.6 and 4.4.7 show combined dispersion of total SO₂ emission from all the stacks of the Panipat TPP for the month of January 2019 for cases with and without FGD respectively. It can be noted from figures 4.4.6 and 4.4.7 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.4.6 and 4.4.7 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.4.8 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

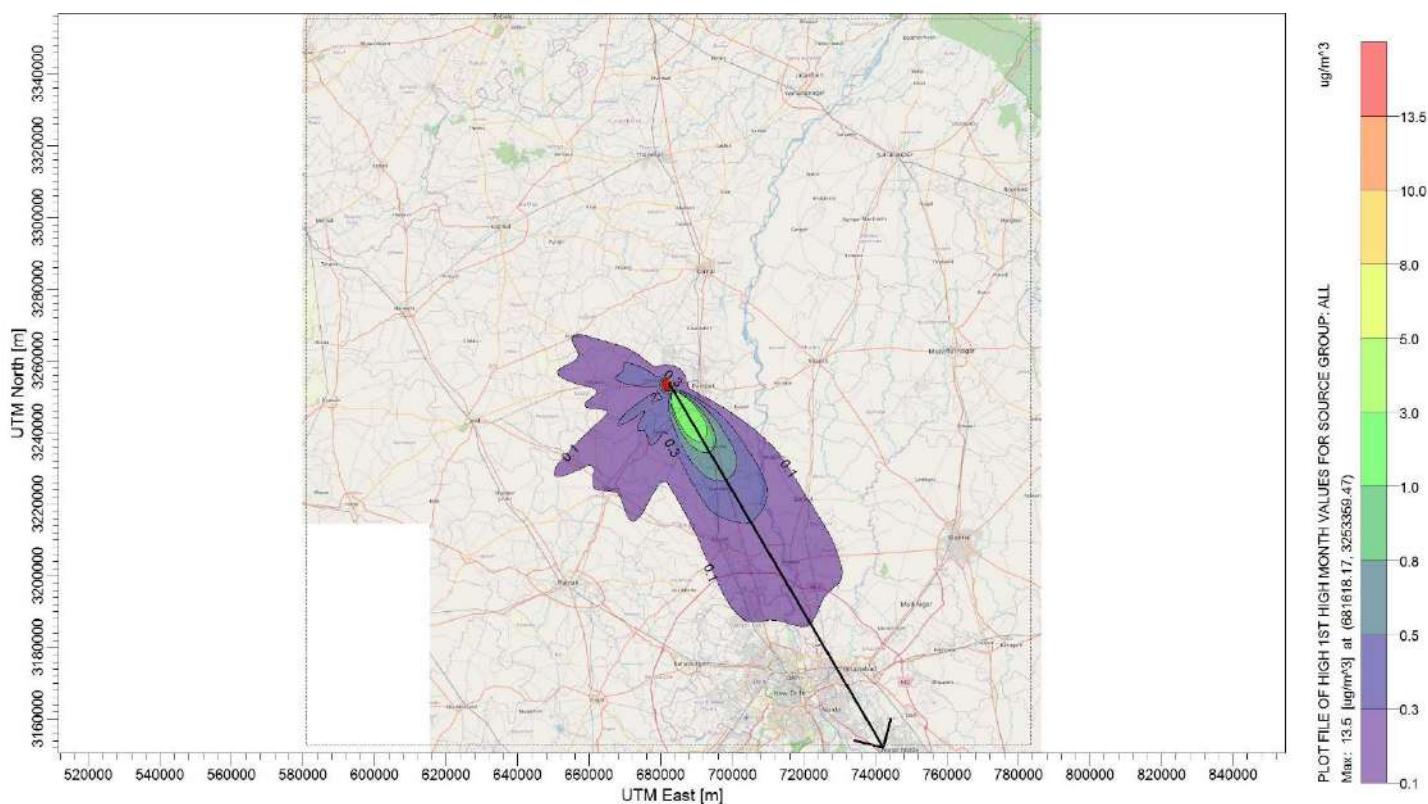


Figure 4.4.6: SO₂ Concentration for January Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

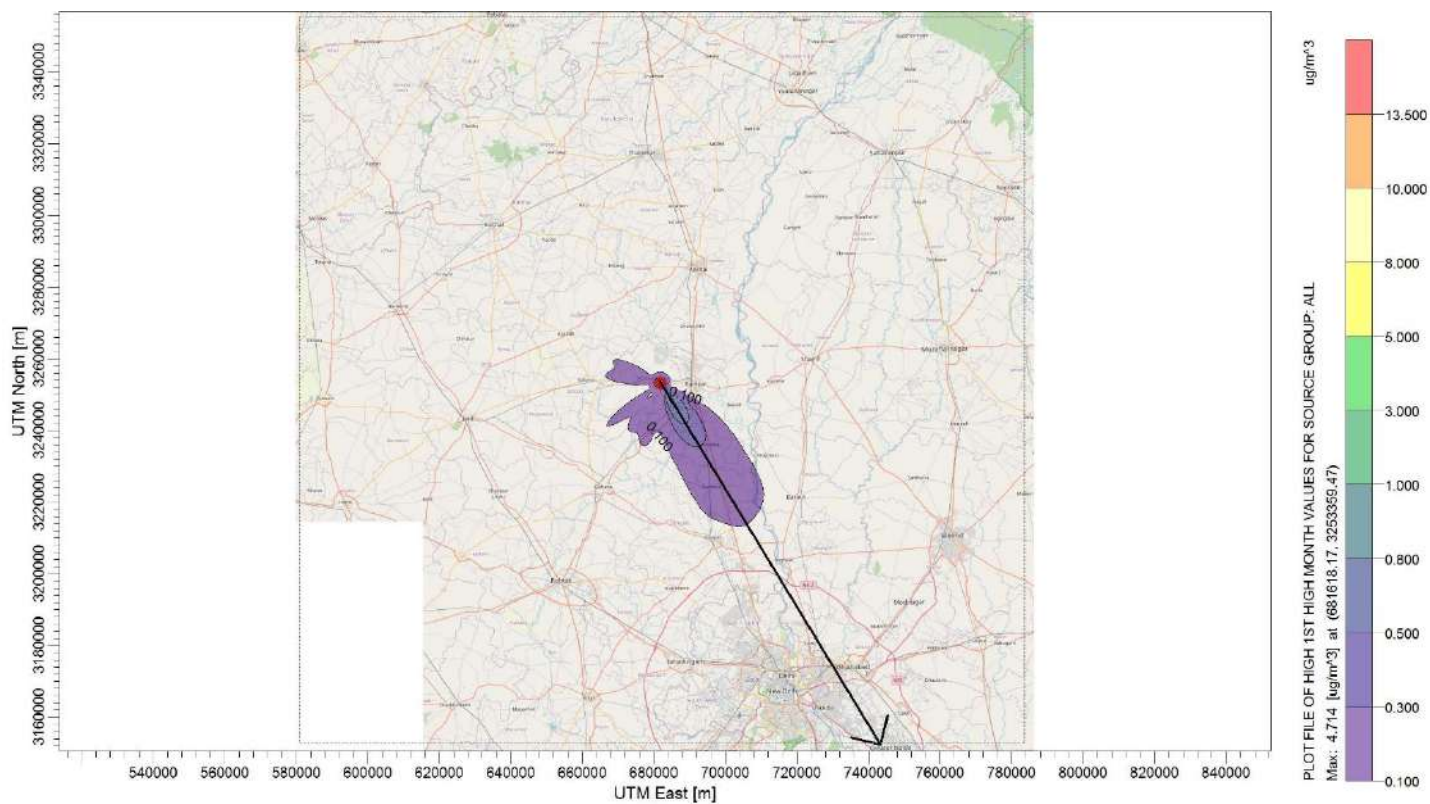


Figure 4.4.7: SO_2 Concentration for January Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

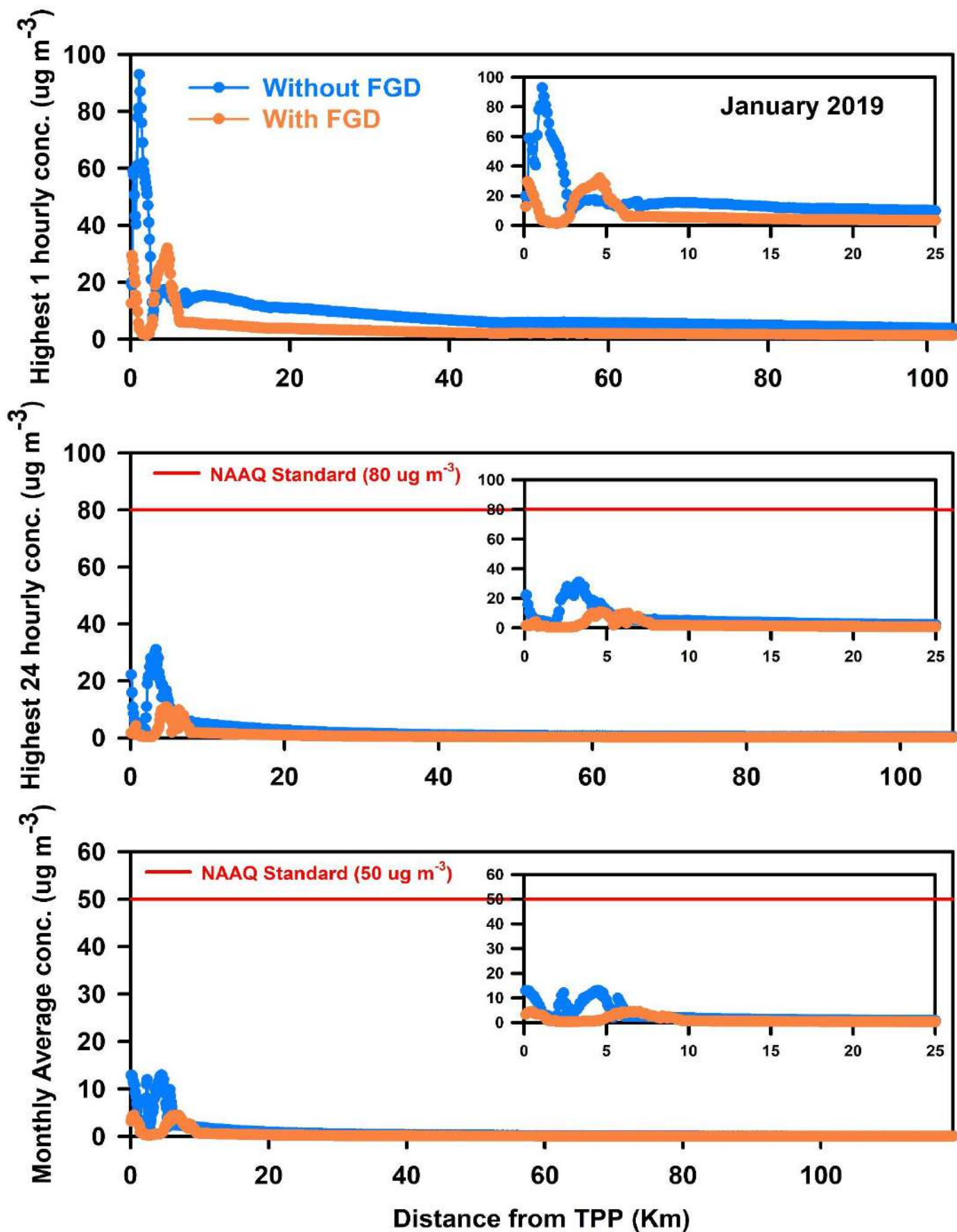


Figure 4.4.8: SO₂ concentration versus distance plot in the direction of maximum dispersion for January

Analysis of dispersion of SO₂ from the Panipat TPP for the month of April 2019

Figures 4.4.9 and 4.4.10 show combined dispersion of total SO₂ emission from all the stacks of the Panipat TPP for the month of April 2019 for cases with and without FGD respectively. It can be noted from figures 4.4.9 and 4.4.10 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.4.9 and 4.4.10 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.4.11 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

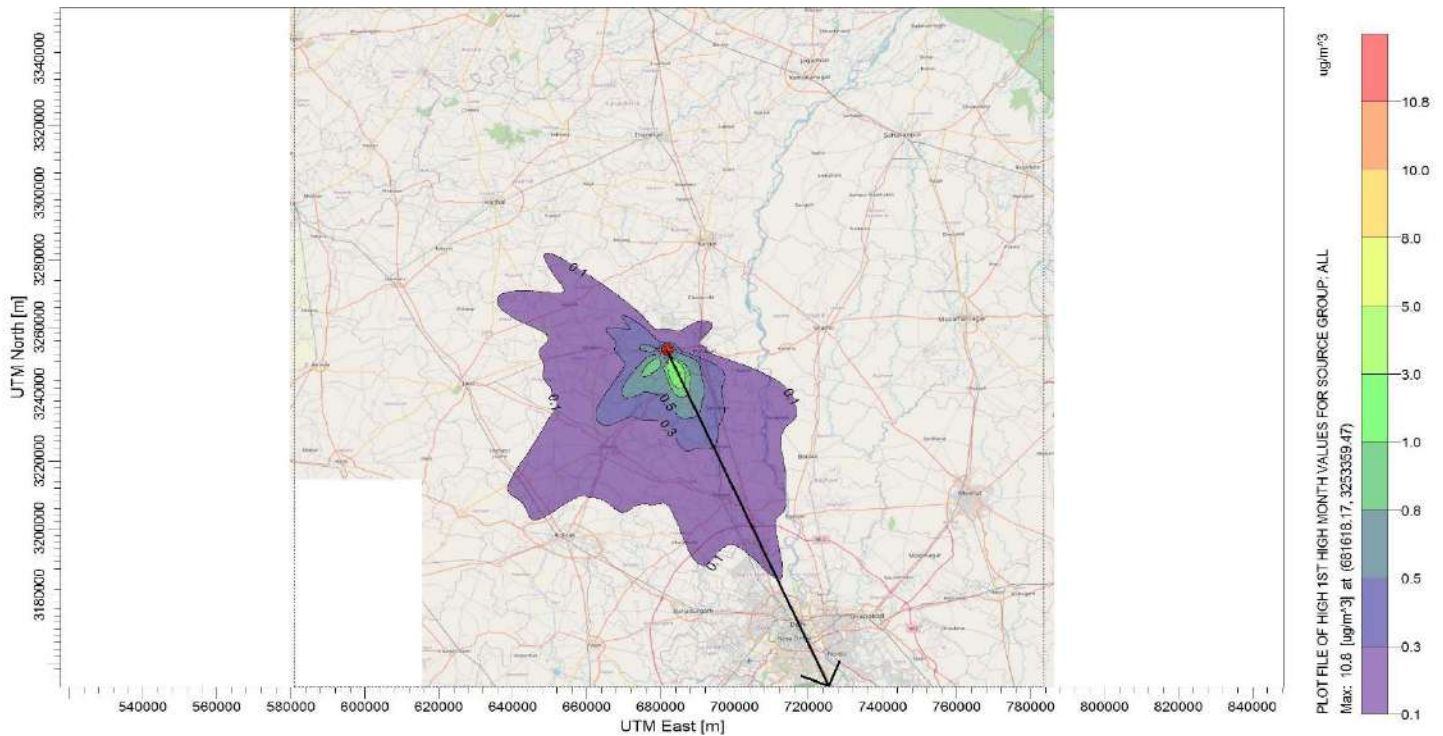


Figure 4.4.9: SO₂ Concentration for April Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

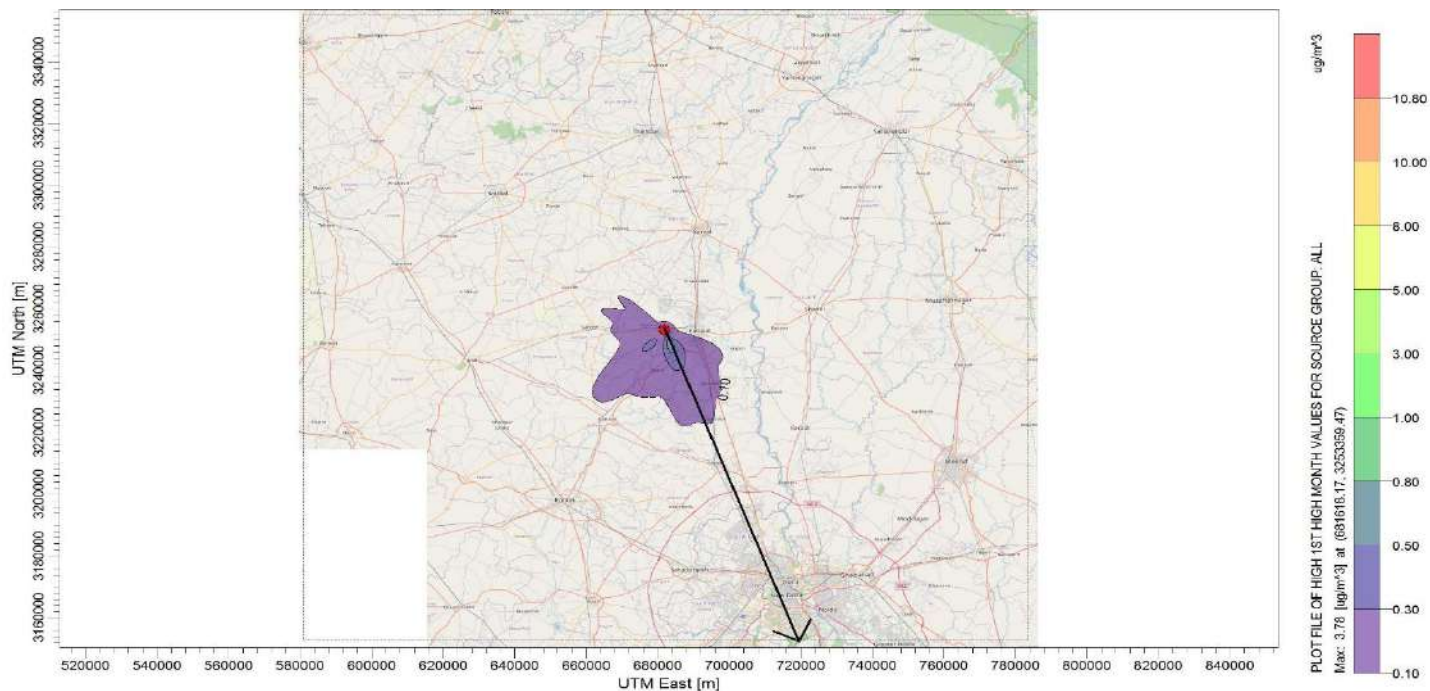


Figure 4.4.10: SO₂ Concentration for April Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

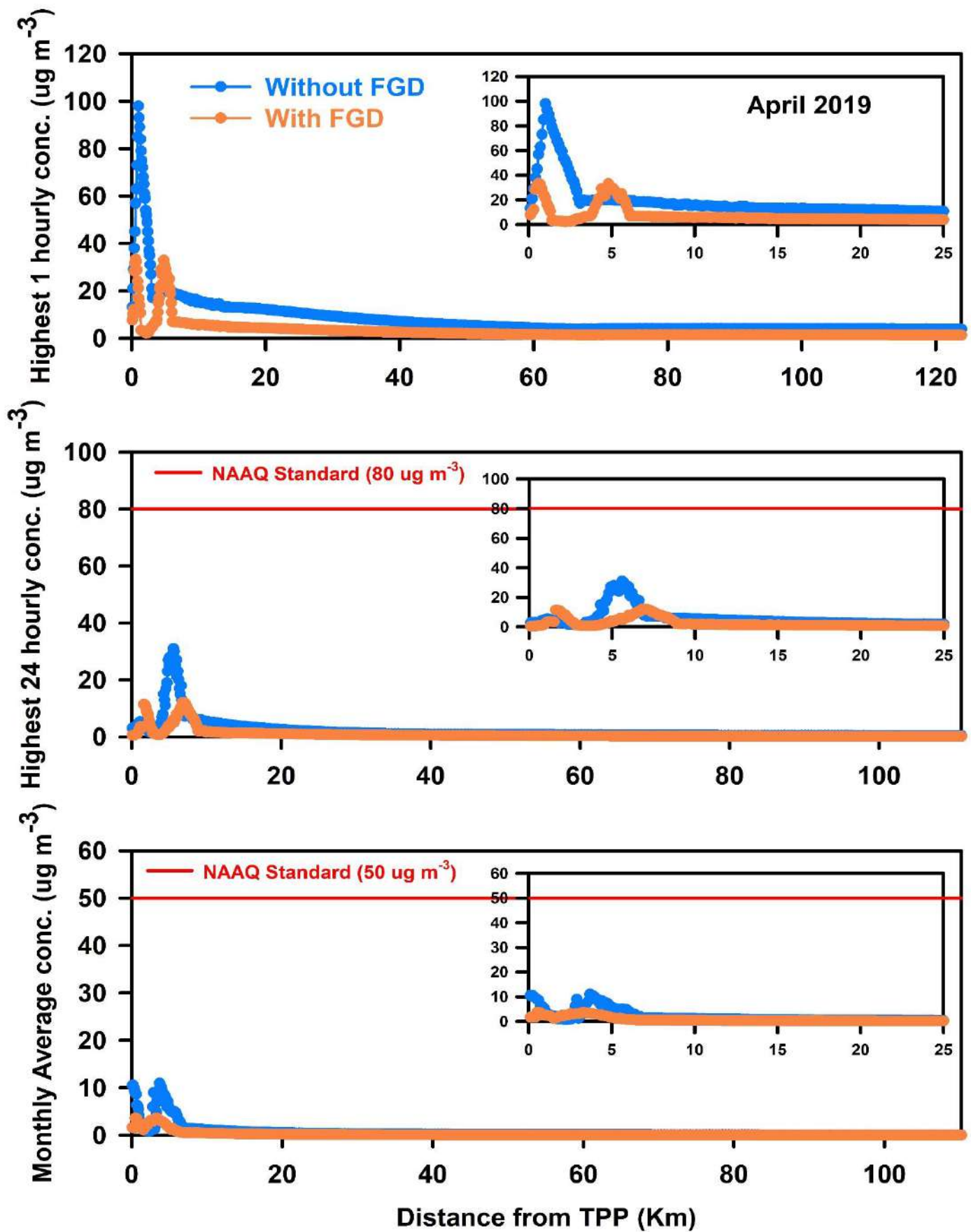


Figure 4.4.11: SO₂ concentration versus distance plot in the direction of maximum dispersion for April

Analysis of dispersion of SO₂ from the Panipat TPP for the month of July 2019

Figures 4.4.12 and 4.4.13 show combined dispersion of total SO₂ emission from all the stacks of the Panipat TPP for the month of July 2019 for cases with and without FGD respectively. It can be noted from figures 4.4.12 and 4.4.13 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.4.12 and 4.4.13 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.4.14 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

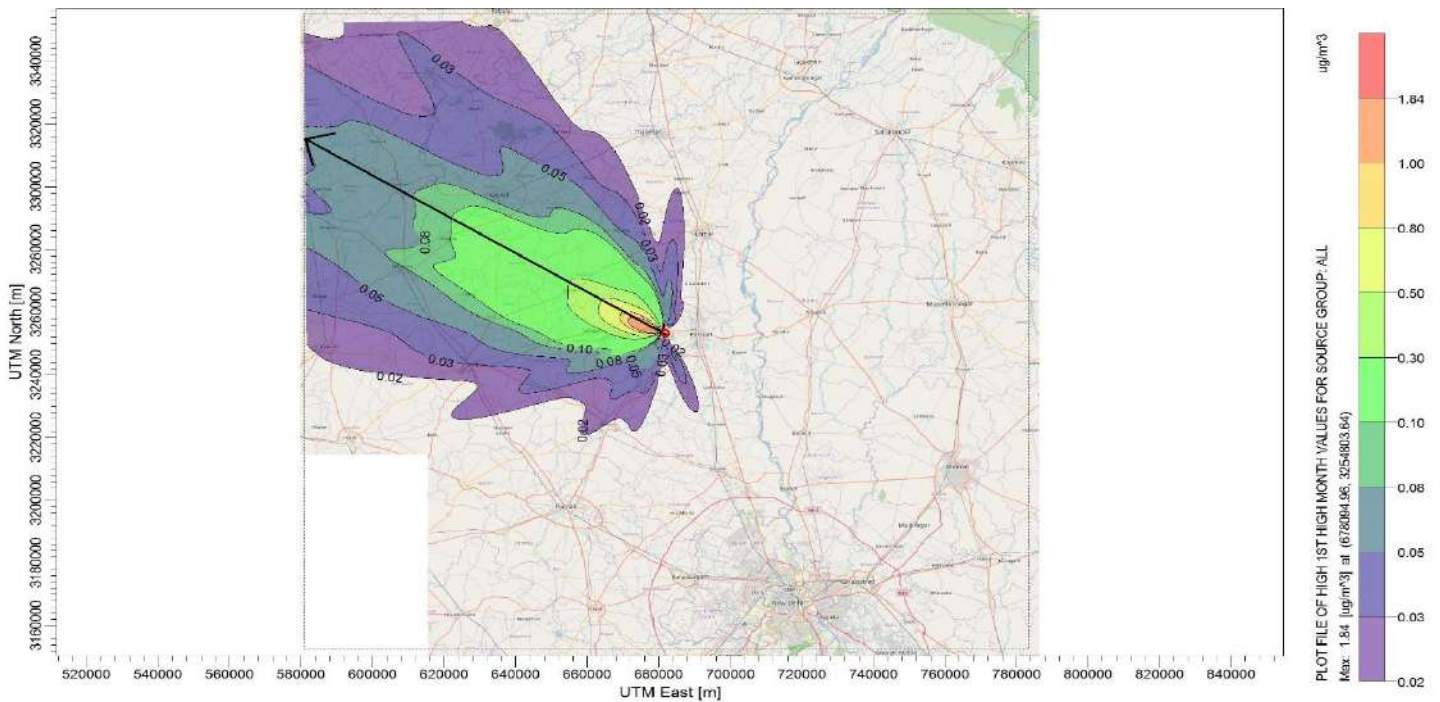


Figure 4.4.12: SO₂ Concentration for July Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

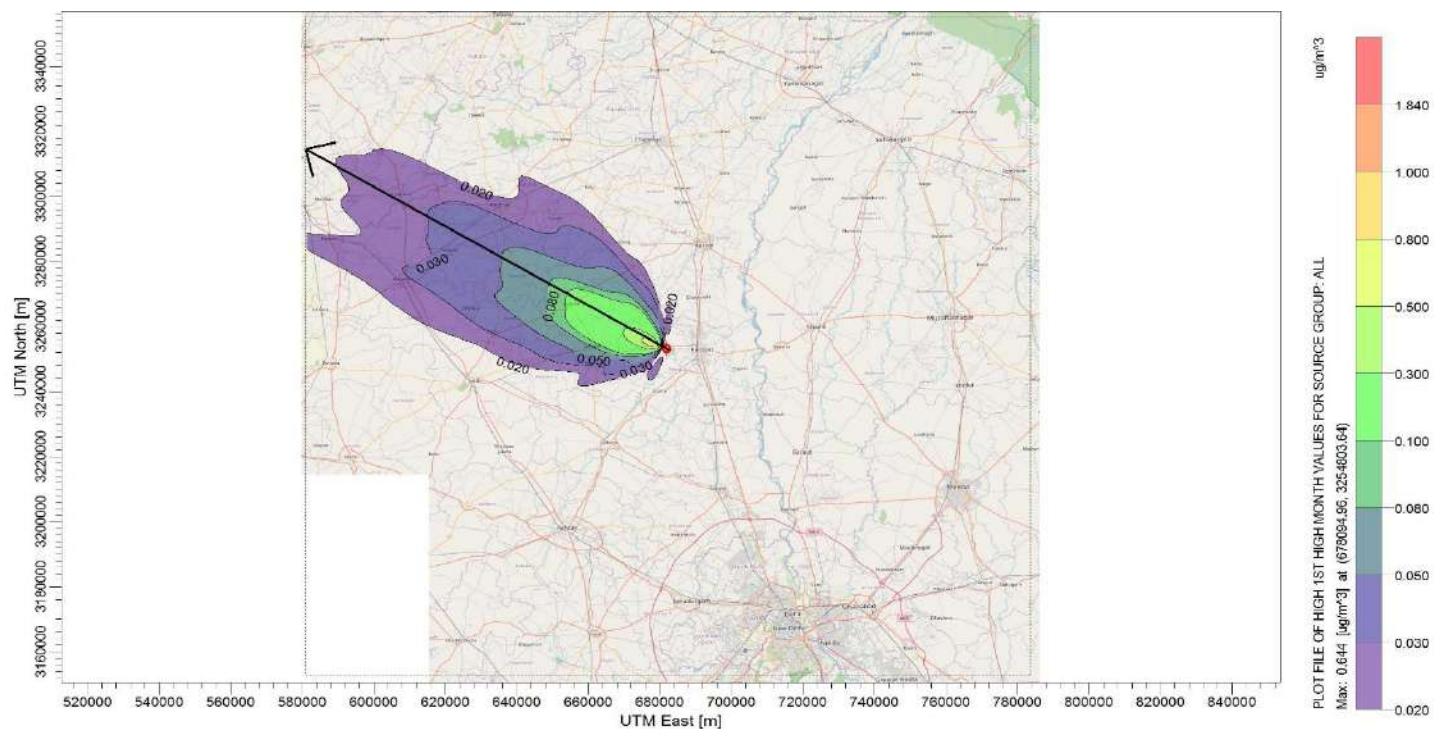


Figure 4.4.13: SO₂ Concentration for July Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

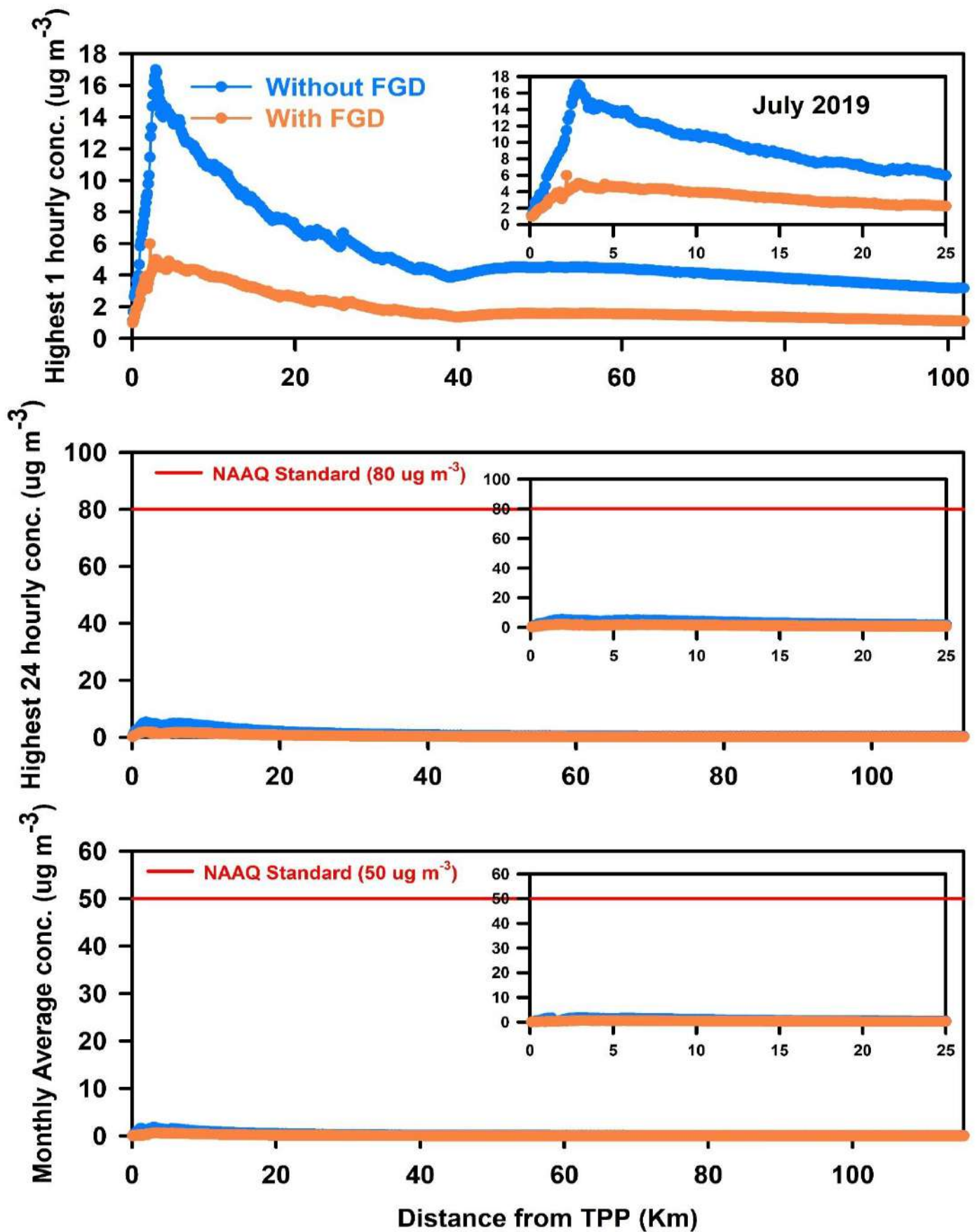


Figure 4.4.14: SO₂ concentration versus distance plot in the direction of maximum dispersion for July

Analysis of dispersion of SO₂ from the Panipat TPP for the month of October 2019

Figures 4.4.15 and 4.4.16 show combined dispersion of total SO₂ emission from all the stacks of the Panipat TPP for the month of October 2019 for cases with and without FGD respectively. It can be noted from figures 4.4.15 and 4.4.16 that there is a considerable amount of reduction in the surface concentrations of SO₂ in the surrounding region for the case with FGD implemented in all stacks of this TPP. Figures 4.4.15 and 4.4.16 also show that the general pattern of dispersion of SO₂ in all directions is quite similar for both cases with and without FGD. Figure 4.4.17 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at different distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion of SO₂ as simulated by the model for both cases with and without FGD and within our AERMOD simulation domain.

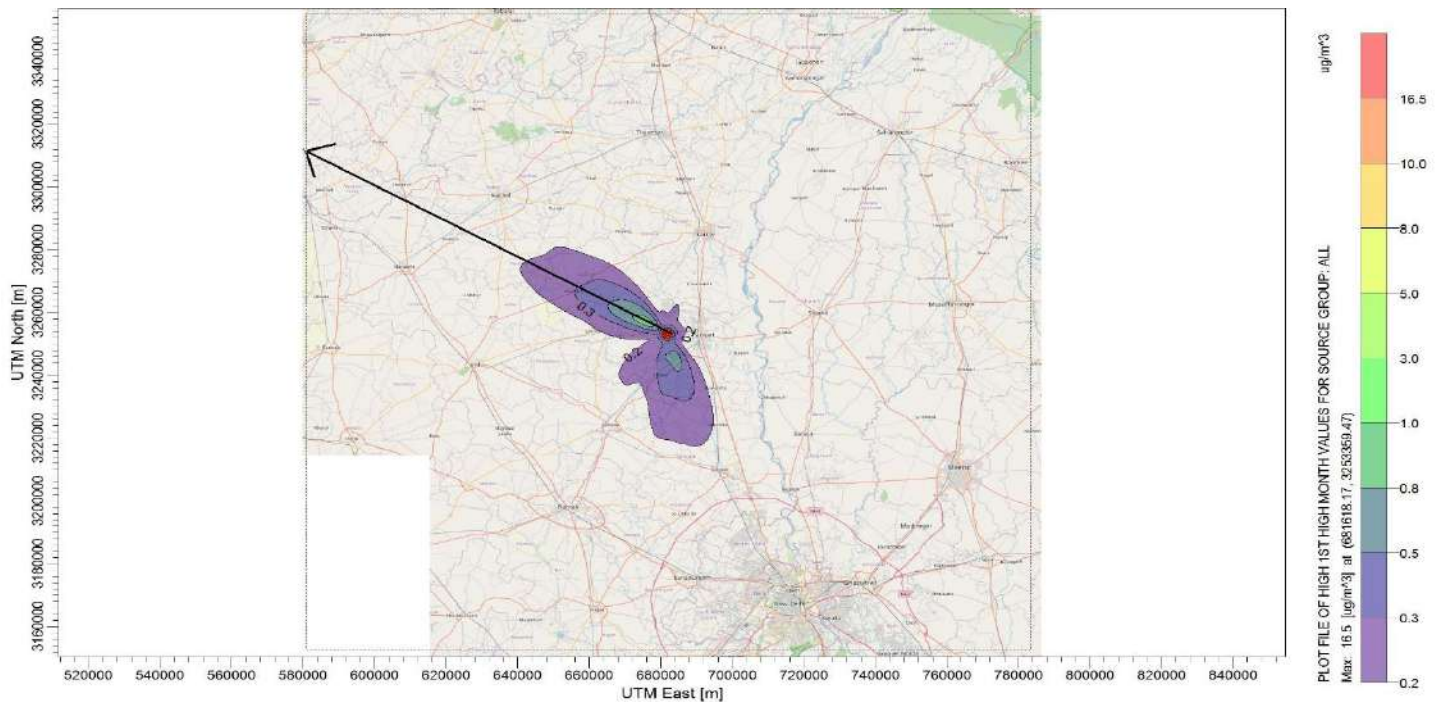


Figure 4.4.15: SO₂ Concentration for October Month without FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

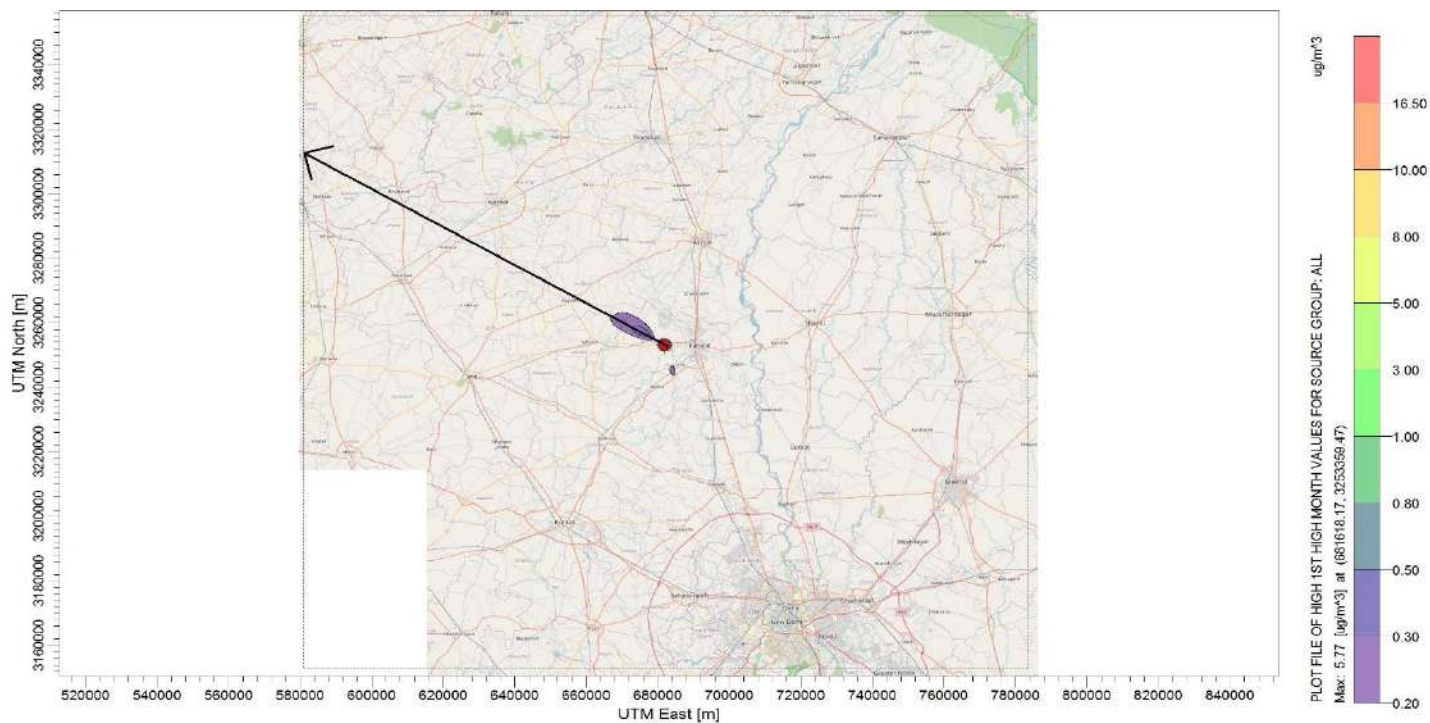


Figure 4.4.16: SO_2 Concentration for October Month with FGD. The black arrow in this figure shows the direction of maximum dispersion as simulated by the model.

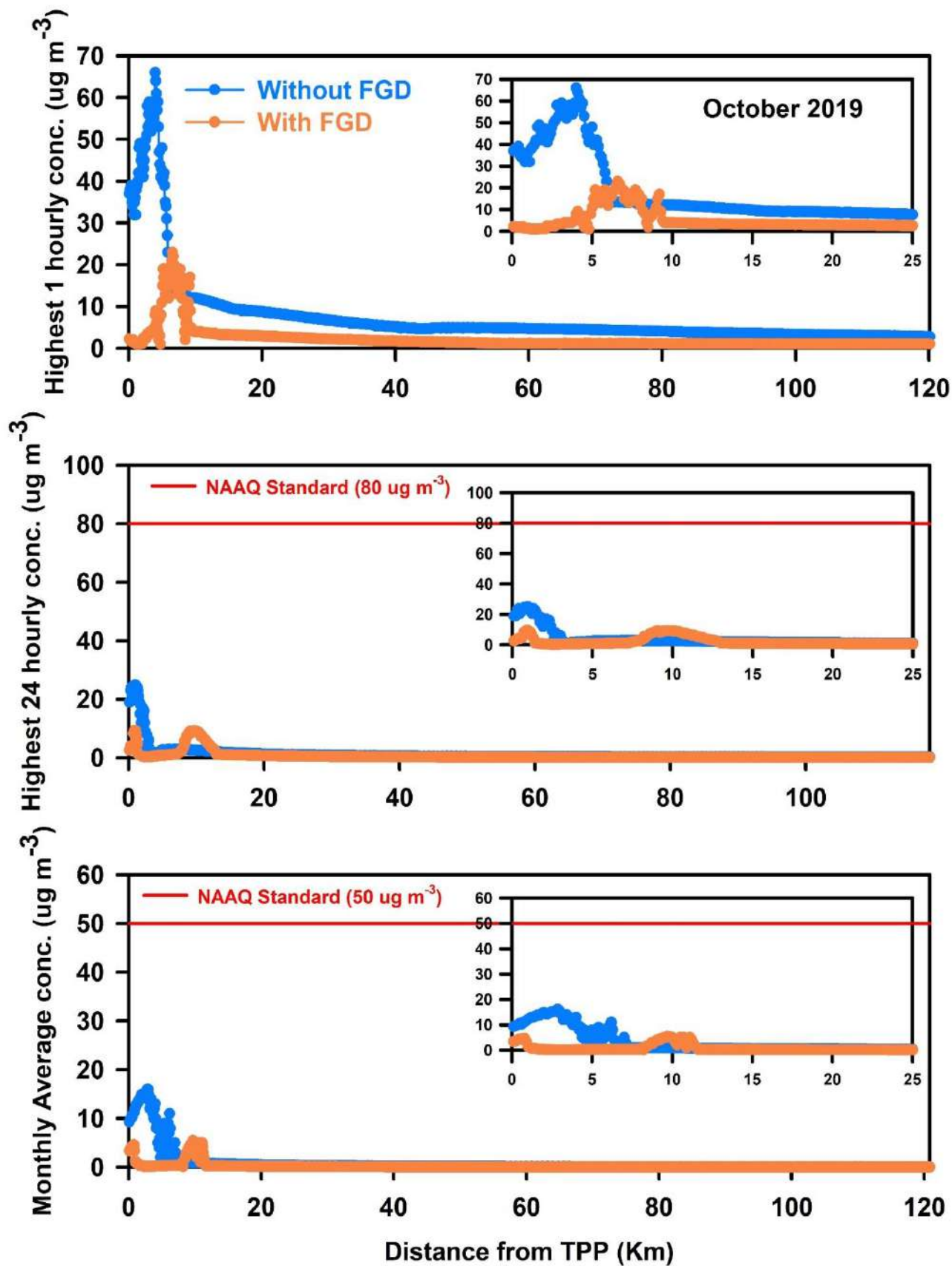


Figure 4.4.17: SO₂ concentration versus distance plot in the direction of maximum dispersion for October

5. Investigation to understand the sensitivity of dispersion of SO₂ from the Vindhyachal TPP as a function of stack height for the month of October 2019

Vindhyachal Thermal Power Plant Stack Height Change:

- I. 0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack).
- II. Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack).
- III. 1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack).

Table 4.5.1 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ at any point within our AERMOD simulation domain and the locations as well as distances of these locations from the Centre of the simulation domain (location of the TPP) for both with and without FGD cases and for three different stack height cases.

Table 4.5.1: SO₂ Dispersion Modeling results for Vindhyachal Power Plant of Madhya Pradesh

Mon	Highest 1 hourly Conc. (µg m ⁻³)	Location of Highest 1 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 1 hourly Conc. from TPP (Km)	Highest 24 hourly Conc. (µg m ⁻³)	Location of Highest 24 hourly Conc. (Lat °N, Lon °E)	Distance of Highest 24 hourly Conc. from TPP (Km)	Highest Monthly Average Conc. (µg m ⁻³)	Location of Highest Monthly Average Conc. (Lat °N, Lon °E)	Distance of Highest Monthly Average conc. from TPP (Km)
Without FGD									
0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)									
APR	59360	24.15, 82.73	10.51	3878	24.13, 82.73	9.26	323	24.13, 82.73	9.26
Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)									
APR	6636	24.12, 82.61	5.26	421	24.10, 82.68	3.24	149	24.12, 82.69	5.26
1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)									
APR	2431	23.75, 82.58	38.47	277	24.10, 82.67	2.32	85	24.10, 82.68	3.24
With FGD									
0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)									
APR	15844	24.14, 82.70	7.53	922	24.14, 82.70	7.53	65	24.14, 82.70	7.53
Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)									
APR	1663	24.15, 82.59	9.03	99	24.14, 82.57	9.84	24	24.03, 82.63	6.97
1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)									
APR	529	24.22, 82.61	15.01	47	24.10, 82.67	2.32	14	24.10, 82.67	2.32

Table 4.5.2 shows the values of highest 1-hourly, 24-hourly, and monthly mean concentrations of SO₂ within the AERMOD simulation domain at various distances from the Centre of the simulation domain (location of the TPP) and in the direction of maximum dispersion simulated by the model for both with and without FGD cases and for three different stack height cases.

Table 4.5.2: SO₂ concentrations (µg/m³) at distances towards direction of maximum dispersion

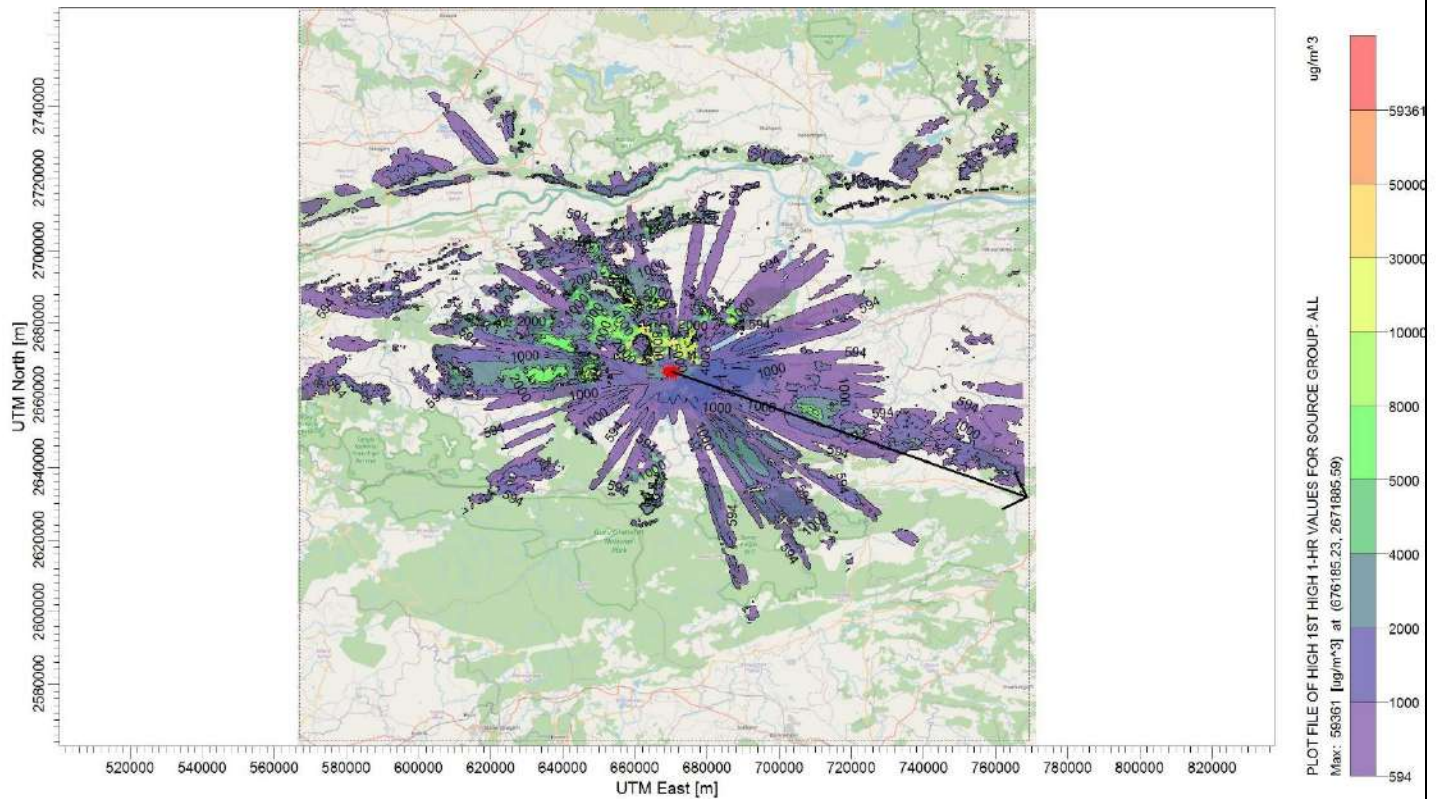
MON	SO ₂	0km	2km	5km	7km	10km	12km	18km	25km	50km	75km	100km
Without FGD												
0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)												
APR	1 Hr	1650	1214	2070	16906	823	802	8253	6470	1560	259	198
	24 Hr	693	421	298	269	194	157	69.3	65.7	72.9	27.6	34
	Mon	208	94.2	61.2	46.4	34	28.8	21.4	15.8	14.6	3.52	5.23
Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)												
APR	1 Hr	2210	1580	5741	2185	358	341	255	233	168	115	
	24 Hr	221	275	89.5	94.2	79.3	68.3	44.4	29.2	12.1	7.82	6.97
	Mon	121	87.5	133	20.5	15.5	13.5	9.64	7.24	4.21	3.85	1.79
1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)												
APR	1 Hr	521	440	302	273	205	184	169	146	78.8	56.4	47.3
	24 Hr	257	66.5	26.3	28.4	33.5	35.5	30.2	22.7	10.4	6.08	7.89
	Mon	69.9	33.2	12.8	9.45	7.28	6.7	4.98	3.99	2.39	1.72	2.29
With FGD												
0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)												
APR	1 Hr	261	195	3773	1020	1940	1910	790	192	100	68.6	45.6
	24 Hr	79.4	111	56.5	36.3	25.4	19.1	11.3	7.77	2.45	1.38	0.87
	Mon	40.5	21.3	10.6	8.19	6.11	5.33	3.62	2.62	1.85	0.46	0.67
Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)												
APR	1 Hr	249	317	102	358	1143	57.9	43.5		26.5	23	
	24 Hr	27.2	21.5	15.6	14.1	87.3	9.86	6.57	4.33	1.77	1.24	1.06
	Mon	21.3	10.6	4.1	21.7	2.5	2.19	1.55	1.16	0.64	0.46	0.27
1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)												
APR	1 Hr	166	145	61.7	43.8	30.3	25.2	20.7	16.7	12.9	59.8	32.5
	24 Hr	46.3	11.4	5.11	6.32	6.63	6.43	4.96	3.6	1.55	0.89	0.86
	Mon	12.9	10.3	2.63	1.78	1.37	1.2	0.91	0.69	0.39	0.29	0.31

1 Hr: Highest 1 hourly Conc., 24Hr: Highest 24-hourly Conc., Mon: Highest Monthly Average Conc.

Sensitivity Analysis of dispersion of SO₂ from the Vindhyachal TPP for the month of April, 2019

1. SO₂ Concentration for April Month without FGD

1.1 Highest 1 hourly Conc. ($\mu\text{g m}^{-3}$)



**Figure 4.5.1: Highest 1 hourly SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month without FGD for
0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)**

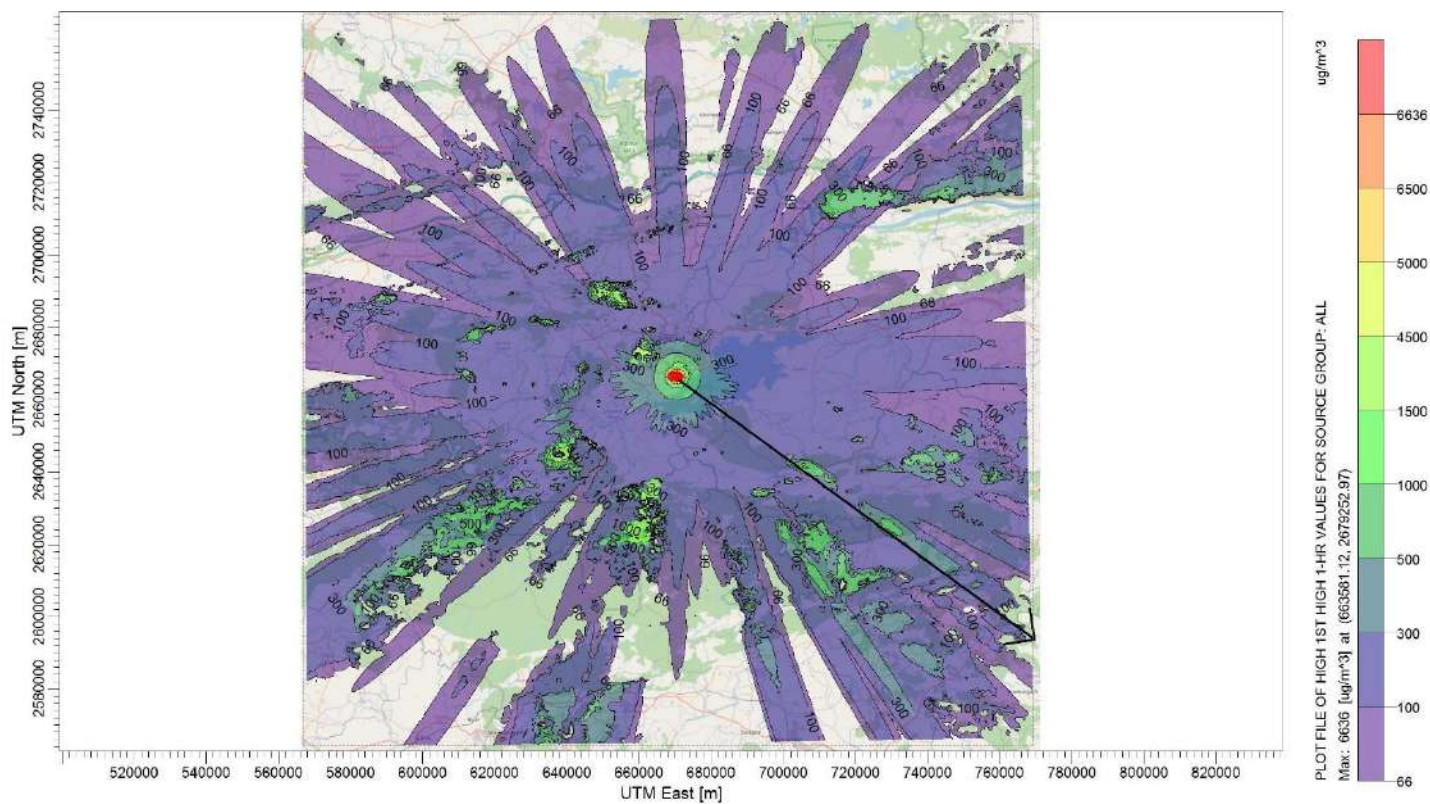


Figure 4.5.2: Highest 1 hourly SO₂ Concentration (µg m⁻³) for April Month without FGD for **Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)**

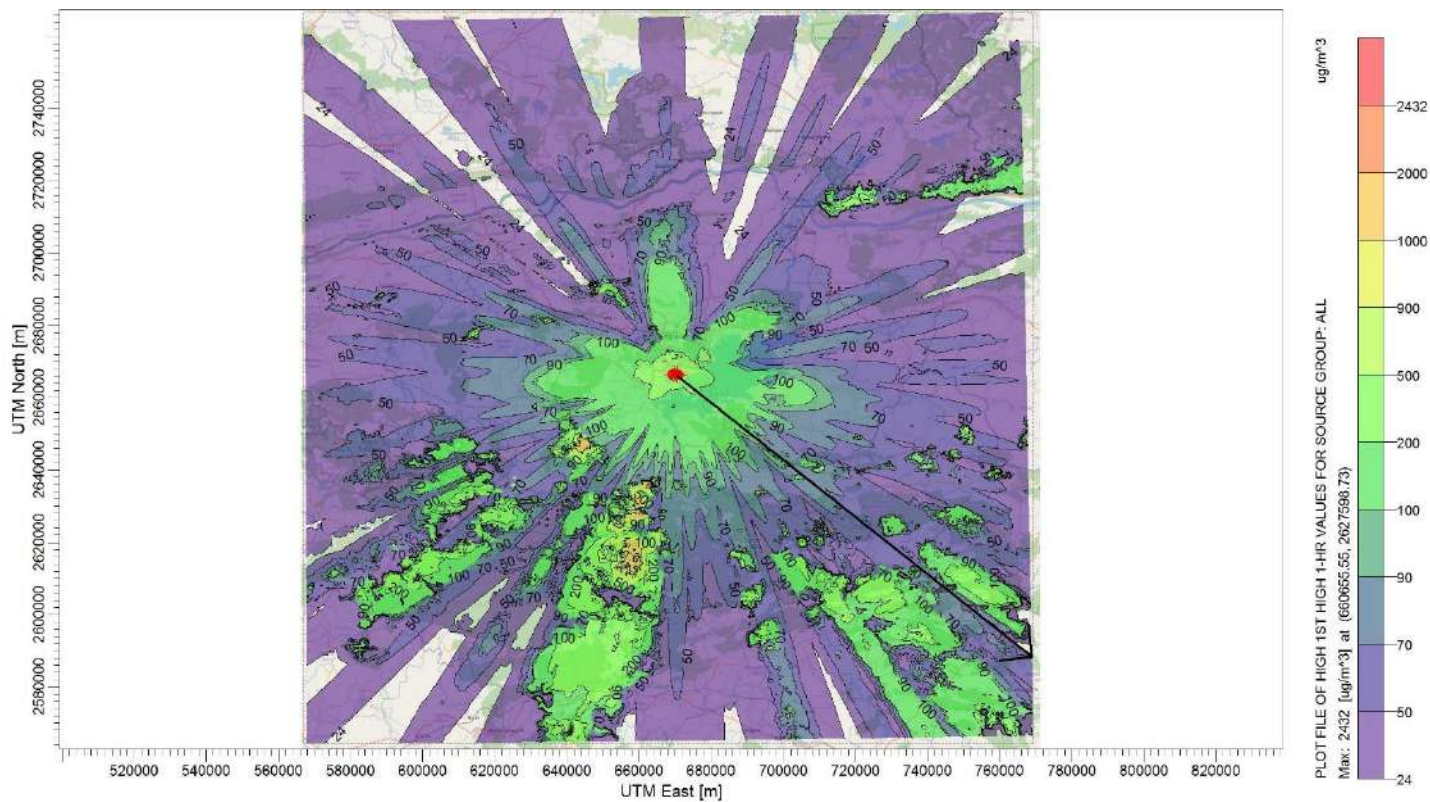


Figure 4.5.3: Highest 1 hourly SO₂ Concentration (µg m⁻³) for April Month without FGD for 1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)

1.2 Highest 24 hourly Conc. ($\mu\text{g m}^{-3}$)

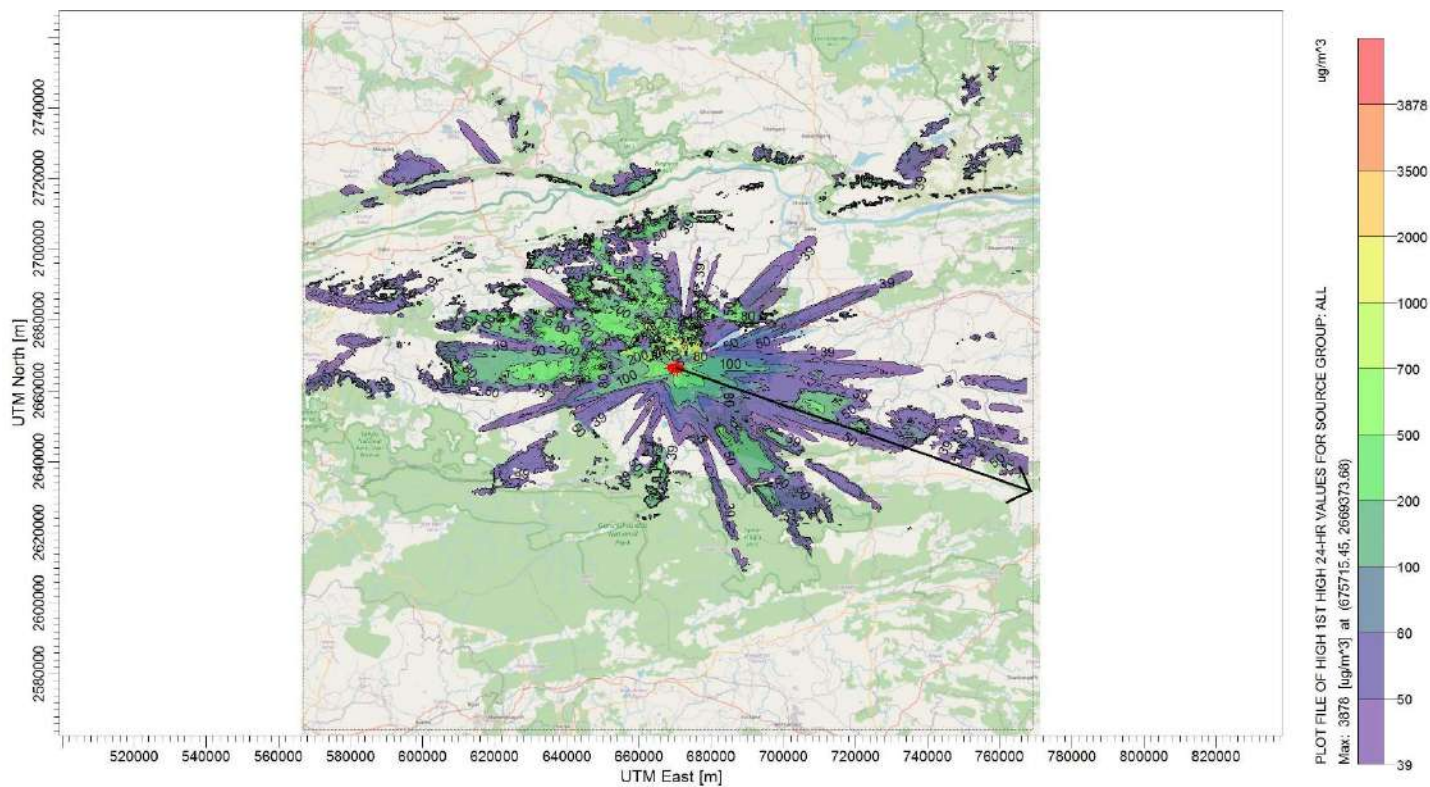


Figure 4.5.4: Highest 24 hourly SO_2 Concentration ($\mu\text{g m}^{-3}$) for April Month without FGD for 0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)

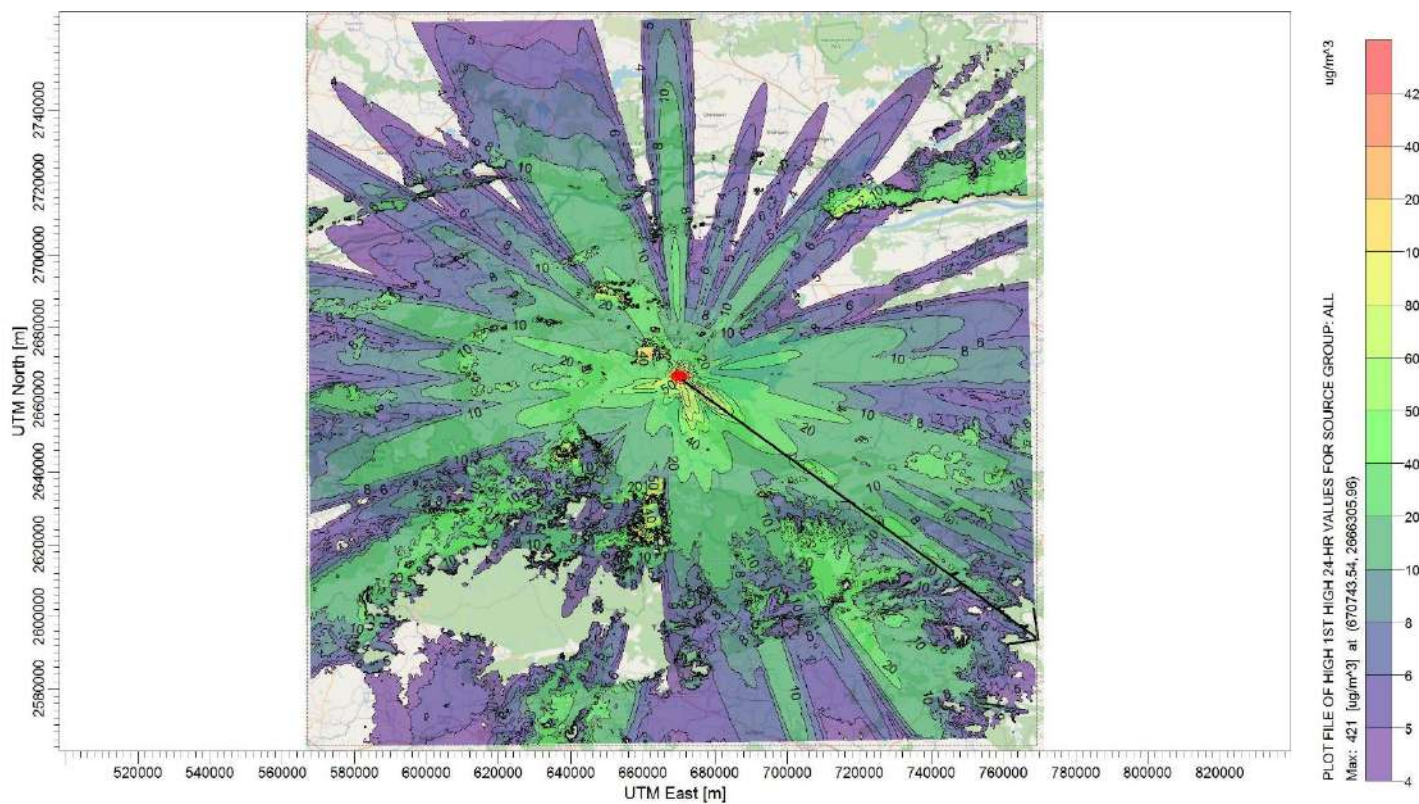


Figure 4.5.5: Highest 24 hourly SO₂ Concentration (µg m⁻³) for April Month without FGD for **Actual Stack Height (220m for 210MW Stack, 275m for 500MW Stack)**

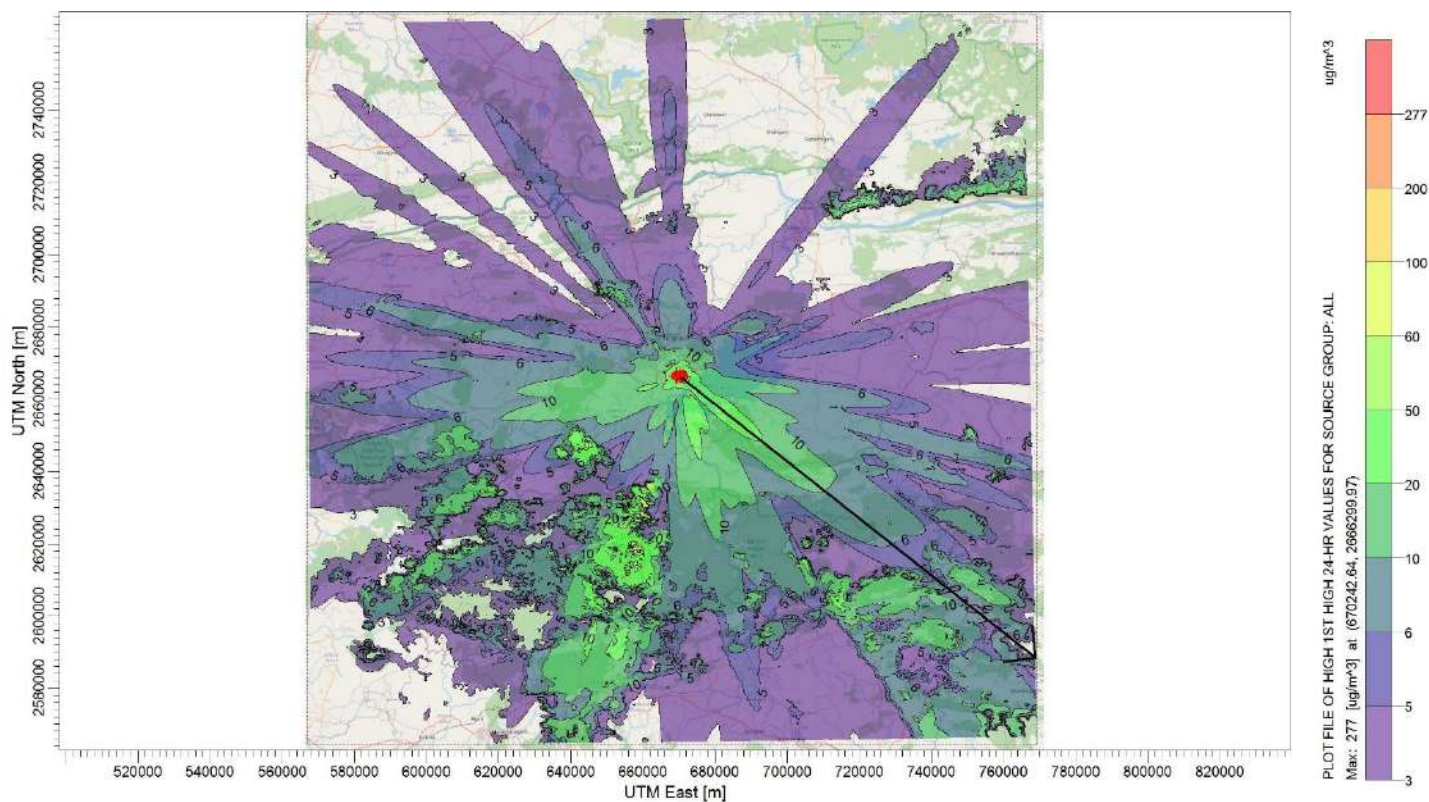


Figure 4.5.6: Highest 24 hourly SO₂ Concentration (µg m⁻³) for April Month without FGD for **1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)**

1.3 Highest Monthly Average Conc. ($\mu\text{g m}^{-3}$)

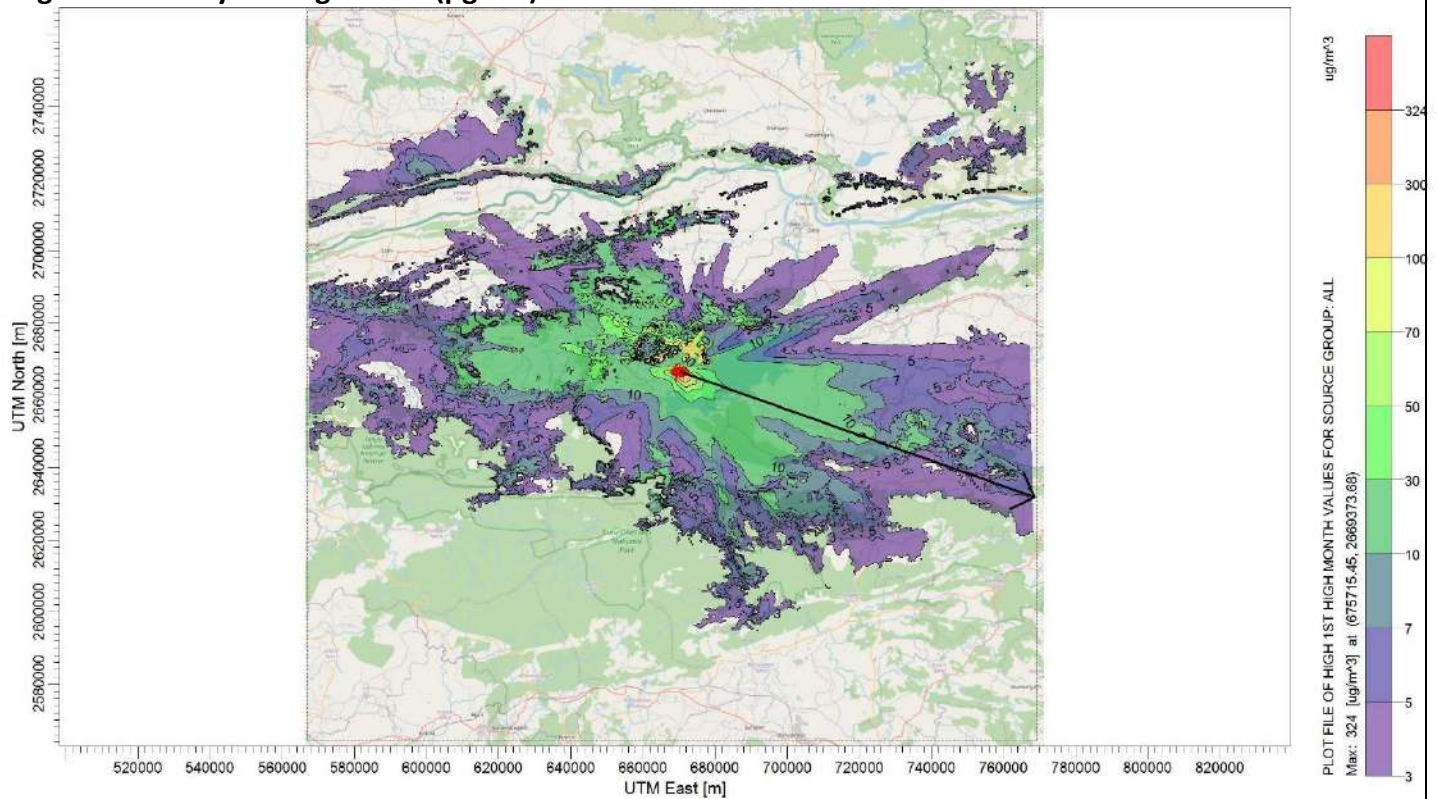


Figure 4.5.7: Highest monthly average SO_2 Concentration ($\mu\text{g m}^{-3}$) for April Month without FGD for **0.5 x Actual Stack Height** (110m for 210MW Stack, 138m for 500MW Stack)

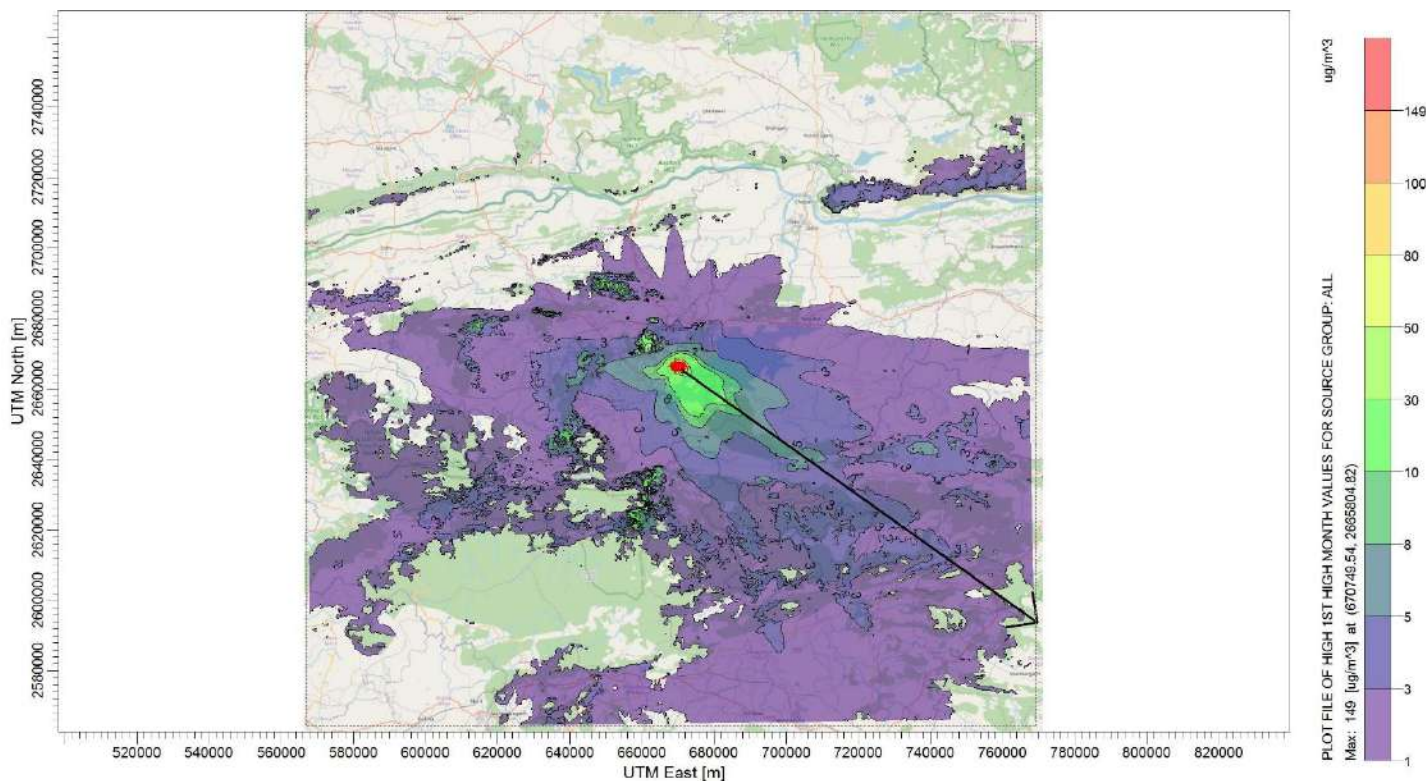


Figure 4.5.8: Highest monthly average SO_2 Concentration ($\mu\text{g m}^{-3}$) for April Month without FGD for **Actual Stack Height** (220m for 210MW Stack, 275m for 500MW Stack)

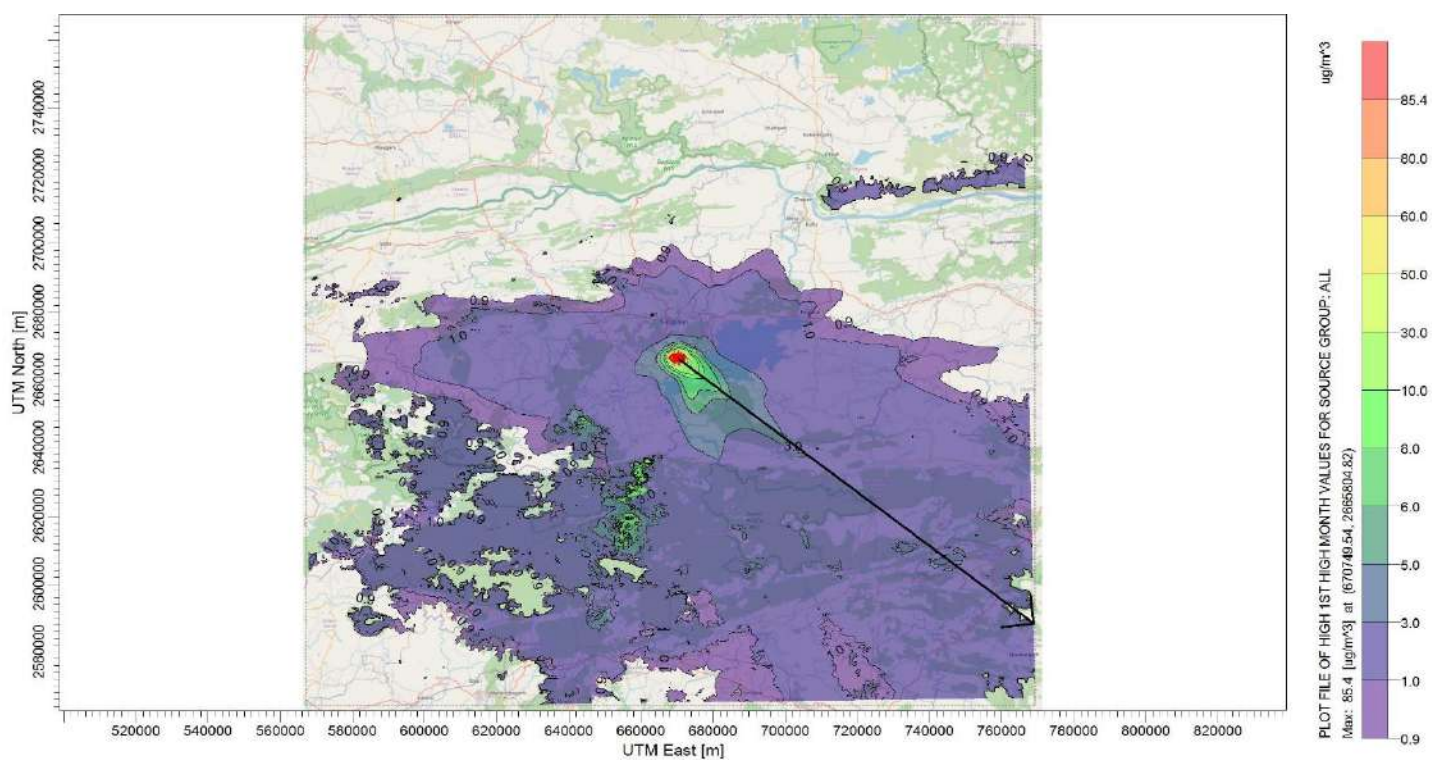


Figure 4.5.9: Highest monthly average SO₂ Concentration (µg m⁻³) for April Month without FGD for 1.5 x Actual Stack Height (330m for 210MW Stack, 413m for 500MW Stack)

2. SO₂ Concentration for April Month with FGD

2.1 Highest 1 hourly Conc. ($\mu\text{g m}^{-3}$)

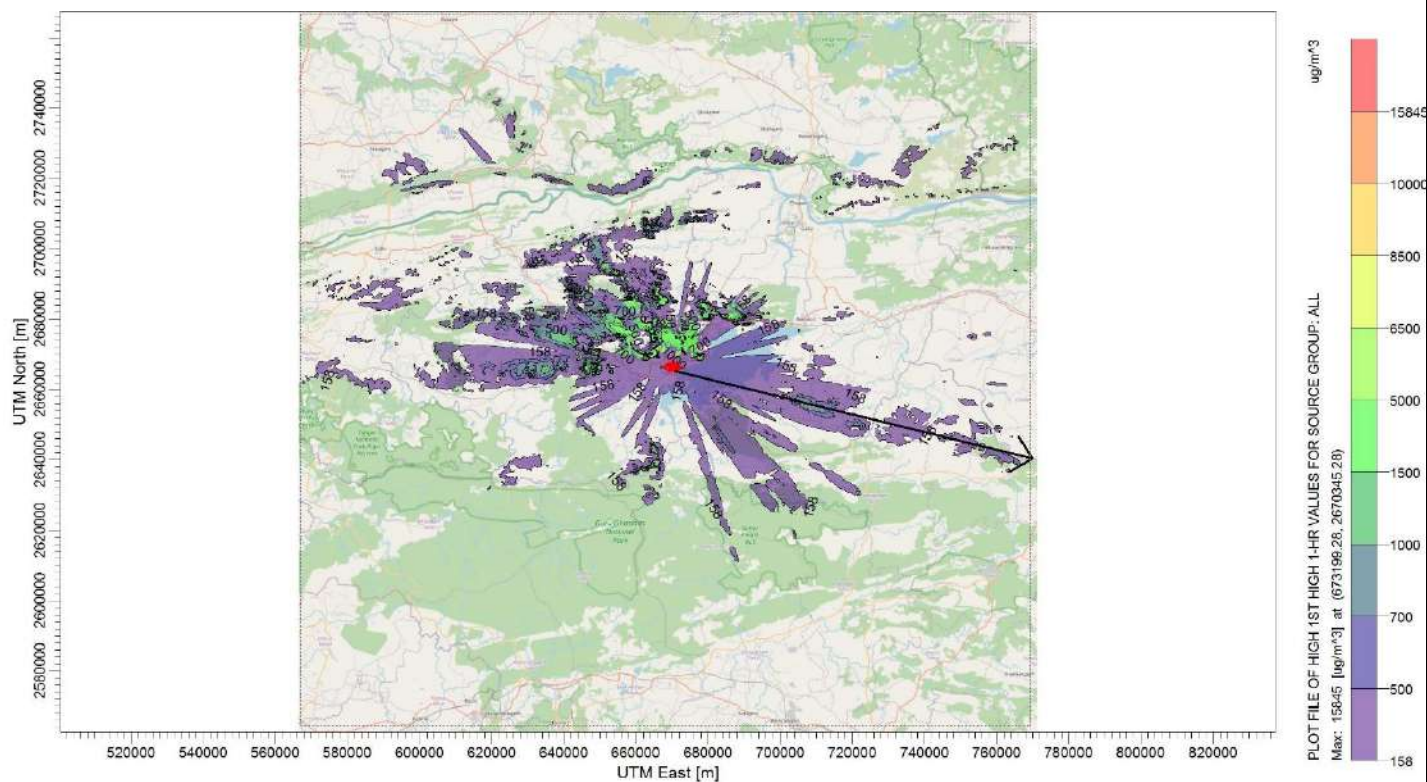


Figure 4.5.10: Highest 1 hourly SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for **0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)**

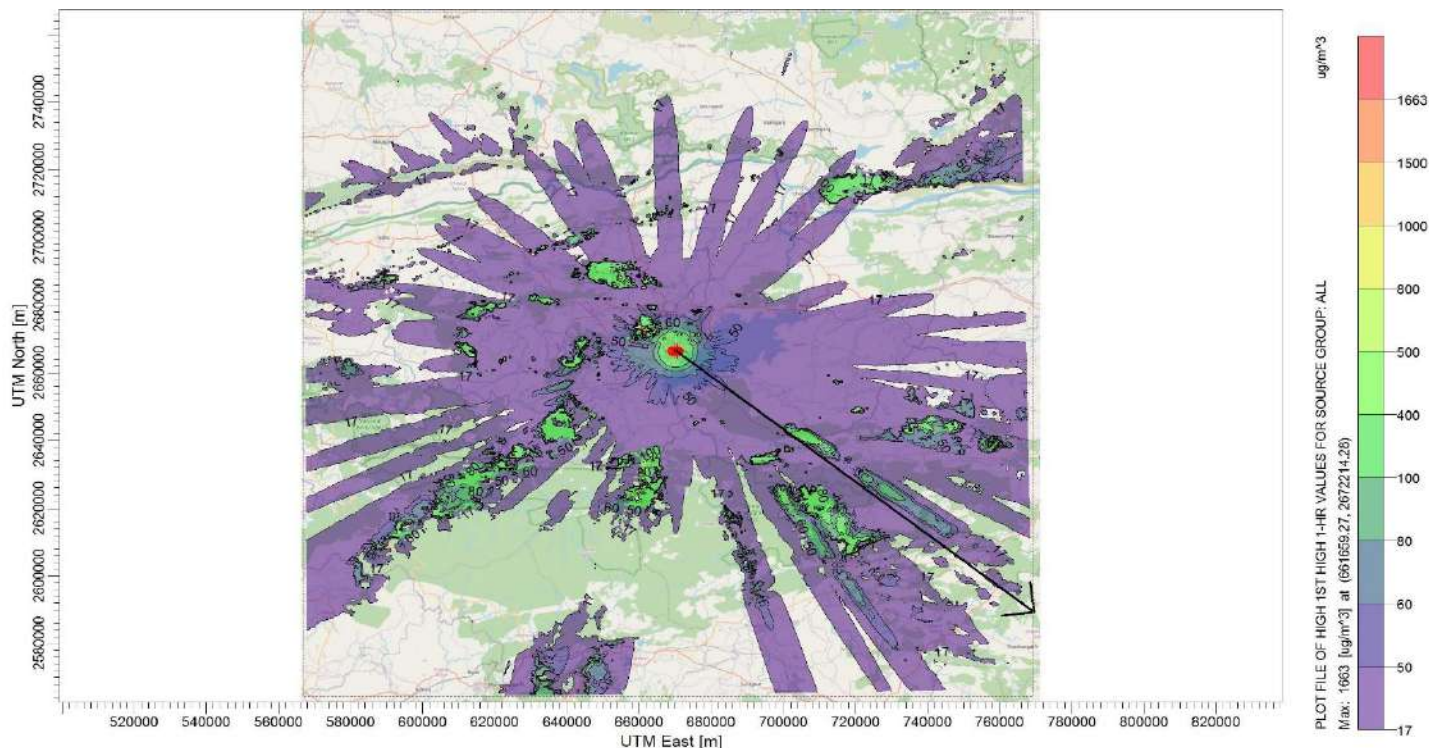


Figure 4.5.11: Highest 1 hourly SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for **Actual Stack Height** (220m for 210MW Stack, 275m for 500MW Stack)

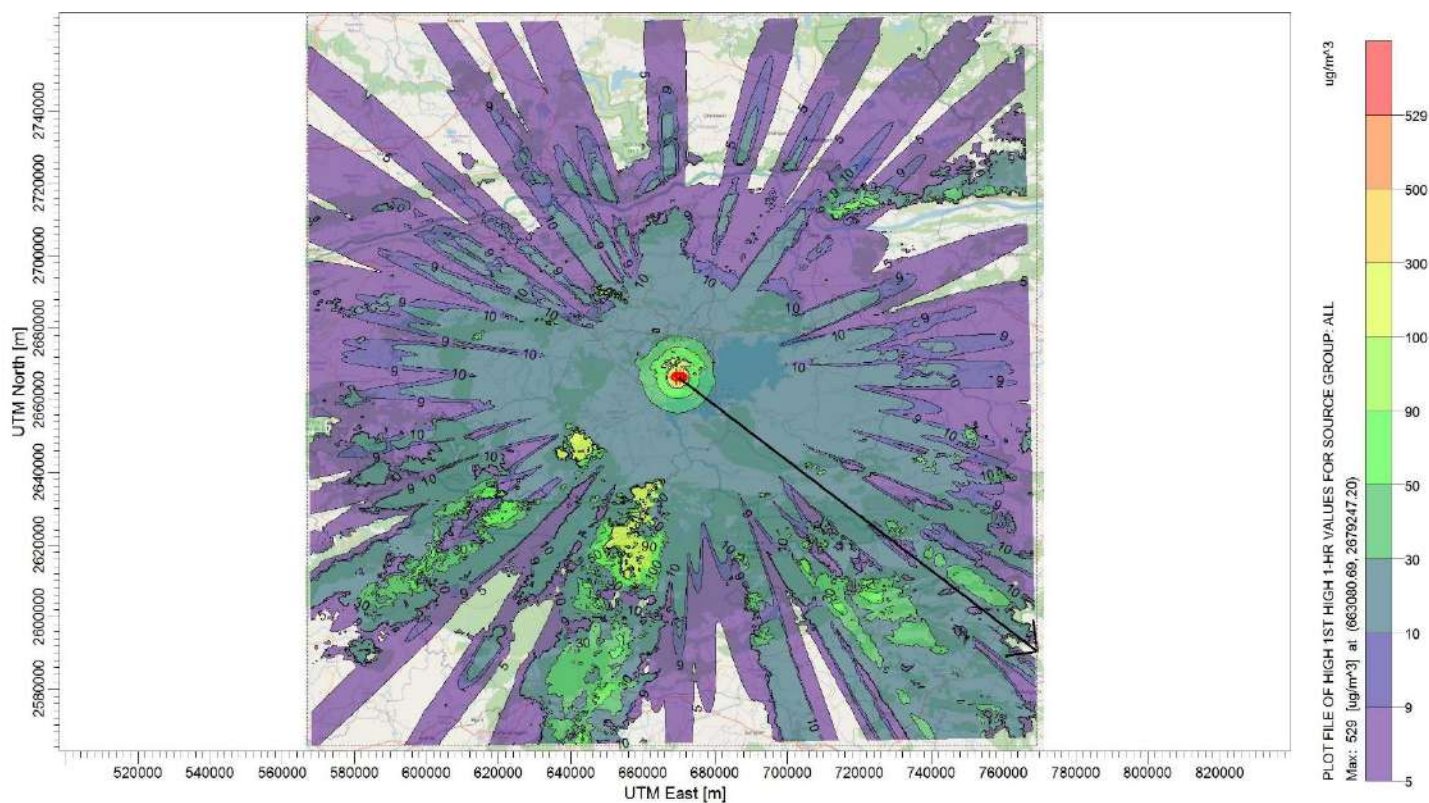


Figure 4.5.12: Highest 1 hourly SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for **1.5 x Actual Stack Height** (330m for 210MW Stack, 413m for 500MW Stack)

2.2 Highest 24 hourly Conc. ($\mu\text{g m}^{-3}$)

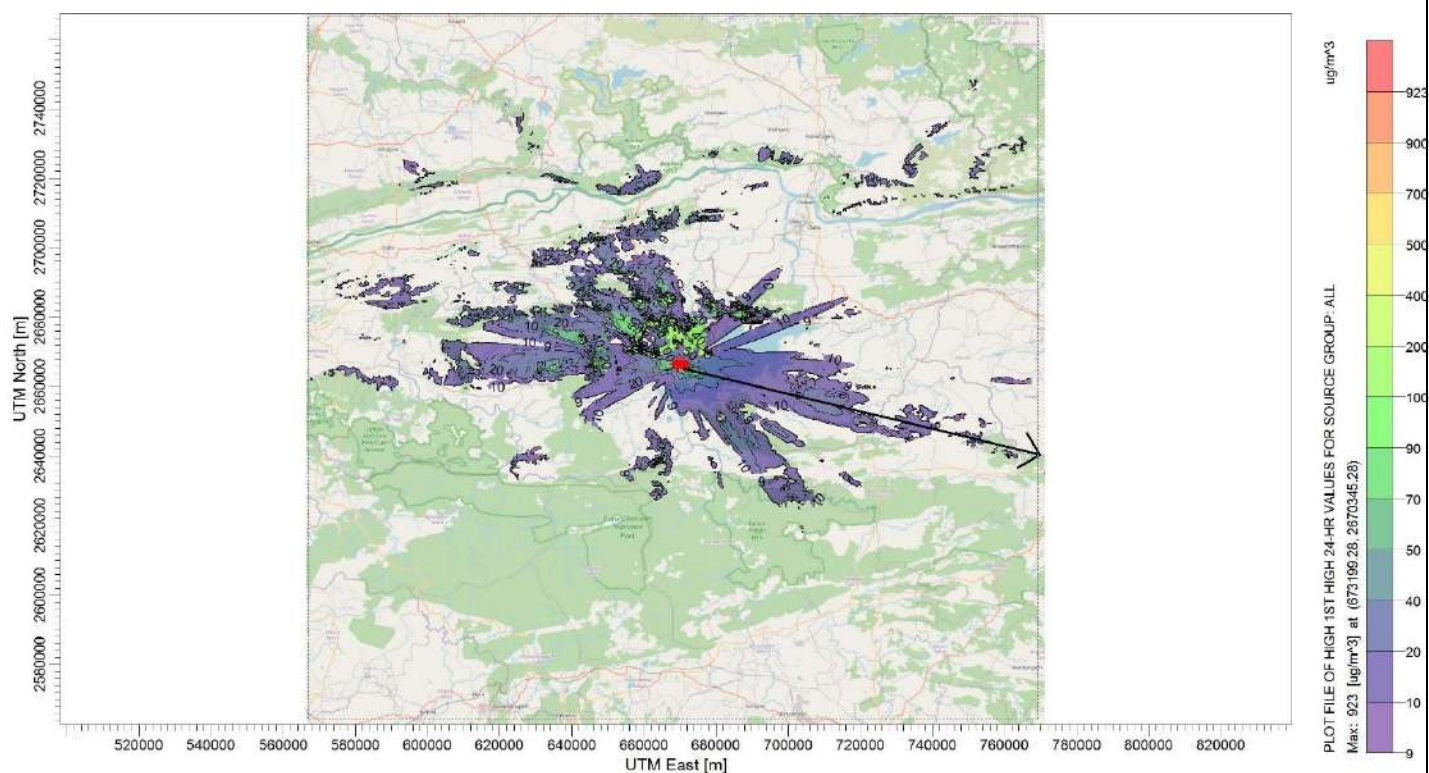


Figure 4.5.13: Highest 24 hourly SO_2 Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for 0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)

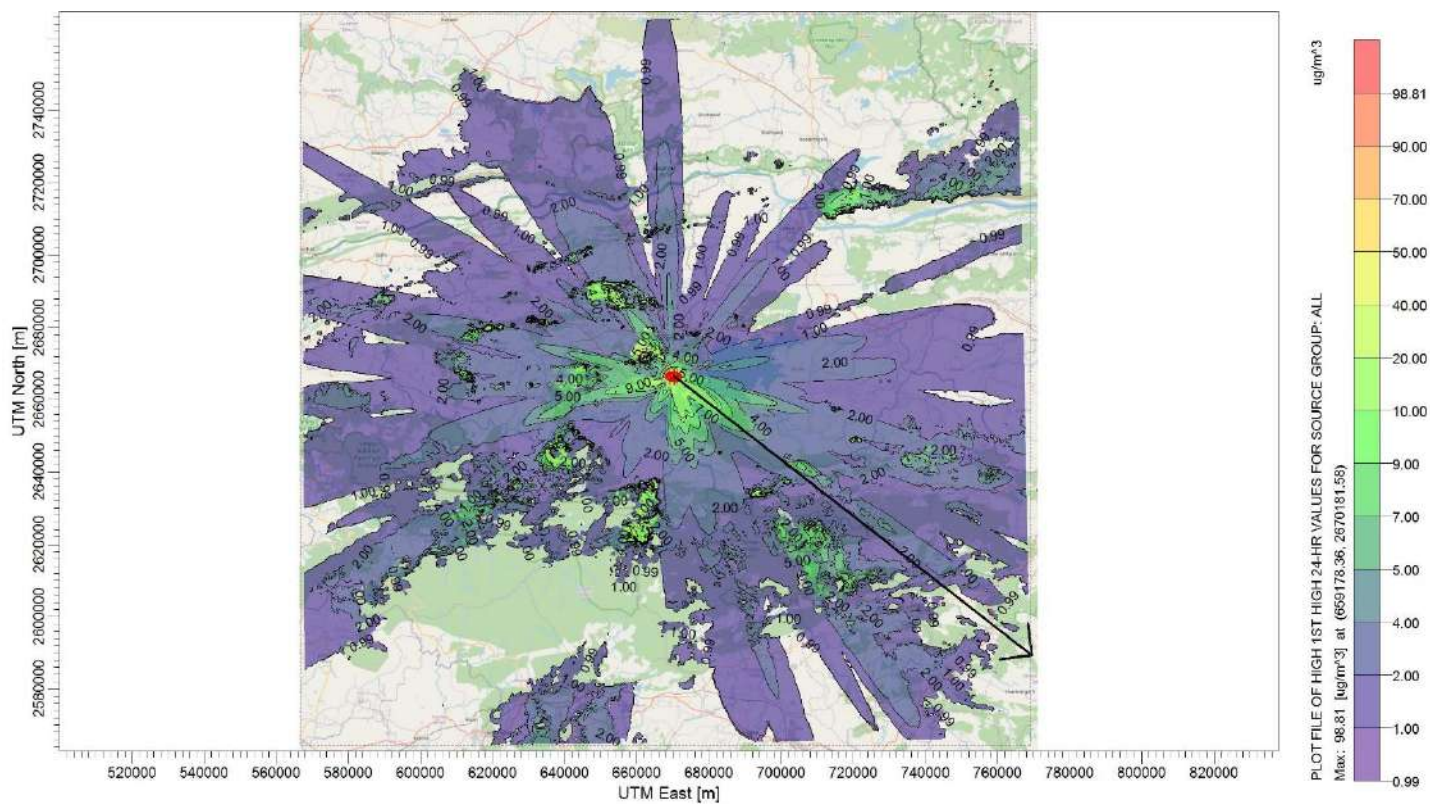


Figure 4.5.14: Highest 24 hourly SO₂ Concentration (µg m⁻³) for April Month with FGD for **Actual Stack Height** (220m for 210MW Stack, 275m for 500MW Stack)

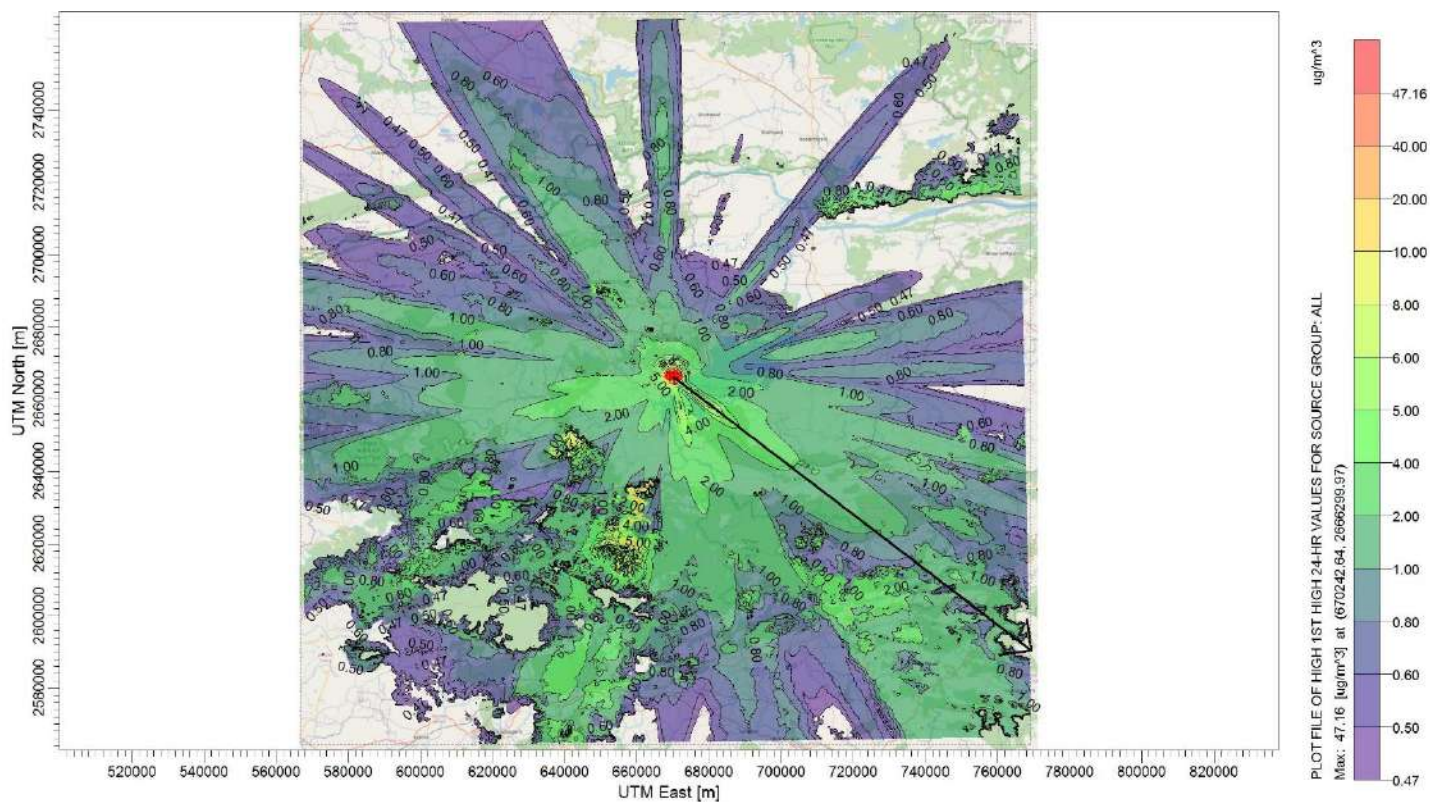


Figure 4.5.15: Highest 24 hourly SO₂ Concentration (µg m⁻³) for April Month with FGD for **1.5 x Actual Stack Height** (330m for 210MW Stack, 413m for 500MW Stack)

2.3 Highest Monthly Average Conc. ($\mu\text{g m}^{-3}$)

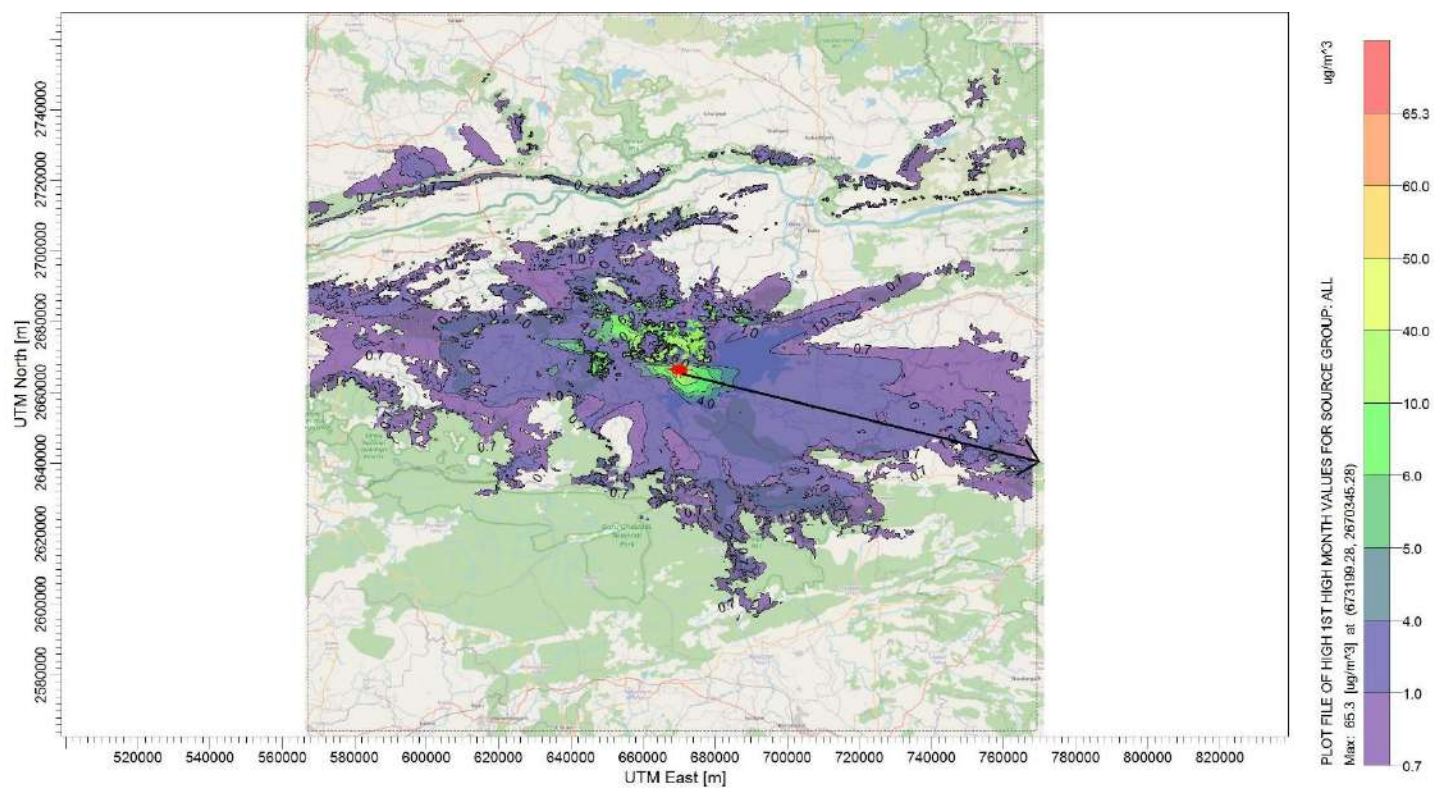


Figure 4.5.16: Highest monthly average SO_2 Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for 0.5 x Actual Stack Height (110m for 210MW Stack, 138m for 500MW Stack)

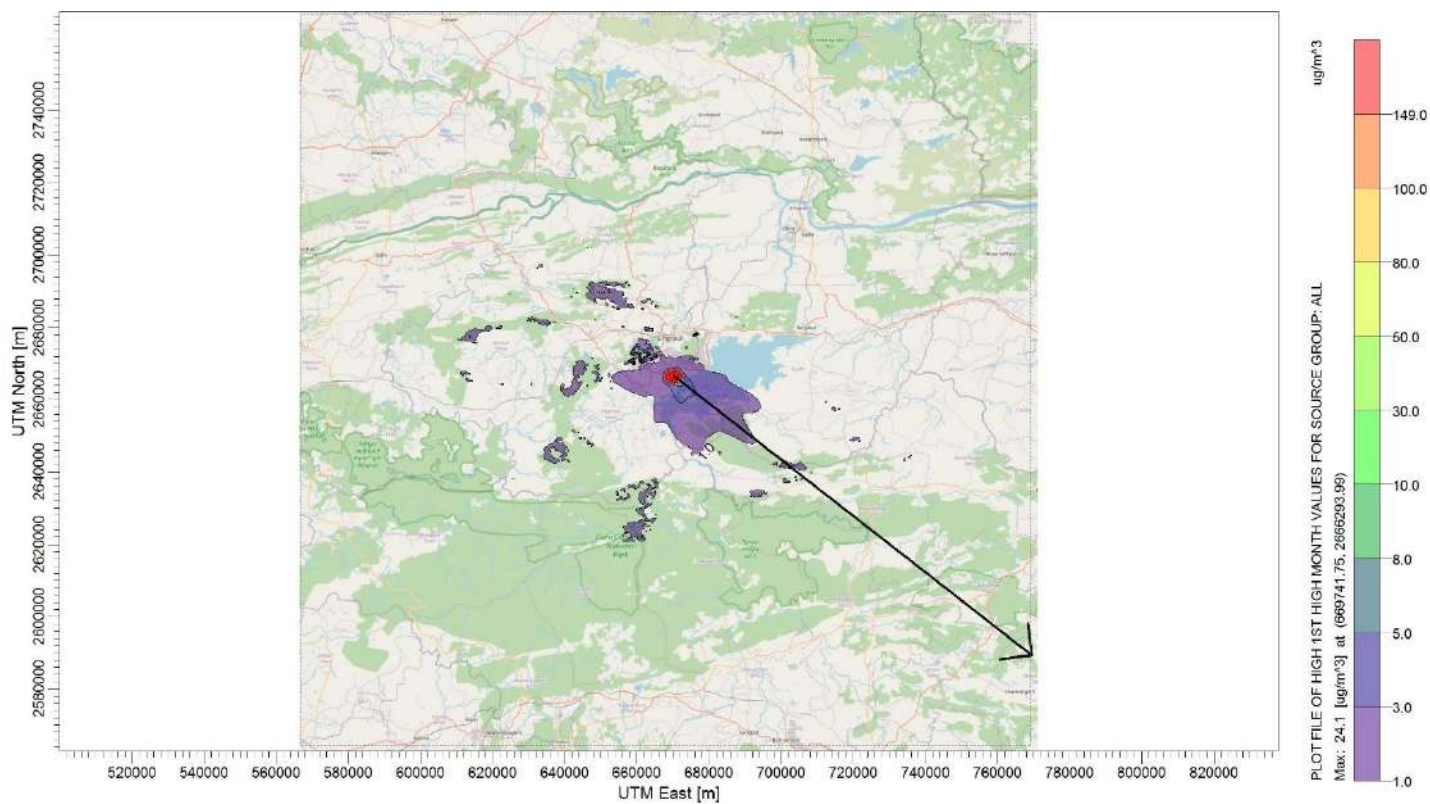


Figure 4.5.17: Highest monthly average SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for **Actual** Stack Height (220m for 210MW Stack, 275m for 500MW Stack)

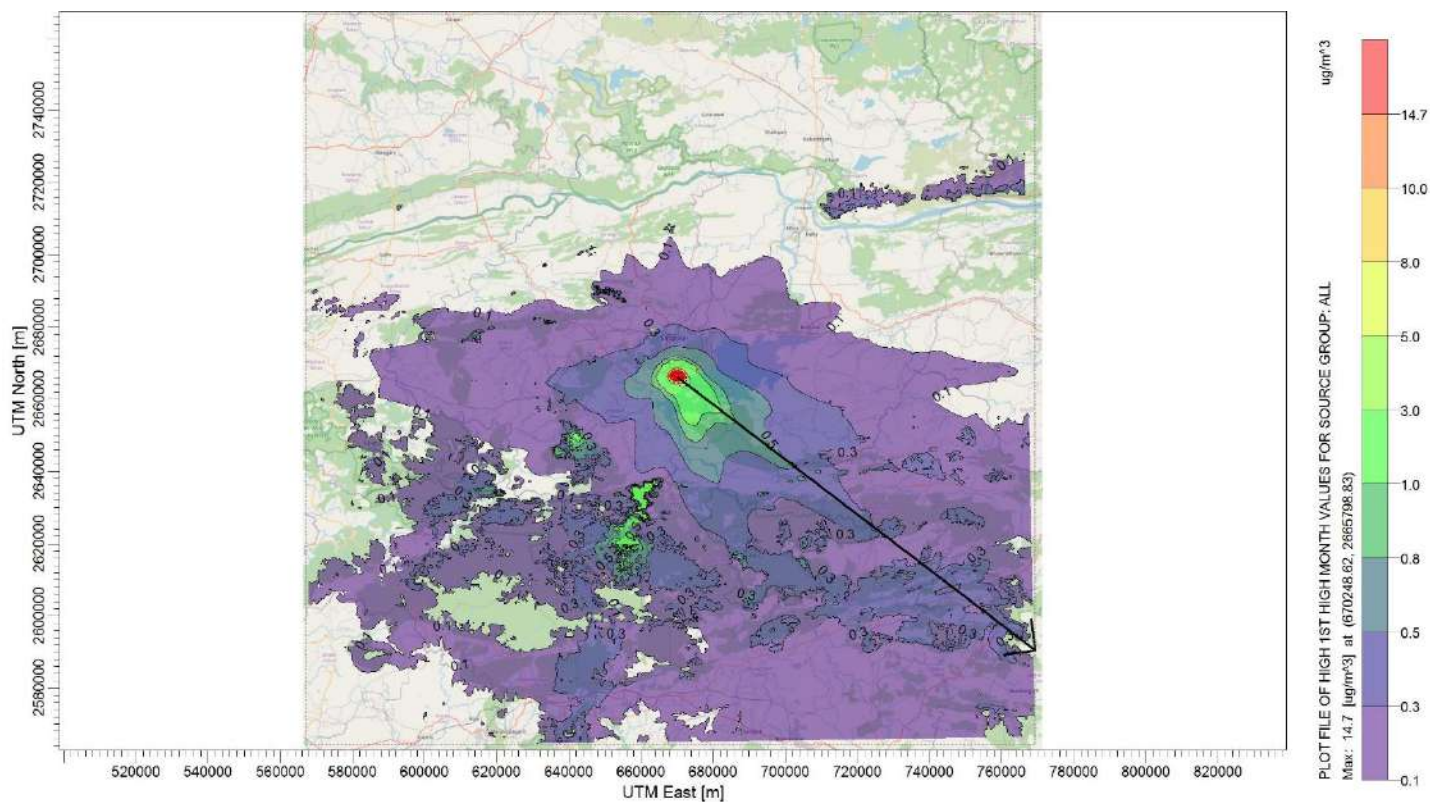


Figure 4.5.18: Highest monthly average SO₂ Concentration ($\mu\text{g m}^{-3}$) for April Month with FGD for **1.5 x Actual** Stack Height (330m for 210MW Stack, 413m for 500MW Stack)

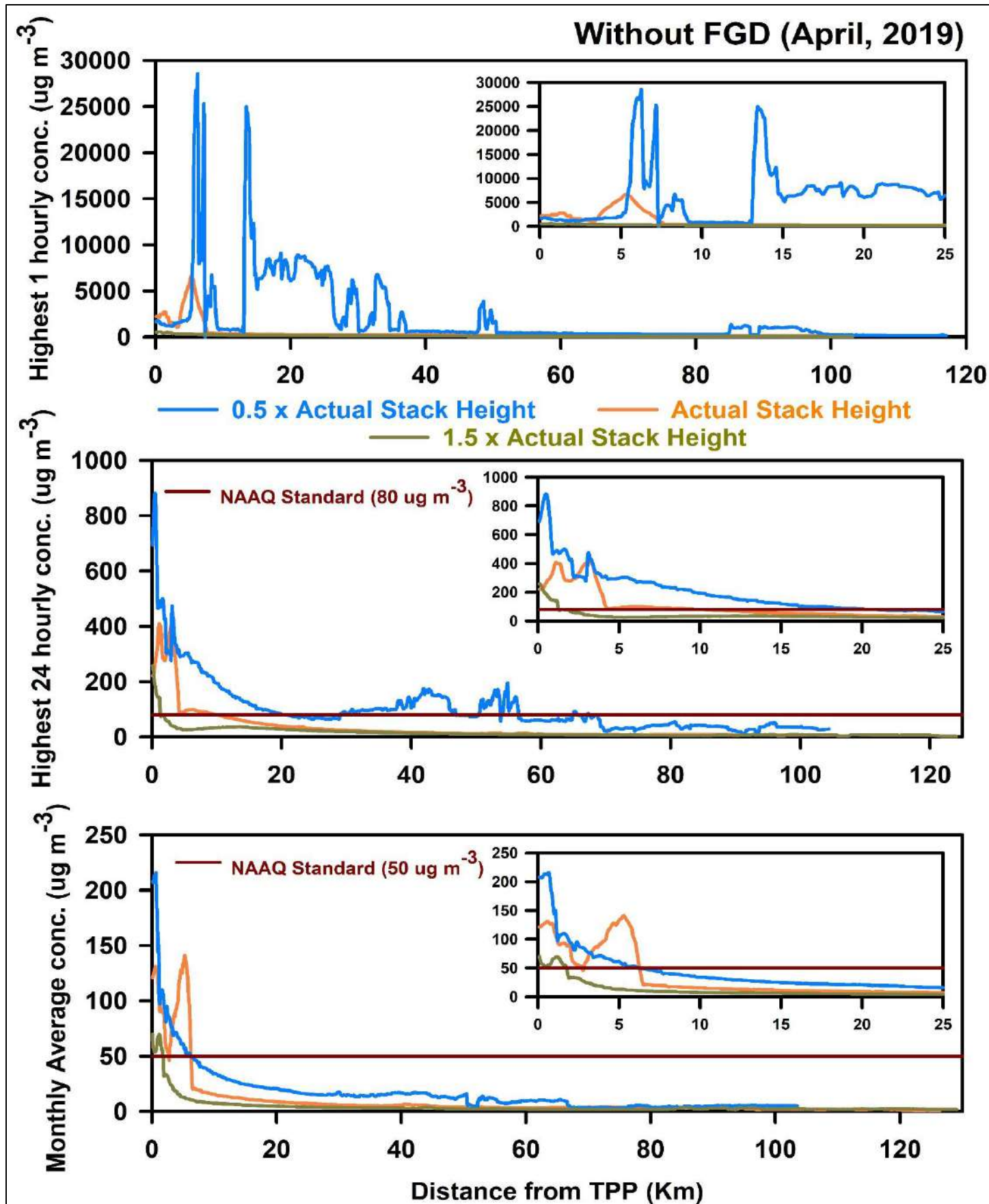


Figure 4.5.19: SO_2 Concentration versus Distance plot for April 2019 (Without FGD)

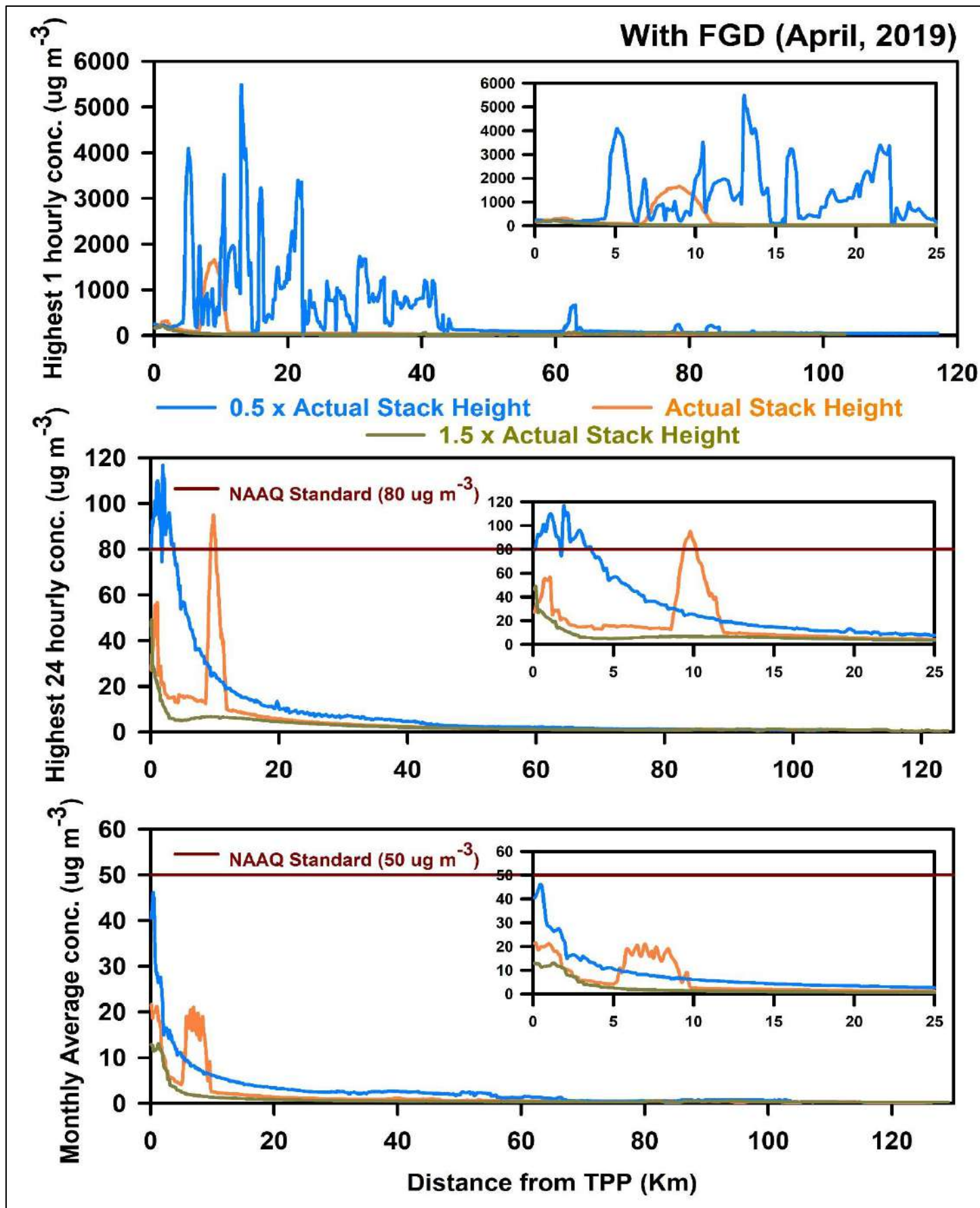


Figure 4.5.20: SO₂ Concentration versus Distance plot for April 2019 (With FGD)

CHAPTER 5: ASSESMENT OF IMPACT OF FGD IMPLEMENTATION IN COAL BASED THERMAL POWER PLANTS ON THE AMBIENT CONCENTRATIONS OF SO₂ AND SULFATE AEROSOL IN THE SURROUNDING REGION USING A CHEMICAL TRANSPORT MODELLING

In this Chapter, we investigate the impact of implementation of flue gas desulfurization (FGD) in coal based thermal power plants (TPPs) across the country on the near surface concentrations of two major air pollutants, namely SO₂ and sulfate aerosols, in the surrounding region of these TPPs by conducting chemical transport model simulations using the Weather Research Forecast model coupled with an atmospheric chemistry module (WRF-Chem). For this purpose, we selected four different TPPs located in four different geographical areas of the country, namely Vindhyachal (Madhya Pradesh), Mundra (Gujarat), Neyveli (Tamil Nadu), and Panipat (Haryana) and conducted two sets of WRF-Chem simulations corresponding to each of these regions by considering FGD system to be implemented and not implemented in these TPPs. A comparison of model output from these two pair of simulations allowed us to understand and quantify the changes in the near surface concentrations of SO₂ and sulfate aerosols that we can expect to see over an area of nearly 500km radius around these TPPs caused by reduction in the emissions of SO₂ with the implementation of FGD in these TPPs.

Model setup and Simulation Details

The Weather Research and Forecasting model coupled with chemistry module (WRF-Chem) is a regional chemical transport and weather prediction system that is designed to serve both operational weather forecasting and atmospheric chemistry research needs (Skamarock, 2008; Powers et al., 2017). In this study, we used WRF-Chem model version 3.8.1 to simulate the meteorology and atmospheric chemistry in a double nested domain setup centred around the selected TPP with the inner domain having a horizontal resolution of 3km x 3km (having 198 × 197 grid cells), the outer domain resolution of 9km x 9km (having 210 × 112 grid cells), and 37 vertical levels (on a hybrid-sigma coordinate system) starting from the surface to about 10 hPa as the model top pressure. We used the ERA-Interim meteorology available at 6 hourly time intervals and with a spatial resolution of 0.25° x 0.25° to provide initial and lateral meteorological boundary conditions to the model. We used previously available results from the Model for Ozone and Related Chemical Tracers – version 4 (MOZART-4) simulations (<http://www.acom.ucar.edu/wrf-chem/mozart.html>) to provide the initial and lateral chemical boundary conditions to our WRF-Chem model simulations (Emmons et al., 2010). Our WRF-Chem simulation setup included the Model of Emissions of Gases and Aerosols from Nature (MEGAN) for online calculation of biogenic emissions and used the Visible and Infrared Imaging Radiometer Suite (VIIRS) data for fire related emissions within the simulation domain. Further, we use the Community Emissions Data System (CEDS) developed for the Coupled Model Intercomparison Project version 6 (CMIP6) for anthropogenic and biomass burning emissions for all chemical species except for Black Carbon (BC) on Organic Carbon (OC). We use the BC and OC emissions based on the Speciated Multipollutant Generator (SMOG – v1) emission inventory for India (Venkataraman et al. 2019). Emissions data from CEDS and SMOG-v1 available up to the year 2015 were extrapolated (based on the trends in emissions between the years 2010 and 2015) to get the emissions data for the simulation year 2019. Various choices of physical and chemical parameterization schemes opted for the WRF-Chem

simulations discussed in this chapter are listed in Table 6.1. Since SMOG-v1 emissions are available only within India, a merged emission inventory was created for this study by taking BC and OC emissions from within India from the SMOG-v1 inventory and emissions from areas outside India taken from the CEDS emission inventory.

Table 5.1: WRF-Chem Physics and Chemistry schemes used in this study

Category	Schemes
Microphysics schemes	Morrison Double-Moment 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
Gas phase chemical mechanism	MOZART + VBS (Volatility Basis Set) for organic aerosol evolution
Aerosol scheme	MOSAIC (4-bin)
Photolysis scheme	Madronich F-TUV photolysis scheme

As mentioned earlier, for each of the selected TPPs, a pair of WRF-Chem simulations are conducted for three different months of the year: first simulation assumes that no FGD system is implemented in the TPP and the second simulation assumes a reduction in emissions of SO₂ from the TPP due to implementation of FGD in the power plant. This reduction in emission of SO₂ from the TPP is estimated by considering FGD efficiency, power production capacity, and the age of the TPP (as the new emission norms issued by MoEF&CC are also based on the age of the TPP). Table 6.2 lists the percentage reduction in SO₂ emission considered for various TPPs in this study corresponding four different geographical areas of the country.

Table 5.2: Percentage Reduction in SO₂ emission considered for various TPPs in this study

Sr. No.	Power Plant location	Percentage Reduction in SO ₂ emission
1	Singrauli, Vindhyachal, Madhya Pradesh	78%
2	Mundra, Gujarat	80%
3	Neyveli, Tamil Nadu	80%
4	Panipat, Haryana	65%

Results and Discussions

1. Vindhyachal TPP, Singrauli (Madhya Pradesh):

The first coal based TPP considered for investigating the impact of FGD implementation and reduced SO₂ emissions from the stacks of the TPP into the ambient atmosphere, on the concentrations of SO₂ and sulfate aerosols over the surrounding region is the Vindhyachal thermal power plant located in Singrauli, Madhya Pradesh, India. This TPP has a power production capacity of 4260 MW and it has geographical co-ordinates of 24.089°N, 82.648°E. The selection of Vindhyachal TPP for this study is based on the fact that it is one of the largest coal based TPP in India and this TPP is located in a region with highest SO₂ atmospheric column burden over India (see Chapter 3) and this region also exhibits the highest increasing trend in SO₂ column burden in India over the last ~20 years (see Chapter 3).

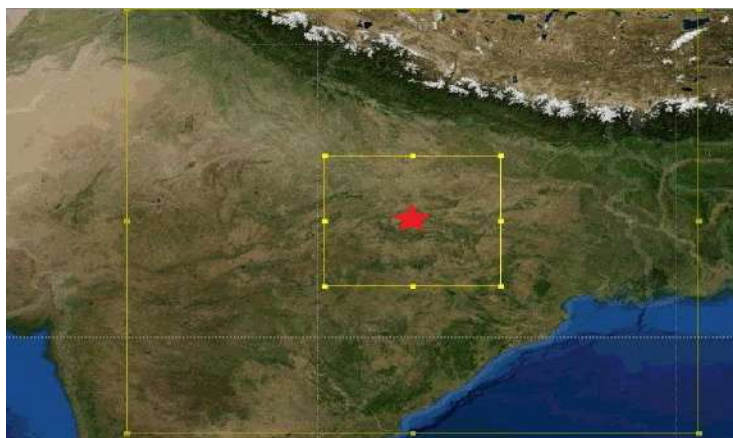


Figure 5.1: Vindhyachal TPP Power Plant location and model domain for WRF-Chem Simulation

Figure 5.1 shows the double nested domain chosen for the WRF-Chem simulation centred around the Vindhyachal thermal power plant (shown using a red colour star in this figure). The light yellow box in Figure 5.1 shows the outer domain having model grid resolution of 9km x 9km (consisting of 210 × 210 grid cells) and the bright yellow box shows the inner domain having model grid resolution of 3km x 3km (consisting of 198 × 198 grid cells).

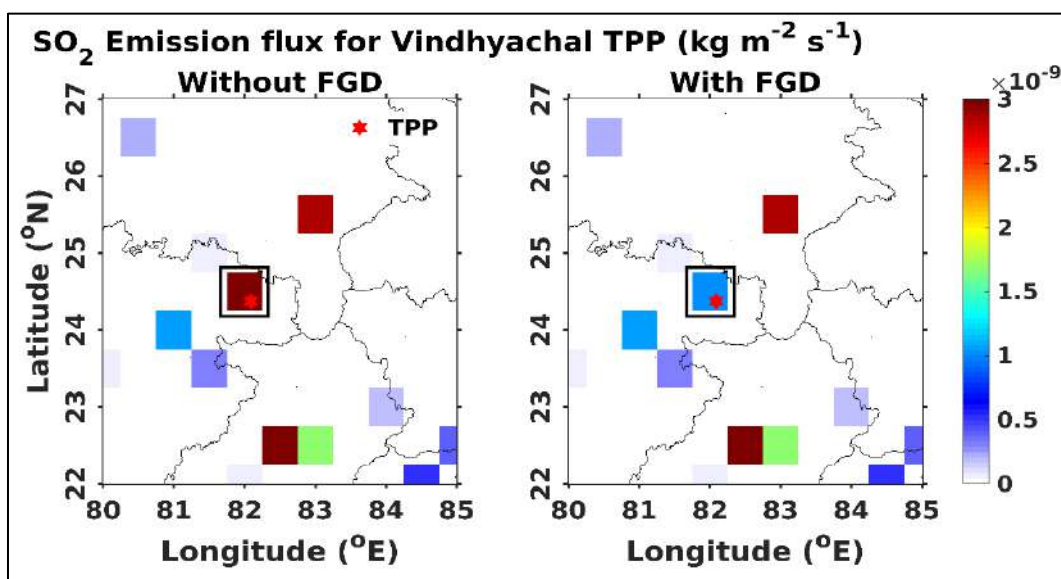


Figure 5.2: Gridded emissions data of SO₂ used in our simulations with and without FGD.

Figure 5.2 shows the gridded SO₂ emission inventory data (CMIP6 + SMOG-v1) for the inner domain of our WRF-Chem simulations conducted with and without FGD system implemented in the Vindhyachal thermal power plant. In the simulation which assumed the FGD system to be implemented in the Vindhyachal thermal power plant, SO₂ emissions from the model grid represented by the TPP has been reduced by 78.75%. This reduction in SO₂ emission from the TPP is estimated after considering FGD efficiency, power production capacity, and age of the particular thermal power plant. Next we compare the absolute values of monthly mean near surface concentration of SO₂ from the pair of WRF-Chem model simulations conducted with and without FGD implementation in the Vindhyachal TPP for January 2019. For both these experiments, simulations start from 16th December 2018, continue up to 1st February 2019 and the results from the last 31 days of the simulations corresponding to 1-31 January 2019 are analysed for understanding the changes in the surface concentrations of SO₂ and sulfate aerosols. Results from the first fifteen days of model output are excluded from our analyses to allow the model to spin up following the initial conditions. Figure 5.3 shows the monthly mean near surface concentration of SO₂ simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. It is evident from Figure 5.3 that the WRF-Chem model is able to capture the hotspot regions with higher SO₂ concentrations around the location of TPPs in both the simulations. It is also evident from Figure 5.3 that the surface concentration of SO₂ decreases significantly (by as much as 10 µg/m³) up to a distance of 60-80 km from the location of the Vindhyachal TPP in the simulation with FGD implemented in this TPP and reduced emission of SO₂ from the grid coinciding with the location of the TPP.

Nevertheless, in order to understand the impact of implementation of FGD in Vindhyachal TPP on the changes in surface concentrations of SO₂ in the surrounding region during the month of January in a better way, we examined the differences in SO₂ concentrations in the surrounding region from simulations conducted with and without FGD implementation in this TPP for January 2019.

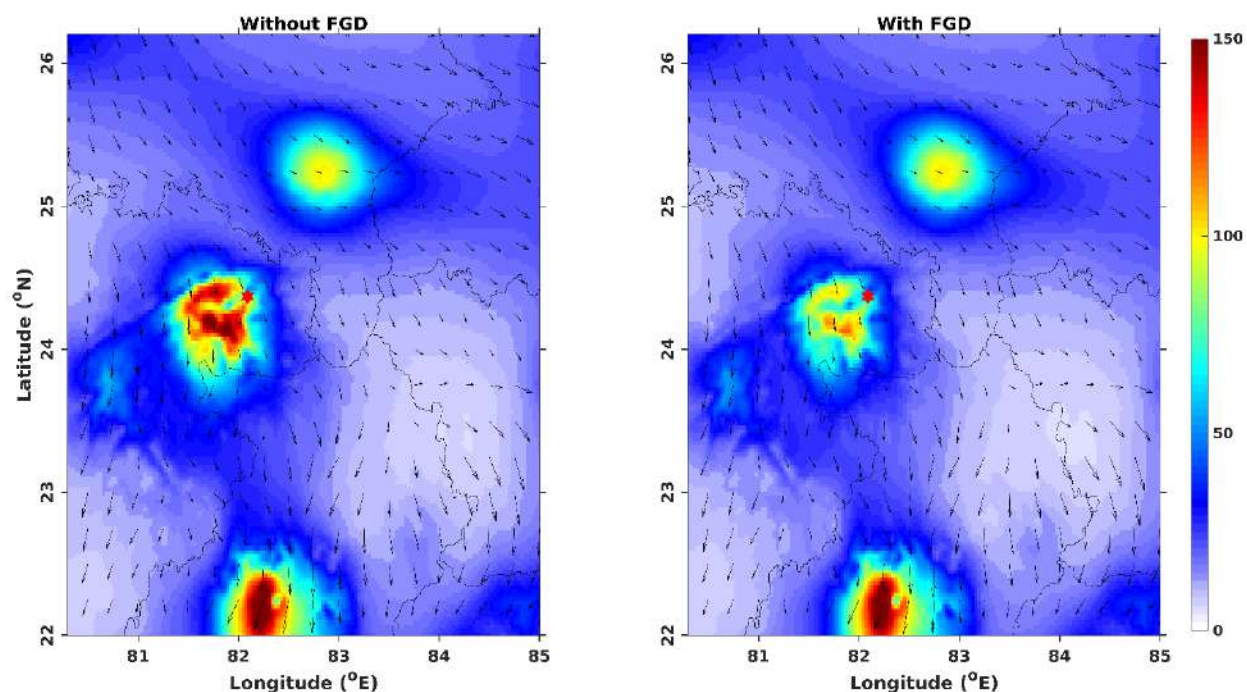


Figure 5.3: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019

Figure 5.4 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (over the inner domain of the model setup as shown in Figure 5.1) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. Negative values for the change in surface concentration of SO_2 as noted in Figure 5.4 are exhibiting a decrease in the concentrations of SO_2 over the surrounding region that we can expect to see with the implementation of FGD in the Vindhyachal TPP. Results of our WRF-Chem simulations show that we can expect to see a decrease in near surface SO_2 concentrations by as much as $40 \mu\text{g}/\text{m}^3$ (or almost up to 27% decrease with respect to without FGD scenario) in the surrounding region with the implementation of FGD in the Vindhyachal TPP. Our results further show that although the implementation of FGD or reduced emission of SO_2 from the Vindhyachal TPP can result in small decreases (up to $1 \mu\text{g}/\text{m}^3$) in SO_2 concentrations in the ambient atmosphere in the downwind areas as far as 200km from the TPP but significant decreases (up to $40 \mu\text{g}/\text{m}^3$) in SO_2 concentrations are likely to occur up to a maximum distance of about 60 km from the location of the Vindhyachal TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

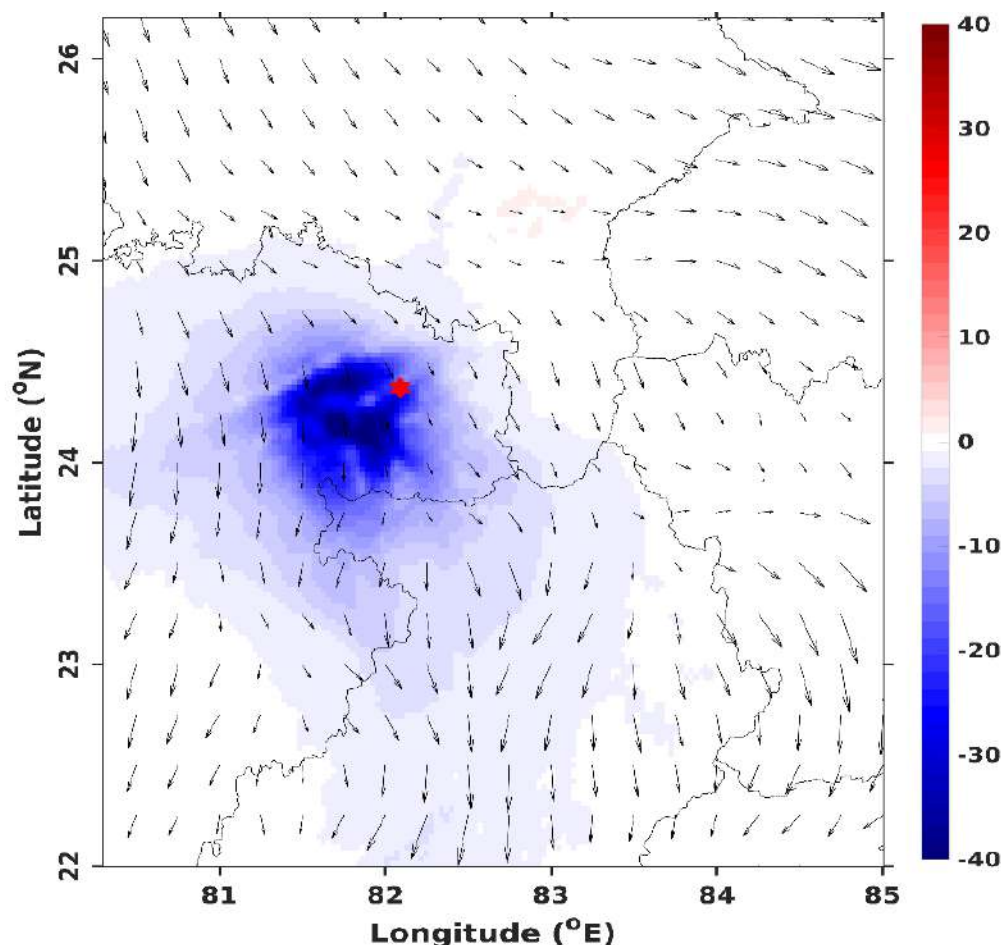


Figure 5.4: *Change in monthly mean surface concentration of SO₂ (in µg/m³) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.*

Next, in order to understand the impact of FGD implementation in Vindhyachal TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of January 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO₂ emitted from coal based TPPs as well as other sources of SO₂. While the primary oxidant responsible for the gaseous phase oxidation of SO₂ in the atmosphere is OH radical, the aqueous phase oxidation of SO₂ largely happens through its reaction with hydrogen peroxide (H₂O₂). Sulphuric acid (H₂SO₄) molecules which form through the oxidation of SO₂ by various oxidants subsequently reacts with ammonia gas (NH₃) and water (H₂O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.5 shows the monthly mean near surface concentration of Sulfate aerosols (in µg/m³) along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. It is evident from Figure 5.5 that sulfate aerosol concentrations are quite high

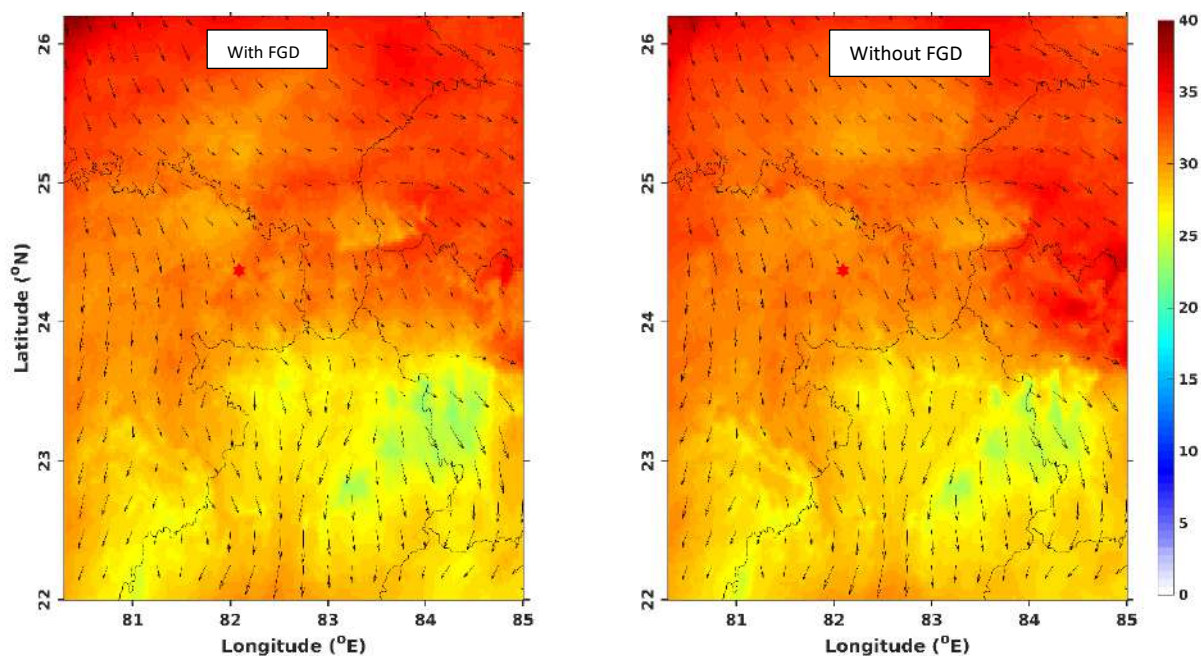


Figure 5.5: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhachal TPP for January 2019

across the inner domain of our WRF-Chem simulation setup with values ranging from 15-40 $\mu\text{g}/\text{m}^3$ during the month of January and higher values are generally noted in the upper half of our domain. Wind patterns during January suggest that the low level (850 hPa and below) winds are predominantly north-westerly or westerly in the upper half of the domain and it is largely northerly in the lower half of the model domain. That means air pollution from upwind areas in the north and north-west parts of the Vindhachal TPP can reach the location of the TPP and air pollutants emitted from this TPP are more likely to be dispersed in the downwind areas which are in the eastern and southern directions of the TPP in the month of January.

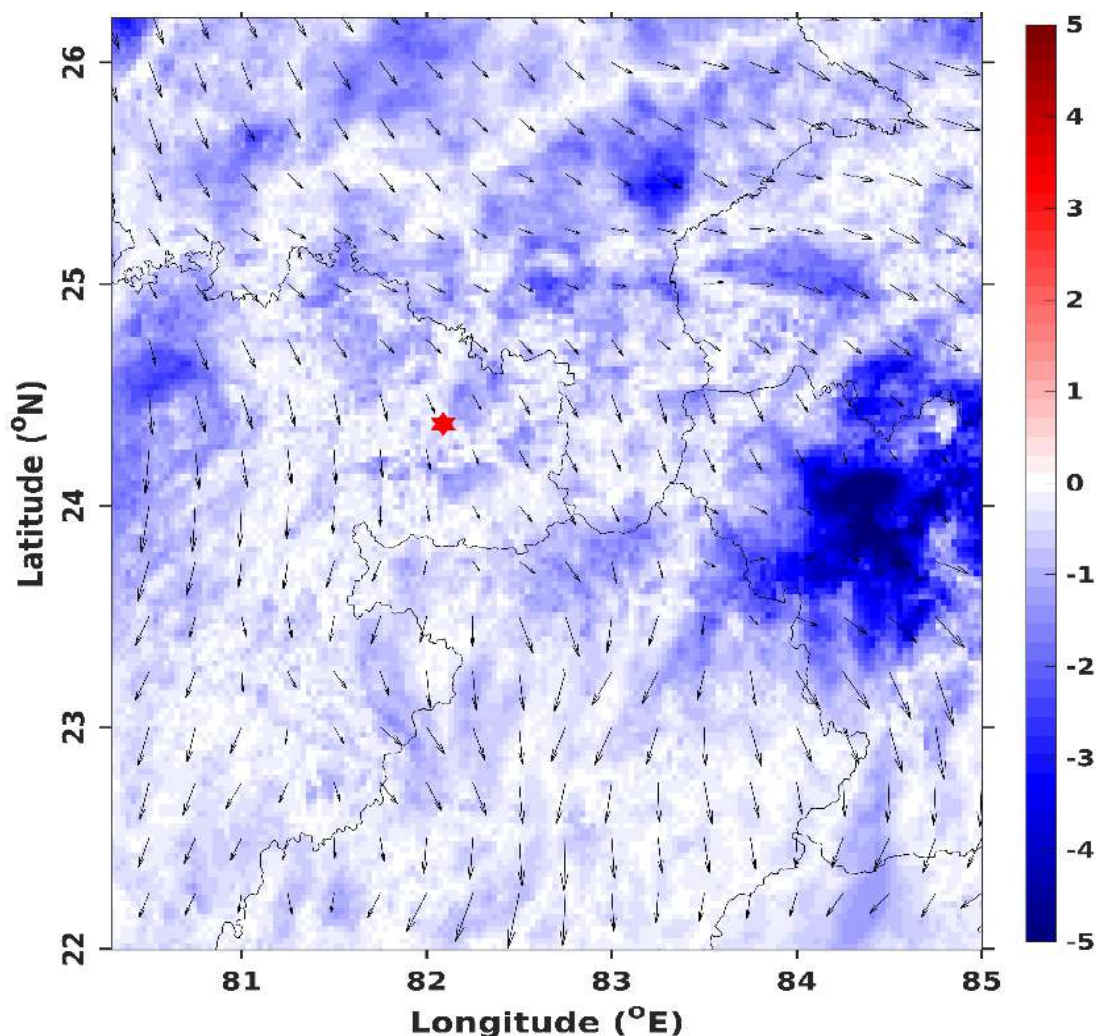


Figure 5.6: *Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.*

Figure 5.6 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for the month of January 2019. Negative values of change in surface concentration of sulfate aerosols across the domain as shown in Figure 5.6 are suggesting that we can expect to see mostly a decrease in the surface concentrations of sulfate aerosols in the surrounding region with the implementation of FGD in the Vindhyachal TPP. Our results are further suggesting that with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by as much as $5 \mu\text{g}/\text{m}^3$ at some places in the surrounding region of the TPP. In other words, with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by up to 12% of the climatological values at certain places which are as far as 200 Km from the location of this TPP. Thus our results show that with the implementation of FGD in the Vindhyachal TPP, while the significant decreases in SO_2 concentrations are mostly

confined in the immediate surrounding areas of the TPP and up to a maximum distance of 60-80 km from the location of the TPP in the direction of maximum dispersal of the air pollutants but, significant decreases in the surface concentrations of sulfate aerosols can be expected at locations which could be as far as 200 Km from the location of this TPP. This happens because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants such as OH radical, hydrogen peroxide (H_2O_2), ozone (O_3), water vapor (H_2O), other reactive gases such as NH_3 , meteorological conditions such as wind speed, wind direction, relative humidity, sunlight and clouds. All these factors influence the atmospheric chemistry involved in the formation of sulfate aerosols in the atmosphere and we noted small but finite differences in most of these factors across the region between the two simulations. Additional model sensitivity simulations are required to explain the sensitivity of sulfate aerosol concentrations to each of these factors but these are beyond the scope of the present study and hence this task will be taken up later as part of a separate investigation.

In order to understand the impact of FGD implementation and reduced SO_2 emissions from the Vindhyachal TPP on the near surface concentrations of SO_2 and sulfate aerosols over the surrounding region during other times of the year, we conducted additional model simulations for two other months, namely July and October 2019. We decided to carry out these additional simulations because the meteorological conditions across India vary greatly as a function of the time of the year and the dispersion of air pollutants as well as formation of secondary pollutants both depend on various meteorological conditions which are different during different seasons of the year.

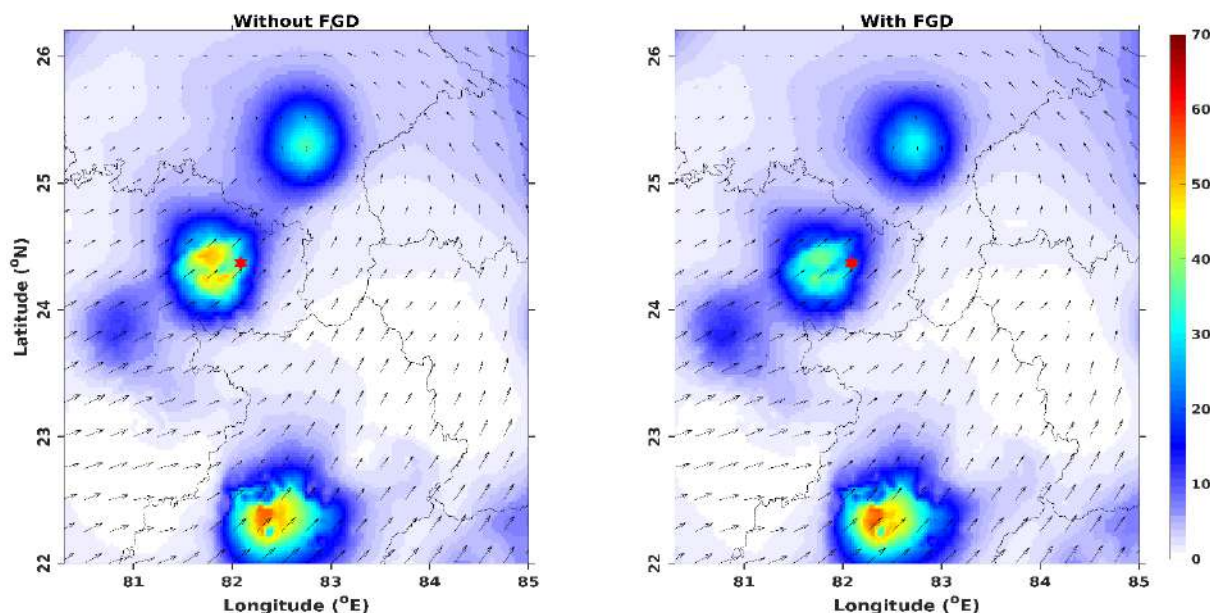


Figure 5.7: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for July 2019

Figure 5.7 shows the monthly mean surface concentration of SO_2 inside the inner domain of our model setup (see Figure 5.1) for WRF-Chem simulations conducted with and without FGD implemented in the Vindhyachal TPP for the month of July 2019. Once again, it is evident from Figure 5.7 that the WRF-Chem model is able to capture the hotspot regions with higher SO_2 concentrations around the location of TPPs in both the simulations. It is also evident from Figure 5.7 that the surface concentration of SO_2 decreases significantly (by as much as $15 \mu\text{g}/\text{m}^3$) up to a distance of 60-80 km from the location of the Vindhyachal TPP in the simulation with FGD implemented in this TPP and reduced SO_2 emissions. However, in order to understand the impact of FGD implementation in the Vindhyachal TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of July in a better way, we analysed the differences in SO_2 concentrations from simulations conducted with and without FGD implementation in this TPP for July 2019.

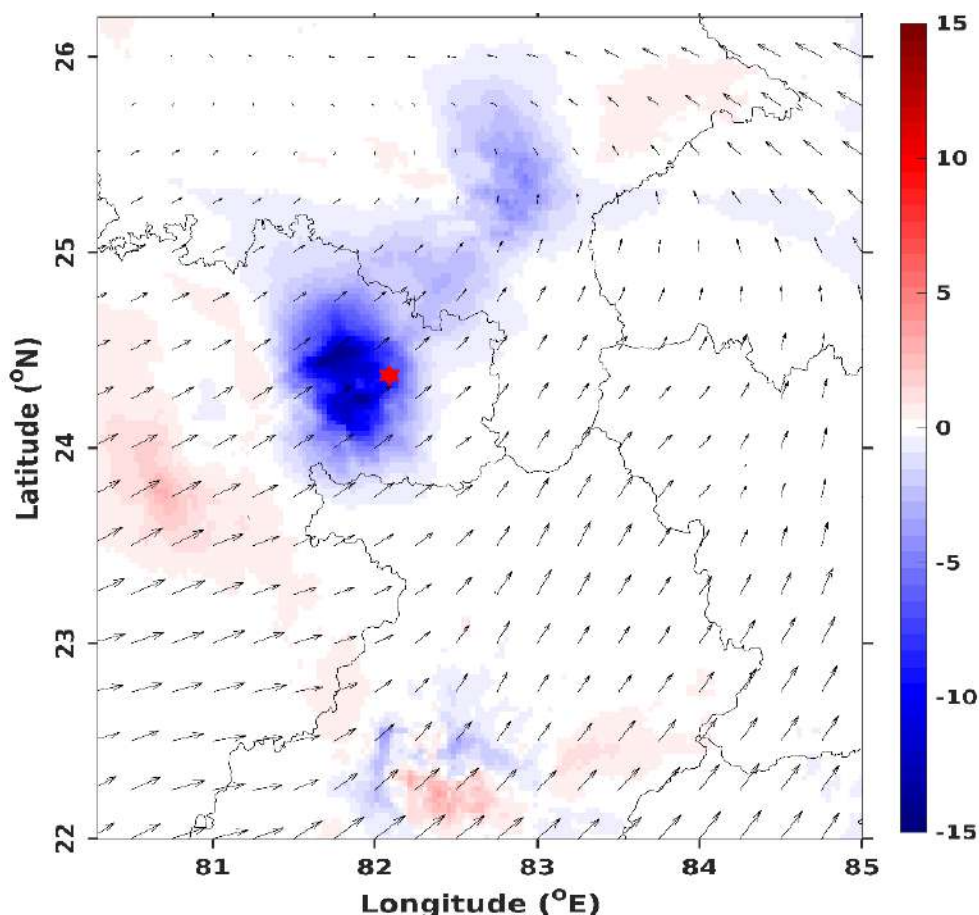


Figure 5.8: Change in monthly mean surface concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for July 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

Figure 5.8 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (inner domain of the model setup as shown in Figure 5.1) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for January 2019. Negative (positive) values for the change in surface concentration of SO_2 as noted in Figure 5.8 are exhibiting decreases (increases) in SO_2 concentrations over the surrounding region

that we can expect to see with the implementation of FGD in the Vindhyachal TPP. Results of our simulations show that we can expect a decrease in near surface SO_2 concentrations by as much as $15 \mu\text{g}/\text{m}^3$ in the surrounding region with the implementation of FGD in the Vindhyachal TPP. That means we can expect to notice a decrease in near surface SO_2 concentrations by up to 21% with respect to the concentrations under business as usual scenario without FGD implementation in this TPP. Our results further show that although the implementation of FGD or reduced emission of SO_2 from the Vindhyachal TPP can result in small decreases (up to $1 \mu\text{g}/\text{m}^3$) in SO_2 concentrations in the ambient atmosphere in the downwind areas as far as 100 Km from the location of the TPP but significant decreases (up to $15 \mu\text{g}/\text{m}^3$) in SO_2 concentrations are likely to occur only up to a distance of about 50 km from the location of the Vindhyachal TPP in the direction of maximum dispersal of the air pollutant during the month of July. Interestingly, in contrast to the overwhelming decreases in the concentrations of SO_2 noted across the simulation domain during the month of January (see Figure 5.4), increases in SO_2 concentrations by up to $3 \mu\text{g}/\text{m}^3$ are also noted at some locations within the model domain in addition to the predominant decreases (up to $15 \mu\text{g}/\text{m}^3$) in SO_2 concentrations occurring with the implementation of FGD during July month (Figure 5.8). These small increases in SO_2 concentrations at a few locations within the model domain (usually at distances greater than 60-80 Km from the TPP) are likely to have happened due to small differences in meteorology between the two simulations which in turn has affected the transport and removal of air pollutants from the atmosphere.

Next, in order to understand the impact of FGD implementation in Vindhyachal TPP on the surface concentrations of sulfate aerosols over the surrounding region in the month of July, first we compare the absolute values of monthly mean sulfate aerosol concentrations from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of July 2019. Figure 5.9 shows the monthly mean near surface concentration of sulfate aerosols simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for July 2019. It is evident from Figure 5.9 that sulfate aerosol concentrations are quite high across the inner domain of our WRF-Chem simulation setup with values ranging from $5\text{--}40 \mu\text{g}/\text{m}^3$ during the month of July with higher values in the northern half of the simulation domain. It is also evident from Figures 6.5 and 6.9 that surface concentration of sulfate aerosols across the domain is higher in the month of January as compared to July. This happens due to efficient scavenging of air pollutants from the atmosphere by higher precipitation and wind speed over this region during the month of July as compared to January. Wind patterns during July suggest that the low level winds are predominantly south-westerly across the model domain.

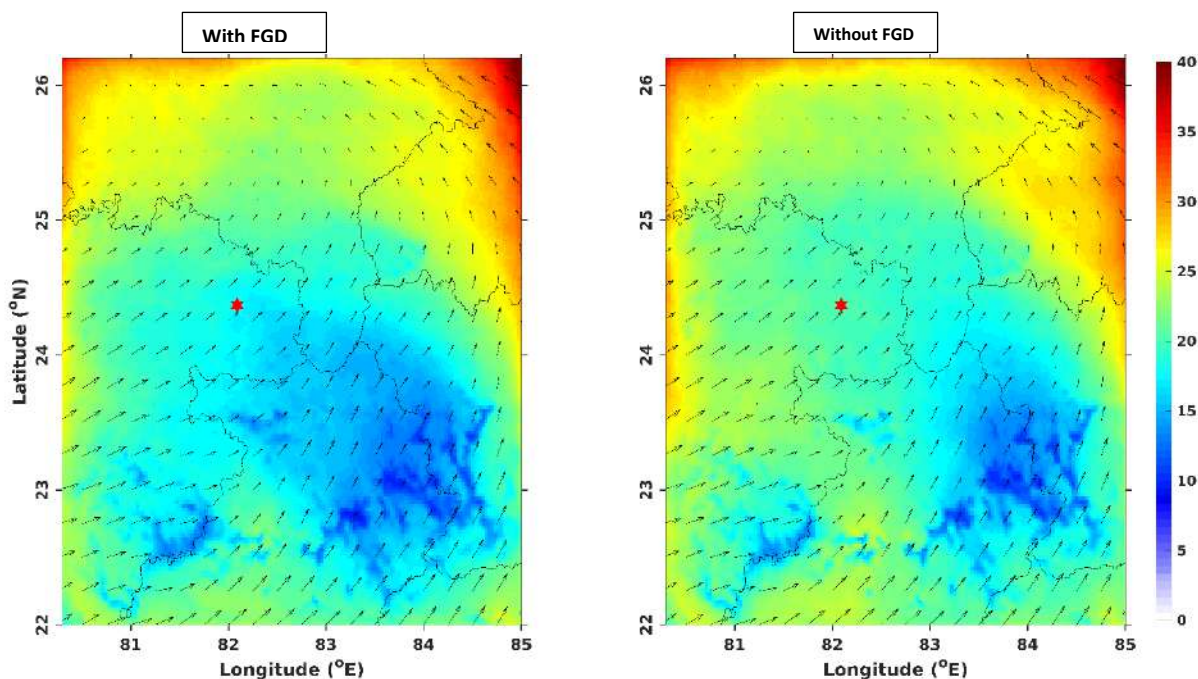


Figure 5.9: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for July 2019

Figure 5.10 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for the month of July 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as evident from Figure 5.10 clearly indicates that the implementation of FGD in the Vindhyachal TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Vindhyachal TPP, monthly mean surface concentrations of sulfate aerosols could decrease by as much as $8 \mu\text{g}/\text{m}^3$ at some places which could be as far as 100 Km from this TPP. That means with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by up to 30% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are as far as 100 Km from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the southern direction of this TPP. As noted earlier for the month of January, decreases in sulfate aerosol concentrations are more widespread across the domain as compared to the decreases in SO_2 concentrations in the month of July as well. While decreases in SO_2 concentrations are largely restricted up to a distance of about 60-80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are noted as far as 200 km from the TPP. This happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions and differences are noted in most of these factors between the two simulations.

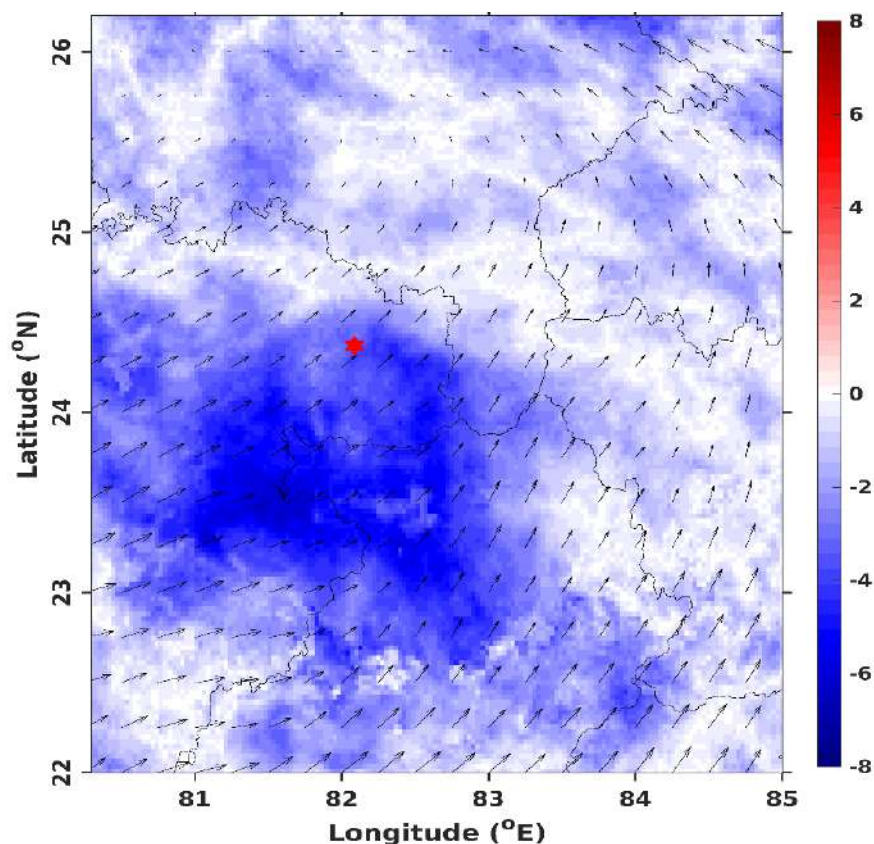


Figure 5.10: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for July 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

In order to understand the impact of FGD implementation and reduced SO_2 emissions from the Vindhyachal TPP on the near surface concentrations of SO_2 and sulfate aerosols over the surrounding region during other times of the year, we conducted additional model simulations for the month October 2019. We decided to carry out these additional simulations because the meteorological conditions over our study region vary greatly with time of the year and the dispersion of air pollutants as well as formation of secondary pollutants in the atmosphere depend on various meteorological conditions which are different during different seasons of the year. Figure 5.11 shows the monthly mean surface concentration of SO_2 inside the inner domain of our model setup (see Figure 5.1) for WRF-Chem simulations conducted with and without FGD implemented in the Vindhyachal TPP for the month of October 2019.

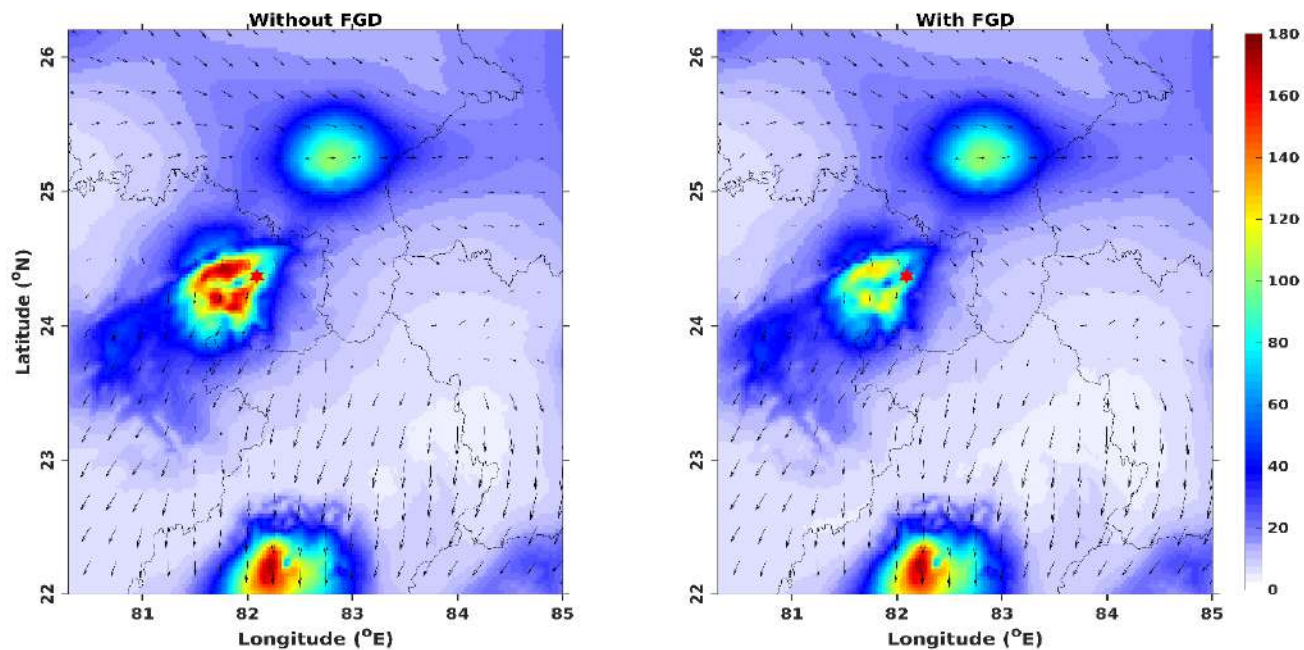


Figure 5.11: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for October 2019

Once again, it is evident from Figure 5.11 that the WRF-Chem model is able to capture the hotspot regions with higher SO_2 concentrations around the location of TPPs in both the simulations. Comparing the SO_2 concentrations simulated by the model in the three months (January, July, and October), we find that higher concentrations of SO_2 are present across the region during both January and October months as compared to July month. This happens due to weaker northerly winds prevalent within the atmospheric boundary layer resulting in slow dispersion of air pollutants as well as lesser rainfall during these months reduces the wet scavenging of air pollutants from the atmosphere during January and October as compared to July month. It is also evident from Figure 5.11 that the surface concentration of SO_2 decreases significantly (by as much as $30 \mu\text{g}/\text{m}^3$) up to a distance of 60-80 km from the location of the Vindhyachal TPP in the simulation which considers reduced SO_2 emissions due to FGD implemented in this power plant.

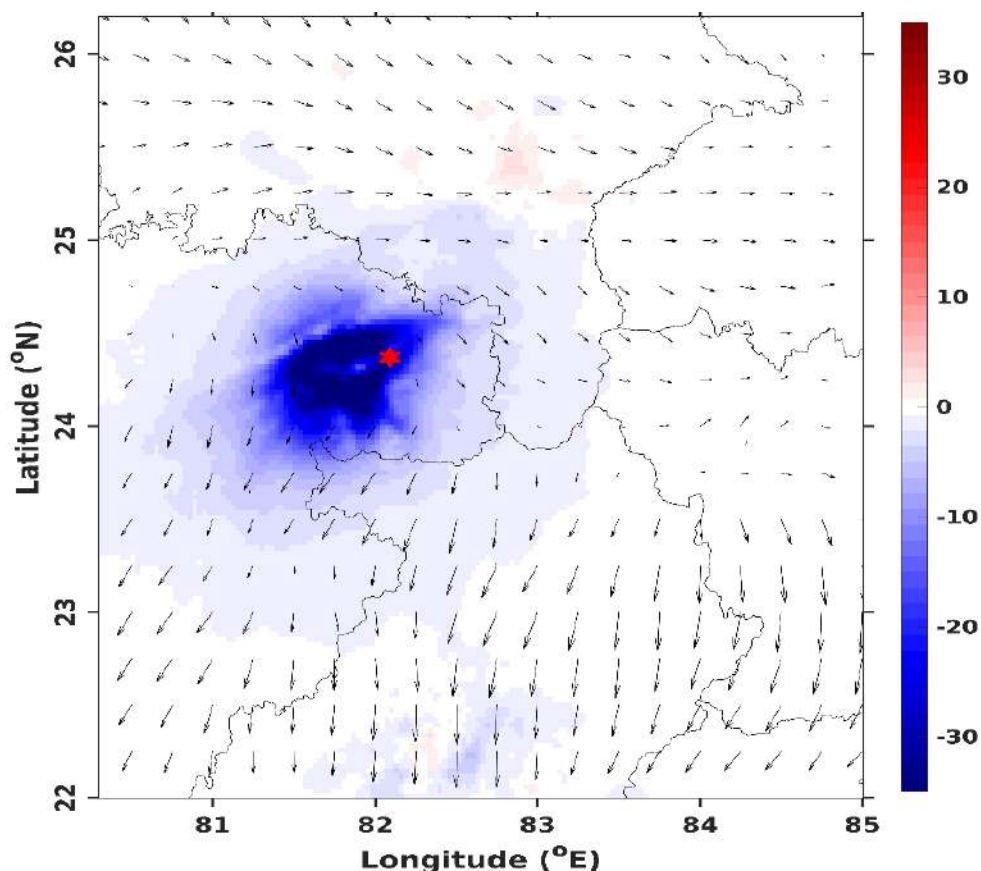


Figure 5.12: Change in monthly mean surface concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for October 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

However, in order to understand the impact of FGD implementation in the Vindhyachal TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of October in a better way, we plotted the differences in SO_2 concentrations over the surrounding region from simulations conducted with and without FGD implementation in this TPP for October 2019. Figure 5.12 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (over the inner domain of the model setup as shown in Figure 5.1) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for October 2019. Negative values for the change in surface concentration of SO_2 as noted in Figure 5.12 are exhibiting a decrease in the surface concentrations of SO_2 over the surrounding region that we can expect to see with the implementation of FGD in the Vindhyachal TPP during the month of October. Results of our simulations show that we can expect to see a decrease in surface concentrations of SO_2 by as much as $35 \mu\text{g}/\text{m}^3$ (nearly 20% decrease with respect to a no FGD scenario) in the surrounding region with the implementation of FGD in the Vindhyachal TPP. It is also evident from Figure 5.12 that although the implementation of FGD or reduced emission of SO_2 from the Vindhyachal TPP can result in small decreases (up to $1 \mu\text{g}/\text{m}^3$) in SO_2 concentrations in the ambient atmosphere in the downwind areas as far as 200 Km from the TPP but significant decreases (up to $35 \mu\text{g}/\text{m}^3$) in SO_2 concentrations are likely to occur maximum up to a distance of about 60 km from the

location of the Vindhychal TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

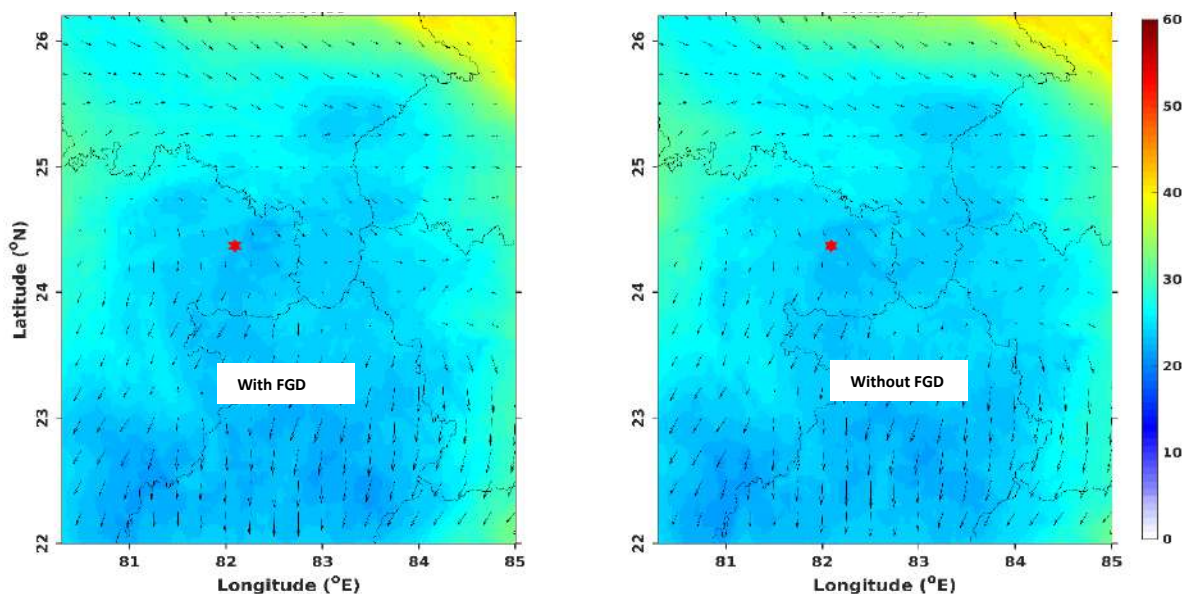


Figure 5.13: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhychal TPP for October 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

Figure 5.13 shows the monthly mean near surface concentration of sulfate aerosols simulated by the WRF-Chem model with and without FGD implemented in the Vindhychal TPP for October 2019. It is evident from Figure 5.13 that sulfate aerosol concentrations are quite high across the inner domain of our WRF-Chem simulation setup with values ranging from 5-50 $\mu\text{g}/\text{m}^3$ during the month of October with higher values in the north-west part of the simulation domain. It is also evident from Figures 6.5, 6.9, and 6.13 that surface concentration of sulfate aerosols across the domain is highest in the month of January, followed by October and lowest in the month of July. This happens due to efficient scavenging of air pollutants from the atmosphere by higher precipitation and wind speed over this region during the month of July as compared to January. Wind patterns during October suggest that the low level winds are predominantly northerly or north easterly across the model domain thereby suggesting that the maximum dispersion of air pollutants originating from the Vindhychal TPP are likely to be in the southern and eastern sides of this power plant during this month.

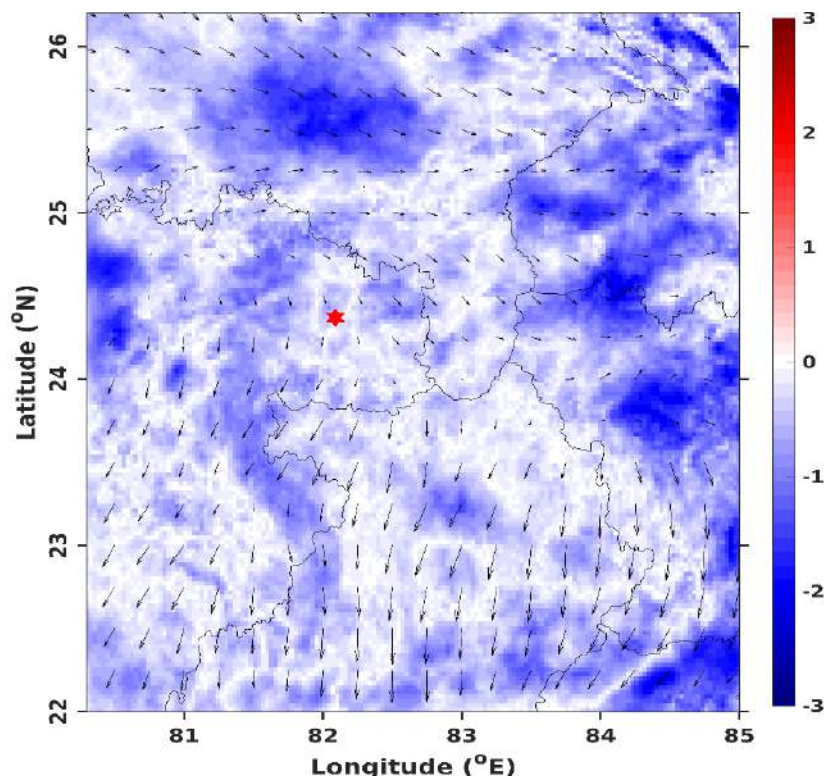


Figure 5.14: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for October 2019.

Figure 5.14 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Vindhyachal TPP for the month of November 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as noticeable in Figure 5.14 suggests that the implementation of FGD in the Vindhyachal TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Vindhyachal TPP, monthly mean surface concentrations of sulfate aerosols could decrease by up to $3 \mu\text{g}/\text{m}^3$ at some places which could be at distances more than 100 Km from this TPP. That means with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by up to 5% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are over 100 Km distant from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the south eastern direction of this TPP. As noted earlier for the month of January, decreases in sulfate aerosol concentrations are more widespread across the domain as compared to the decreases in SO_2 concentrations in the month of October as well. While decreases in SO_2 concentrations are largely restricted up to a distance of about 60-80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are noted as far as 200 km from the TPP. Once again this happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions the

atmosphere and differences are noted in most of these factors between the two simulations conducted with and without FGD implemented in the Vindhyachal TPP.

2. Mundra TPP (Gujarat):

The second coal based TPP considered for investigating the impact of FGD implementation and reduced SO₂ emissions from the stacks of the TPP into the ambient atmosphere, on the concentrations of SO₂ and sulfate aerosols over the surrounding region is the Mundra thermal power plant located in Mundra, Gujarat, India with approximate geographical co-ordinates of 22.82 °N, 69.55 °E. There are actually two separate coal based TPPs located very close to each other in Mundra. First one is the Tata Power plant named Mundra UMTTP having a capacity of 4000MW with five stacks of 800MW capacity each and the second one is Adani Power Ltd TPP named Mundra TPS has a capacity of 4620MW with nine stacks (four-330MW and five-660MW). The selection of Mundra TPP for this study is based on the fact that these are among the largest coal based TPPs in the state of Gujarat and this TPP is located in a completely different geographical region experiencing different meteorological variations as compared to the previous Vindhyachal TPP. Mundra TPP is also located in a region that exhibits an increasing trend in SO₂ column burden in India over the last ~20 years (see Chapter 3). Since the Mundra UMTTP and Mundra TPS are located so close to each other, for the purposes of the present study, we have assumed them to be as one TPP.

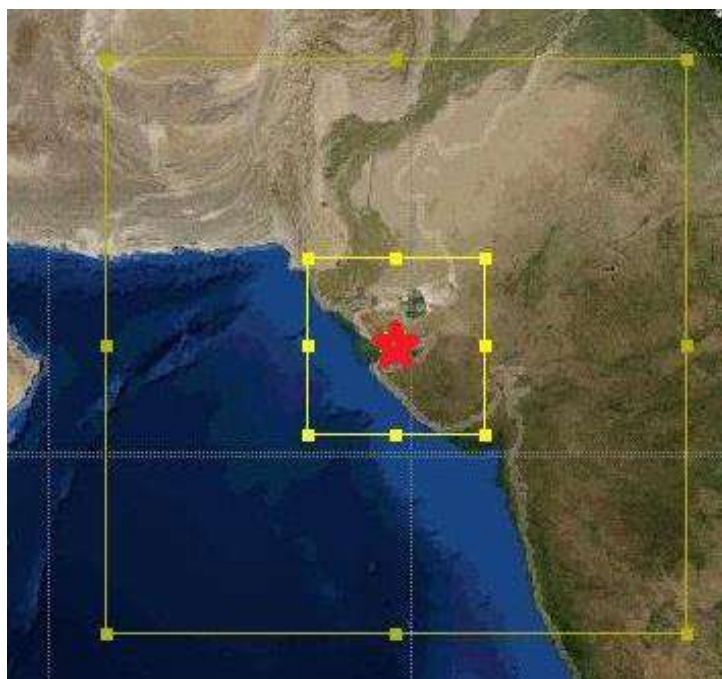


Figure 5.15: Mundra TPP Power Plant location and model domain for WRF-Chem Simulation

Figure 5.15 shows the double nested domain chosen for the WRF-Chem simulation centred around the Mundra thermal power plant (shown using a red colour star in this figure). The light yellow box in Figure 5.1 shows the outer domain having model grid resolution of 9km

x 9km (consisting of 180×180 grid cells) and the bright yellow box shows the inner domain having model grid resolution of 3km x 3km (consisting of 166×166 grid cells). Figure 5.16 shows the gridded SO₂ emission inventory data (CMIP6 + SMOG-v1) for the inner domain of our WRF-Chem simulations conducted with and without FGD system implemented in the Mundra thermal power plant. In the simulation which assumed the FGD system to be implemented in the Mundra thermal power plant, SO₂ emissions from the model grid represented by the TPP has been reduced by 80%. This reduction in SO₂ emission from the Mundra TPP is estimated after considering FGD efficiency, power production capacity, and age of this particular TPP.

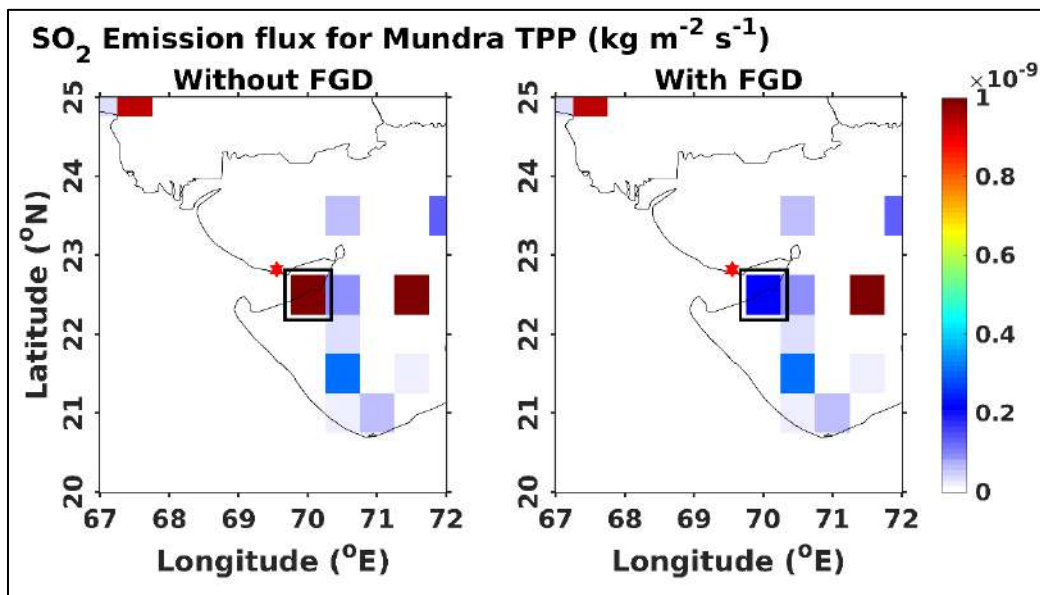


Figure 5.16: Gridded emissions data of SO₂ used in our simulations with and without FGD.

Next we compare the monthly mean near surface concentration of SO₂ from the pair of WRF-Chem model simulations conducted with and without FGD implementation in the Mundra TPP for July 2019. For both these experiments, simulations started from 16th June 2019, continued up to 1st August 2019 and the results from the last 31 days of the simulations corresponding to the period 1-31 July 2019 are analysed for understanding the changes in the surface concentrations of SO₂ and sulfate aerosols with the implementation of FGD in the Mundra TPP. Results from the first fifteen days of model output are excluded from our analyses to allow the model to spin up following the initial conditions. Figure 5.17 shows the monthly mean near surface concentration of SO₂ simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019. It is evident from Figure 5.17 that the WRF-Chem model is able to capture the hotspot regions with higher SO₂ concentrations around the location of TPPs in both the simulations. It is also evident from Figure 5.17 that the surface concentration of SO₂ decreases significantly (by as much as 5 µg/m³) up to a distance of 60-80 Km from the location of the Mundra TPP in the simulation with FGD implemented in this TPP and reduced emission of SO₂ from this power plant.

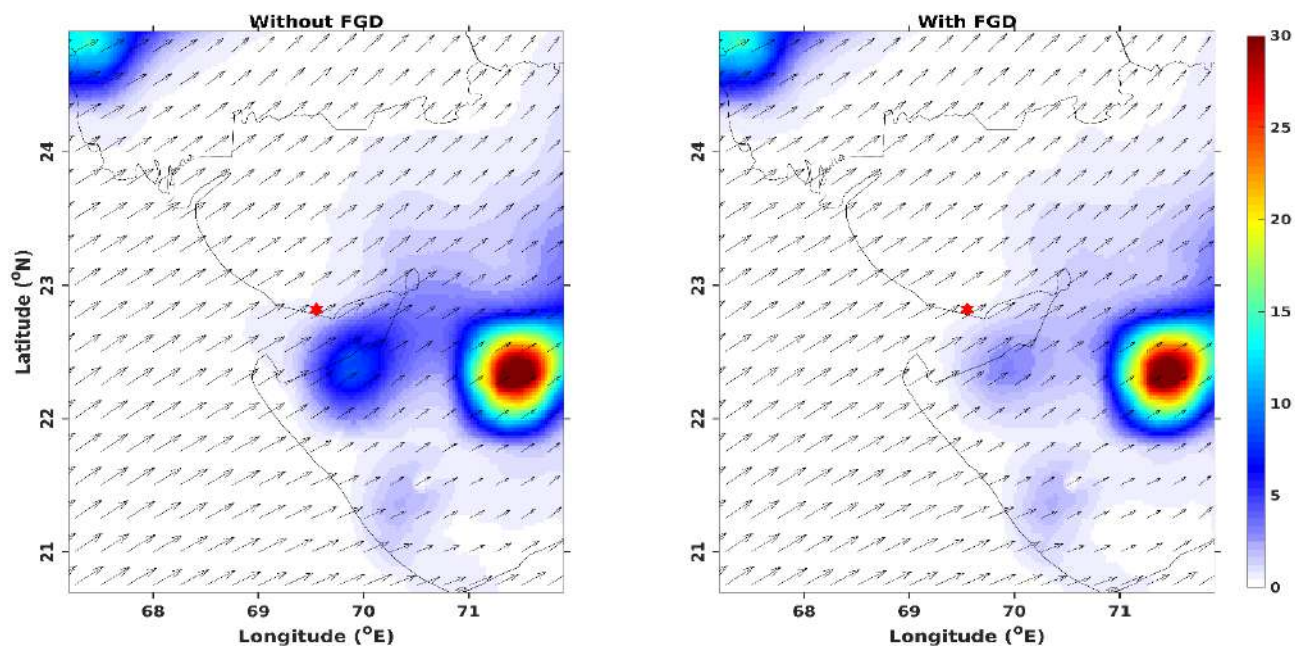


Figure 5.17: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019

Nevertheless, in order to understand the impact of implementation of FGD in Mundra TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of July in a better way, we examined the differences in SO_2 concentrations in the surrounding region from simulations conducted with and without FGD implementation in this TPP for July 2019. Figure 5.18 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (over the inner domain of the model setup as shown in Figure 5.15) as simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019. Negative values for the change in surface concentration of SO_2 as noted in Figure 5.18 are exhibiting a decrease in the concentrations of SO_2 over the surrounding region that we can expect to see with the implementation of FGD in the Mundra TPP. Results of our WRF-Chem simulations show that we can expect to see a decrease in near surface SO_2 concentrations by as much as $5 \mu\text{g}/\text{m}^3$ (that means a decrease by almost up to 38% with respect to without FGD scenario) in the surrounding region with the implementation of FGD in the Mundra TPP. Our results further show that although the implementation of FGD or reduced emission of SO_2 from the Mundra TPP can result in small decreases (up to $0.5 \mu\text{g}/\text{m}^3$) in SO_2 concentrations in the ambient atmosphere in the downwind areas as far as 200 Km from the TPP but significant decreases (up to $5 \mu\text{g}/\text{m}^3$) in SO_2 concentrations are likely to occur up to a maximum distance of about 60 km from the location of the Vindhyachal TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

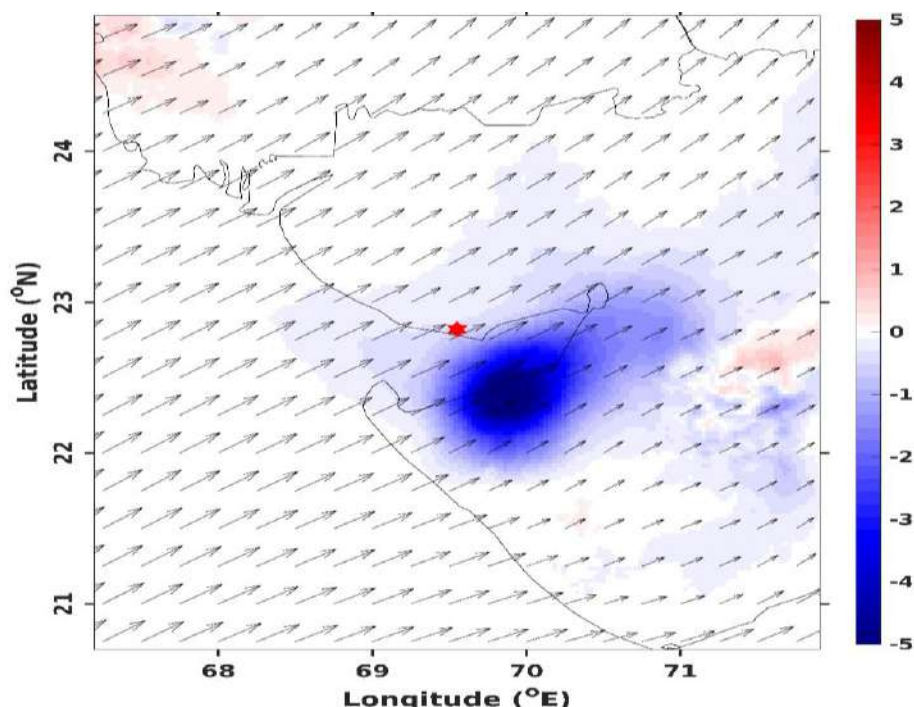


Figure 5.18: Change in monthly mean surface concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

Next, in order to understand the impact of FGD implementation in Vindhyachal TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of July 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO_2 emitted from coal based TPPs as well as other sources of SO_2 . While the primary oxidant responsible for the gaseous phase oxidation of SO_2 in the atmosphere is OH radical, the aqueous phase oxidation of SO_2 largely happens through its reaction with hydrogen peroxide (H_2O_2). Sulphuric acid (H_2SO_4) molecules which form through the oxidation of SO_2 by various oxidants subsequently reacts with ammonia gas (NH_3) and water (H_2O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.19 shows the monthly mean near surface concentration of Sulfate aerosols along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019. It is evident from Figure 5.19 that sulfate aerosol concentrations across the simulation domain varies in the range 5-30 $\mu\text{g}/\text{m}^3$ with higher values noted in the upper half of the domain during the month of July. Wind patterns during July suggest that the low level (850 hPa and below) winds are predominantly south-westerly across the domain. That means relatively pristine air from upwind areas in the Arabian Sea can reach the location of the TPP and air pollutants emitted from this TPP are more likely to be dispersed in the downwind areas which are in the north-eastern and eastern directions of the TPP in the month of July.

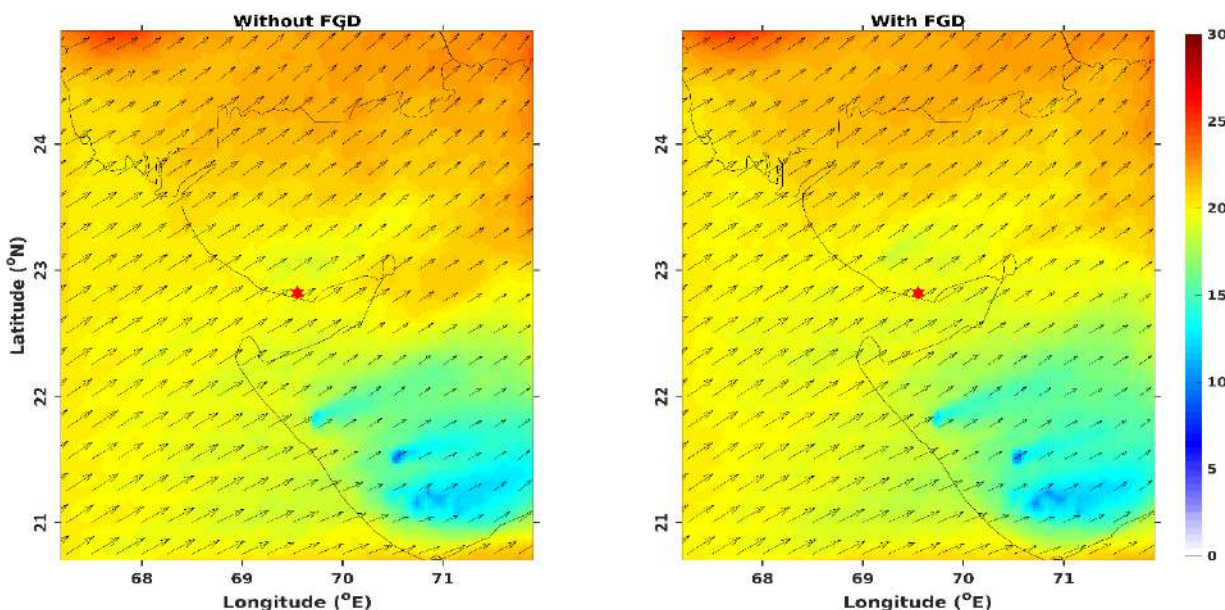


Figure 5.19: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019

Figure 5.20 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for the month of July 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as evident from Figure 5.20 indicates that the implementation of FGD in the Mundra TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Mundra TPP, monthly mean surface concentrations of sulfate aerosols could decrease by as much as $2 \mu\text{g}/\text{m}^3$ at some places which could be as far as 100 Km from this TPP. That means with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols in the range of 10-15% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are as far as 100 Km from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the eastern direction of this TPP. As noted earlier in the case of Vindhyachal TPP, decreases in sulfate aerosol concentrations in the surrounding region of Mundra TPP are also more widespread across the domain as compared to the decreases in SO_2 concentrations. This happens because while decreases in SO_2 concentrations are largely restricted up to a distance of about 80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are also noted as far as 200 km from the TPP. This happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions and differences are noted in most of these factors between the two simulations.

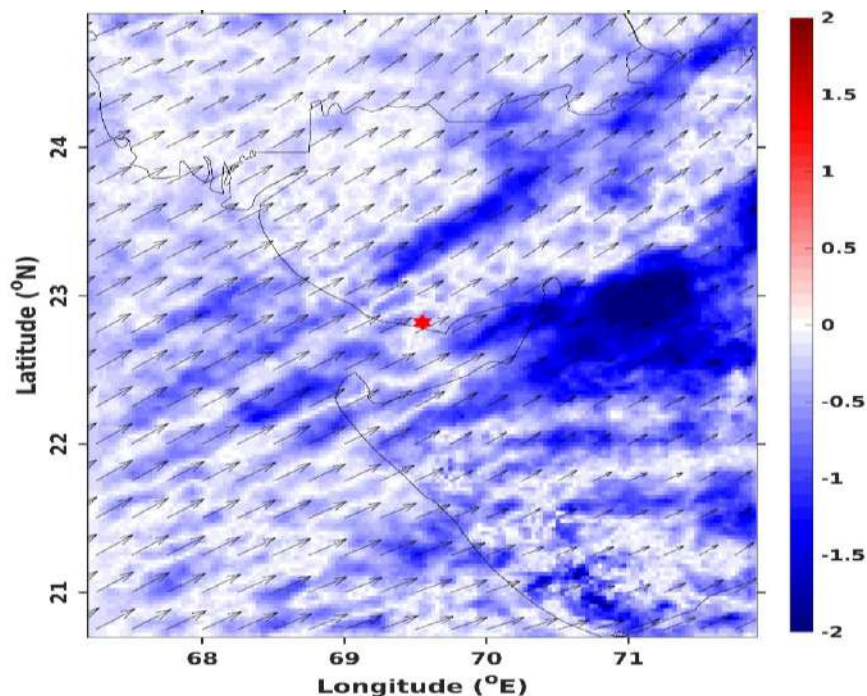


Figure 5.20 *Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for July 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.*

In order to understand the impact of FGD implementation and reduced SO_2 emissions from the Mundra TPP on the near surface concentrations of SO_2 and sulfate aerosols over the surrounding region during other times of the year, we conducted additional model simulations for the month October 2019. We decided to carry out these additional simulations because the meteorological conditions over our study region vary greatly with time of the year and the dispersion of air pollutants as well as formation of secondary pollutants in the atmosphere depend on various meteorological conditions which are different during different seasons of the year. Figure 5.21 shows the monthly mean surface concentration of SO_2 inside the inner domain of our model setup (see Figure 5.15) for WRF-Chem simulations conducted with and without FGD implemented in the Mundra TPP for the month of October 2019.

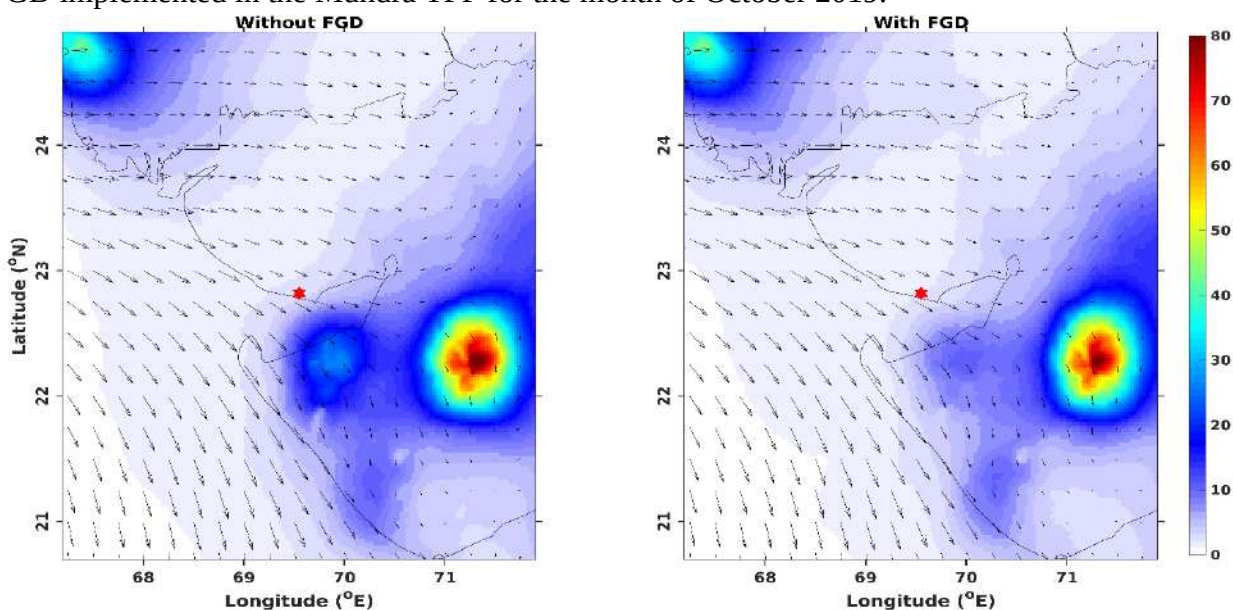


Figure 5.21: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019

Once again, it is evident from Figure 5.21 that the WRF-Chem model is able to capture the hotspot regions with higher SO_2 concentrations around the location of TPPs in both the simulations. Comparing the SO_2 concentrations simulated by the model in July and October, we find that higher concentrations of SO_2 are present across the region during October as compared to July month. This happens due to weaker north-westerly winds prevalent within the atmospheric boundary layer resulting in slow dispersion of air pollutants as well as lesser rainfall over the region during October (as compared to relatively stronger south-westerly winds coming from the oceanic region in the south) results in less efficient wet scavenging of air pollutants from the atmosphere during and October as compared to July month. It is also evident from Figure 5.21 that the surface concentration of SO_2 decreases significantly (by as much as $15 \mu\text{g}/\text{m}^3$) up to a distance of 60-80 km from the location of the Mundra TPP in the simulation which considers reduced SO_2 emissions due to FGD implemented in this power plant.

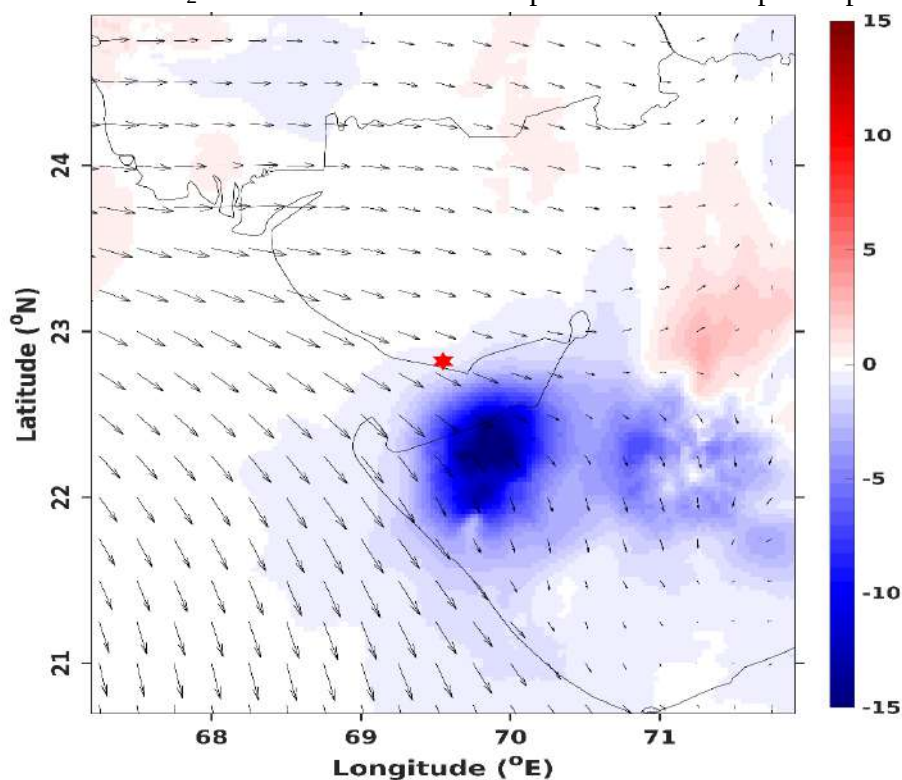


Figure 5.22: Change in monthly mean surface concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

In order to understand the impact of FGD implementation in the Mundra TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of October in a better way, we plotted the differences in SO_2 concentrations over the surrounding region from simulations conducted with and without FGD implementation in this TPP for October 2019. Figure 5.22 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (over the inner domain of the model setup as shown in Figure 5.15) as simulated by the

WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019. Negative values for the change in surface concentration of SO₂ as noted in Figure 5.12 are exhibiting a decrease in the surface concentrations of SO₂ over the surrounding region that we can expect to see with the implementation of FGD in the Mundra TPP during the month of October. Results of our simulations show that we can expect to see a decrease in surface concentrations of SO₂ by as much as 15 µg/m³ (nearly 35% decrease with respect to a no FGD scenario) in the surrounding region with the implementation of FGD in the Mundra TPP. It is also evident from Figure 5.22 that although the implementation of FGD or reduced emission of SO₂ from the Mundra TPP can result in small decreases (up to 1 µg/m³) in SO₂ concentrations in the ambient atmosphere in the downwind areas as far as 200 Km from the TPP but significant decreases (up to 15 µg/m³) in SO₂ concentrations are likely to occur maximum up to a distance of about 70 km from the location of the Mundra TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

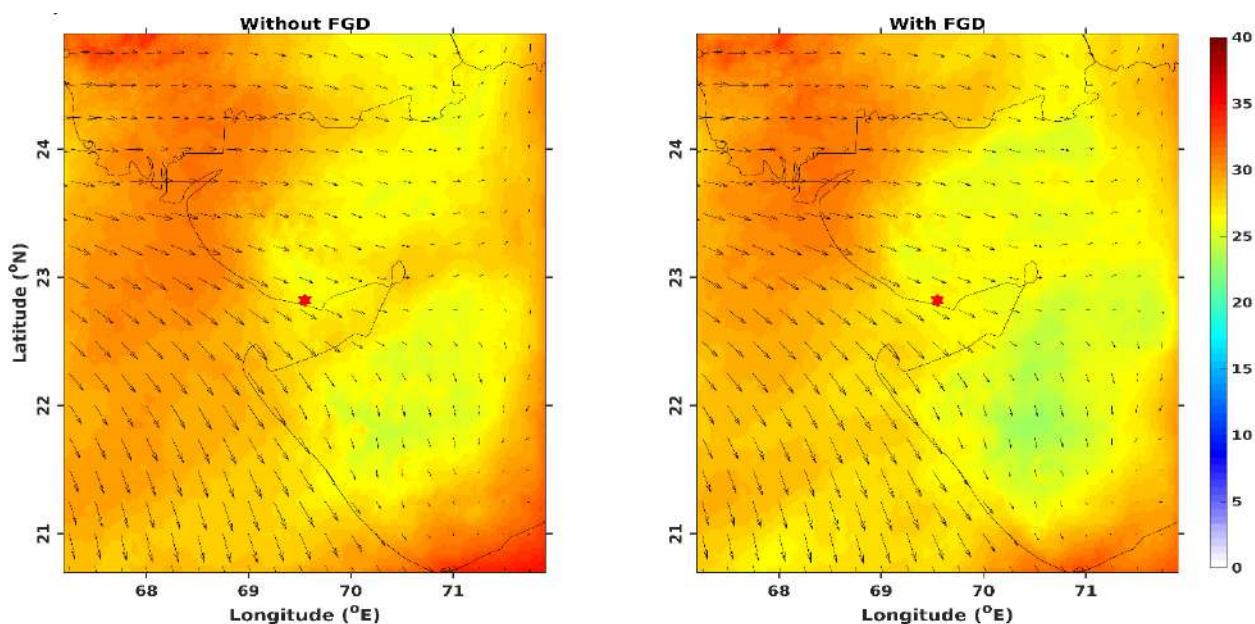


Figure 5.23: Monthly mean near surface concentration (in µg/m³) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019

Figure 5.23 shows the monthly mean near surface concentration of sulfate aerosols simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for the month of October 2019. It can be noted from Figure 5.23 that sulfate aerosol concentrations are relatively higher in the north-western and south-eastern parts of our simulation domain with values going up to 40 µg/m³ in these areas during the month of October. A comparison of sulfate aerosol distribution shown in Figures 6.19 and 6.23 show that surface concentration of sulfate aerosols across the domain is higher in the month of October than in July. This happens due to efficient scavenging of air pollutants from the atmosphere by higher precipitation and wind speed over this region during the month of July as compared to October. Wind patterns during October suggest that the low level winds are predominantly westerly or north-westerly across the

model domain thereby suggesting that the maximum dispersion of air pollutants originating from the Mundra TPP are likely to be in the eastern and south-eastern sides of this power plant during the month of October.

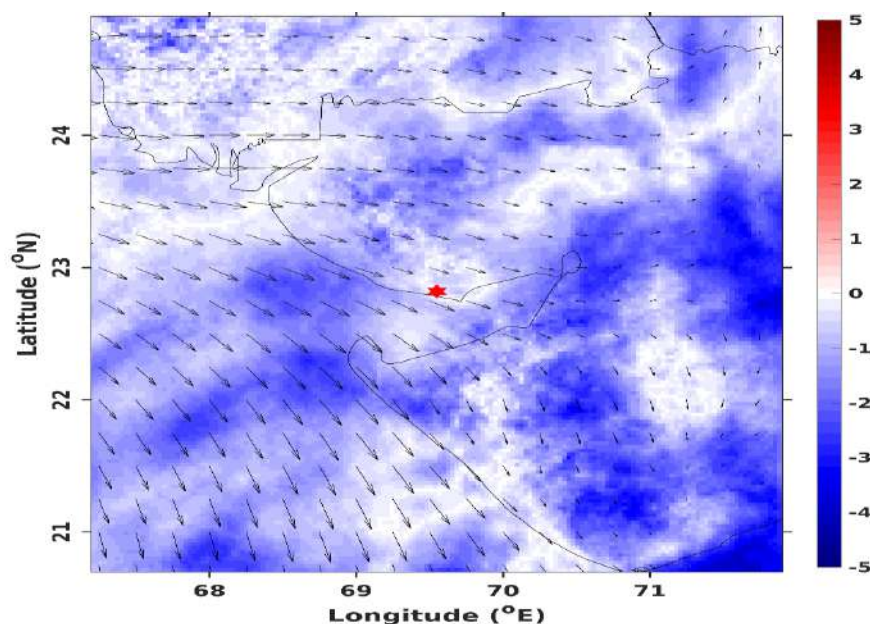


Figure 5.24: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

Figure 5.24 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for the month of October 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as noticeable in Figure 5.24 suggests that the implementation of FGD in the Mundra TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Mundra TPP, monthly mean surface concentrations of sulfate aerosols could decrease by up to $5 \mu\text{g}/\text{m}^3$ at some places which could be as far as 200 Km from this TPP. That means with the implementation of FGD in the Mundra TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols anywhere in the range of 0-10% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are far as 200 Km distant from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the eastern and south eastern directions of this TPP. As noted earlier for the month of July, decreases in sulfate aerosol concentrations are more widespread across the domain as compared to the decreases in SO_2 concentrations in the month of October as well. While decreases in SO_2 concentrations are largely restricted up to a distance of about 60-80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are noted as far as 200 km from the TPP. As mentioned earlier, this happened because the changes in the concentrations of sulfate aerosols

not only depend on the changes in the concentrations of the precursor gas SO₂ but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions the atmosphere and differences are noted in most of these factors between the two simulations conducted with and without FGD implemented in this TPP.

3. Neyveli TPP (Tamil Nadu)

The third coal based TPP considered for investigating the impact of FGD implementation and reduced SO₂ emissions from the stacks of the TPP into the ambient atmosphere on the concentrations of SO₂ and sulfate aerosols over the surrounding region is the Neyveli thermal power plant located in Tamil Nadu, India. This TPP has a power production capacity of 420 MW and it has geographical co-ordinates of 11.59 °N, 79.47 °E. The selection of Neyveli TPP for this study is based on the fact that it is one of the largest coal based TPP in the state of Tamil Nadu and this TPP is located in a distinctly different geographical region experiencing different meteorological variations as compared to the previous Vindhyachal TPP and Mundra TPP.

Figure 5.25 shows the double nested domain chosen for the WRF-Chem simulation centred around the Neyveli thermal power plant (shown using a red colour star in this figure). The light yellow box in Figure 5.25 shows the outer domain having model grid resolution of 9km x 9km (consisting of 180 × 180 grid cells) and the bright yellow box shows the inner domain having model grid resolution of 3km x 3km (consisting of 166 × 166 grid cells).

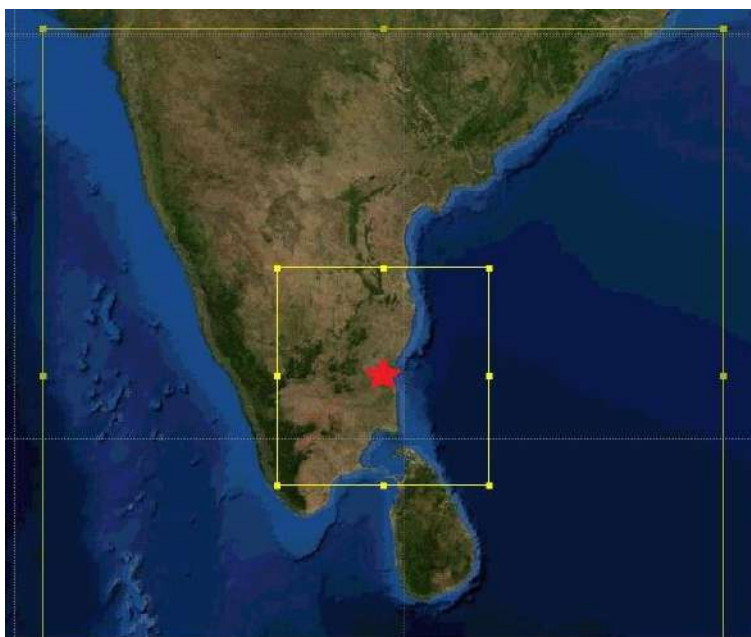


Figure 5.25: Neyveli Thermal Power Plant location and model domain for WRF-Chem Simulation

Figure 5.26 shows the gridded SO₂ emission inventory data (CMIP6 + SMOG-v1) for the inner domain of our WRF-Chem simulations conducted with and without FGD system implemented in the Neyveli thermal power plant. In the simulation which assumed the FGD system to be implemented in the Neyveli thermal power plant, SO₂ emissions from the model grid represented by the TPP has been reduced by 80%. This reduction in SO₂ emission from the

Neyveli TPP is estimated after considering FGD efficiency, power production capacity, and age of this particular TPP.

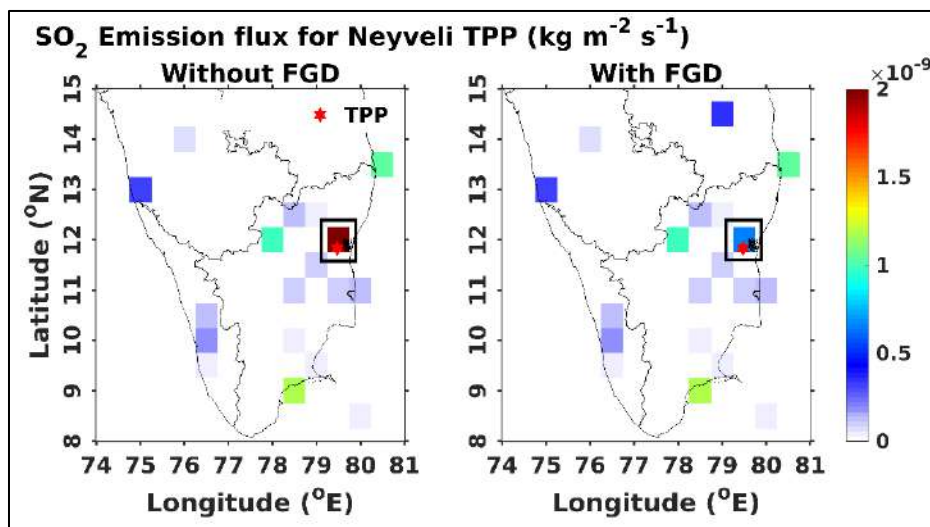


Figure 5.26: Gridded emissions data of SO_2 used in our simulations with and without FGD.

Next we compare the absolute values of monthly mean near surface concentration of SO_2 from the pair of WRF-Chem model simulations conducted with and without FGD implementation in the Neyveli TPP for July 2019. For both these experiments, simulations start from 16th June 2019, continue up to 1st August 2019 and the results from the last 31 days of the simulations corresponding to 1-31 July 2019 are analysed for understanding the changes in the surface concentrations of SO_2 and sulfate aerosols. Results from the first fifteen days of model output are excluded from our analyses to allow the model to spin up following the initial conditions. Figure 5.27 shows the monthly mean near surface concentration of SO_2 simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019. It is evident from Figure 627 that the WRF-Chem model is able to capture the hotspot regions with higher SO_2 concentrations around the location of TPPs in both the simulations. It is also evident from Figure 5.27 that the surface concentration of SO_2 decreases significantly by as much as $40 \mu\text{g}/\text{m}^3$ in the neighbourhood of the TPP and up to a distance of about 50 km from the location of the Neyveli TPP in the simulation with FGD implemented in this TPP and reduced emission of SO_2 from the grid coinciding with the location of the TPP.

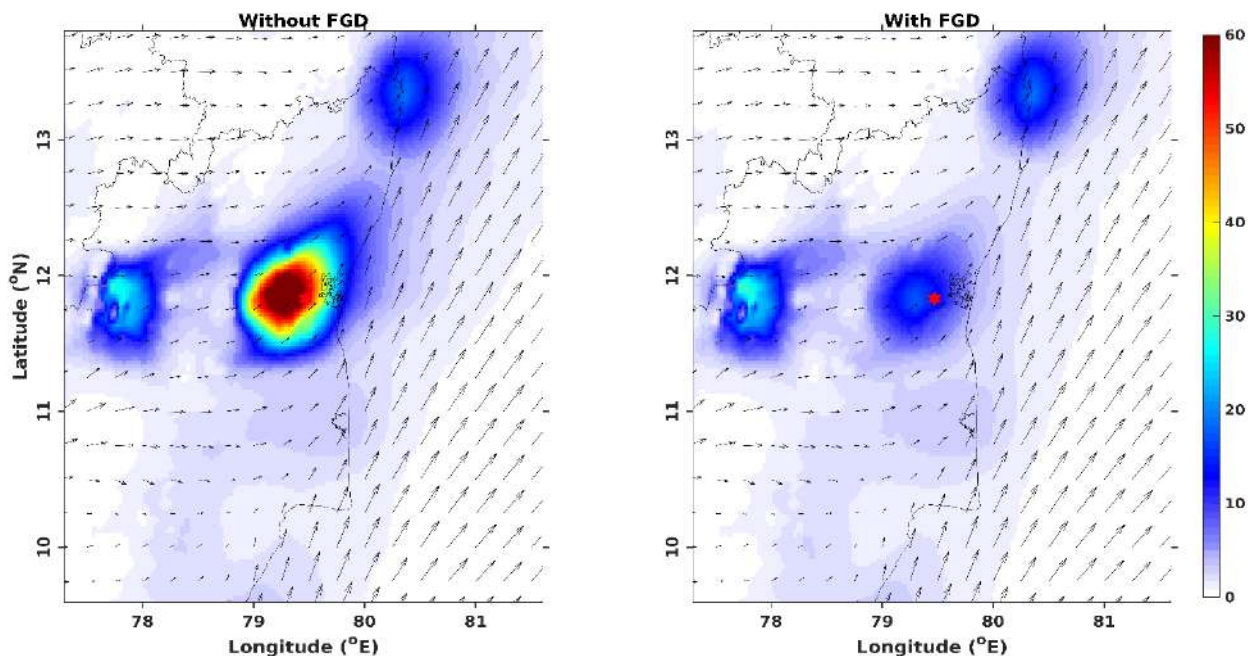


Figure 5.27: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019

Nevertheless, in order to understand the impact of implementation of FGD in Neyveli TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of January in a better way, we examined the differences in SO_2 concentrations in the surrounding region from simulations conducted with and without FGD implementation in this TPP for July 2019.

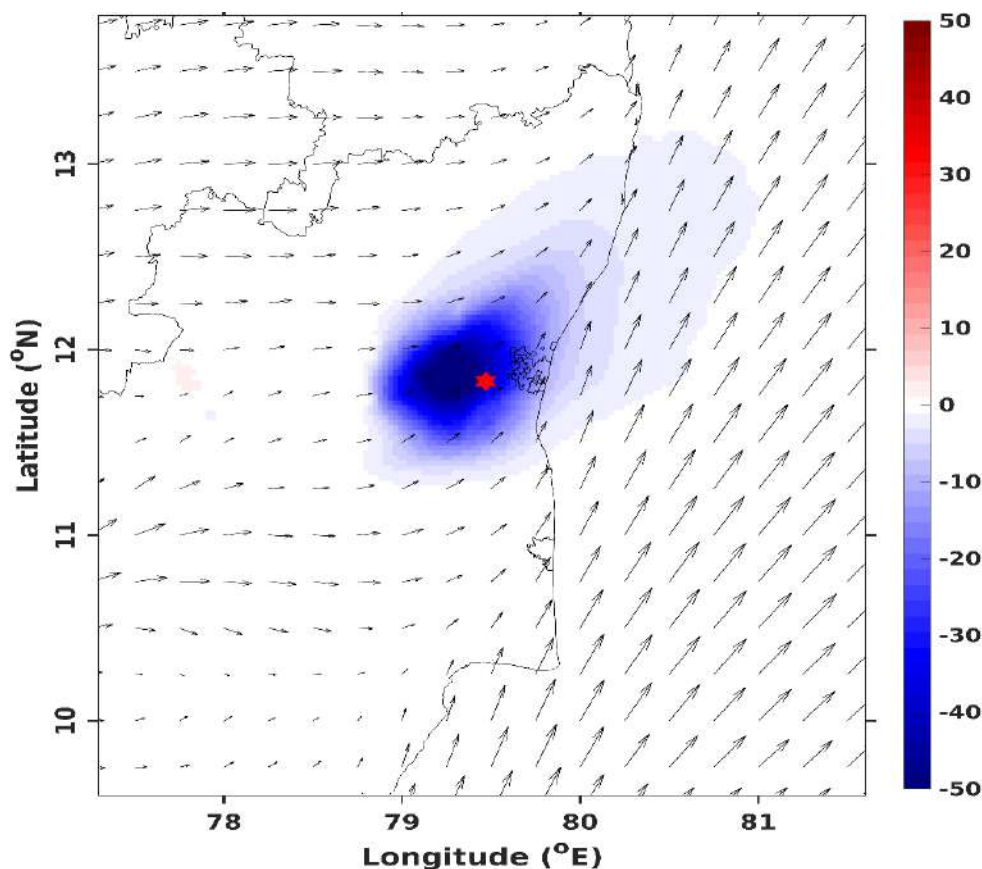


Figure 5.28: Change in monthly mean surface concentration of SO₂ (in µg/m³) simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

Figure 5.28 shows the change in monthly mean surface concentration of SO₂ in the surrounding region (over the inner domain of the model setup as shown in Figure 5.25) as simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019. Negative values for the change in surface concentration of SO₂ as noted in Figure 5.28 are exhibiting a decrease in the concentrations of SO₂ over the surrounding region that we can expect to see with the implementation of FGD in the Neyveli TPP. Results of our WRF-Chem simulations show that we can expect to see a decrease in near surface SO₂ concentrations by as much as 50 µg/m³ (that means a decrease by almost up to 80% with respect to without FGD scenario) in the surrounding region with the implementation of FGD in the Neyveli TPP. Our results further show that although the implementation of FGD or reduced emission of SO₂ from the Neyveli TPP can result in small decreases (up to 5 µg/m³) in SO₂ concentrations in the ambient atmosphere in the downwind areas as far as 100 Km from the TPP but significant decreases (up to 50 µg/m³) in SO₂ concentrations are likely to occur up to a maximum distance of about 15 km from the location of the Neyveli TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

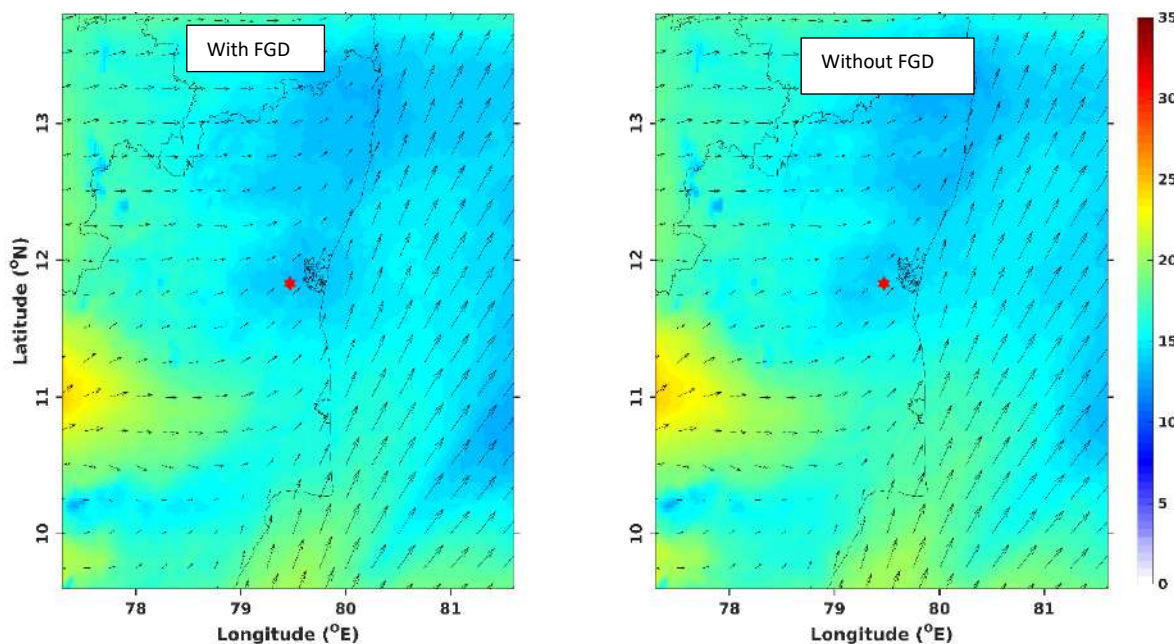


Figure 5.29: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019

Next, in order to understand the impact of FGD implementation in Neyveli TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of July 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO_2 emitted from coal based TPPs as well as other sources of SO_2 . While the primary oxidant responsible for the gaseous phase oxidation of SO_2 in the atmosphere is OH radical, the aqueous phase oxidation of SO_2 largely happens through its reaction with hydrogen peroxide (H_2O_2). Sulphuric acid (H_2SO_4) molecules which form through the oxidation of SO_2 by various oxidants subsequently reacts with ammonia gas (NH_3) and water (H_2O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.29 shows the monthly mean near surface concentration of Sulfate aerosols along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019. It is evident from Figure 5.29 that sulfate aerosol concentrations across the simulation domain varies in the range 5-25 $\mu\text{g}/\text{m}^3$ with higher values noted in the south-western part of the domain during the month of July. Wind patterns during July suggest that the low level (850 hPa and below) winds are predominantly westerly over the land areas and southerly over the oceanic regions within the domain. That means air pollutants emitted from the Neyveli TPP are more likely to be dispersed in the downwind direction which are in the north-eastern and eastern directions of this TPP in the month of July.

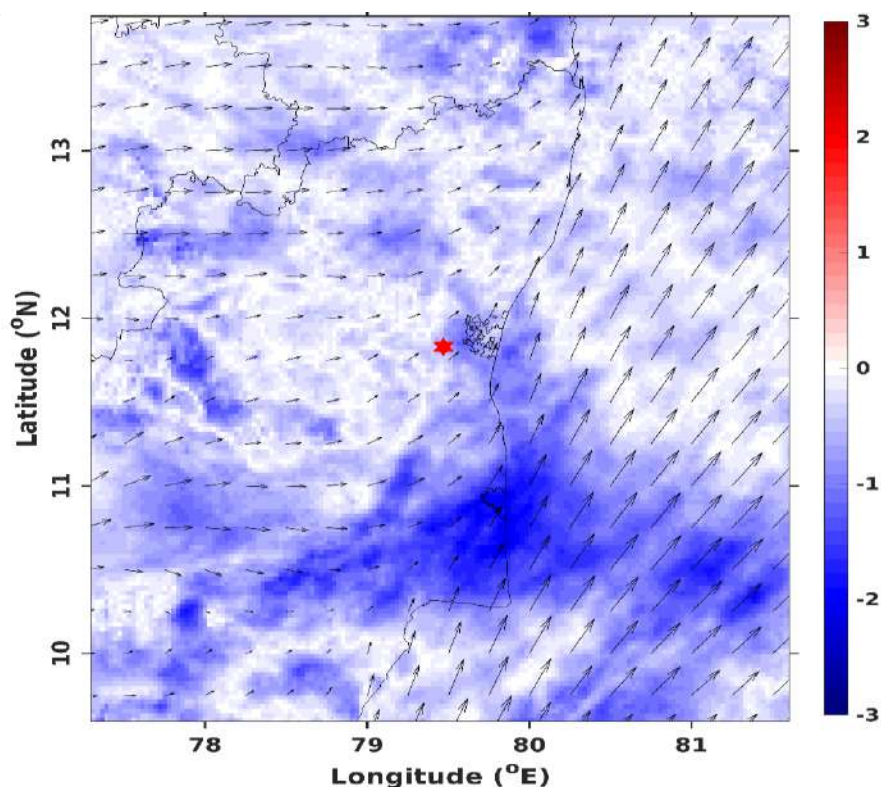


Figure 5.30: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for July 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

Figure 5.30 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for the month of July 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as evident from Figure 5.30 indicates that the implementation of FGD in the Neyveli TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Neyveli TPP, monthly mean surface concentrations of sulfate aerosols could decrease by as much as $3 \mu\text{g}/\text{m}^3$ at some places which could be as far as 100 Km from this TPP. That means with the implementation of FGD in the Neyveli TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols up to about 15% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are as far as 100 Km from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the south-eastern direction of this TPP. As noted earlier in the case of Vindhyachal and Mundra TPP, decreases in sulfate aerosol concentrations in the surrounding region of Neyveli TPP are also more widespread across the domain as compared to the decreases in SO_2 concentrations. This happens because while decreases in SO_2 concentrations are largely restricted up to a distance of about 60 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are also noted as far as 200 km from the TPP. This happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in

the concentrations of oxidants, other reactive gases, and meteorological conditions and differences are noted in most of these factors between the two simulations.

In order to understand the impact of FGD implementation and reduced SO₂ emissions from the Neyveli TPP on the near surface concentrations of SO₂ and sulfate aerosols over the surrounding region during other times of the year, we conducted additional model simulations for the month October 2019. We decided to carry out these additional simulations because the meteorological conditions over our study region vary greatly with time of the year and the dispersion of air pollutants as well as formation of secondary pollutants in the atmosphere depend on various meteorological conditions which are different during different seasons of the year. Figure 5.31 shows the monthly mean surface concentration of SO₂ inside the inner domain of our model setup (see Figure 5.25) for WRF-Chem simulations conducted with and without FGD implemented in the Neyveli TPP for the month of October 2019.

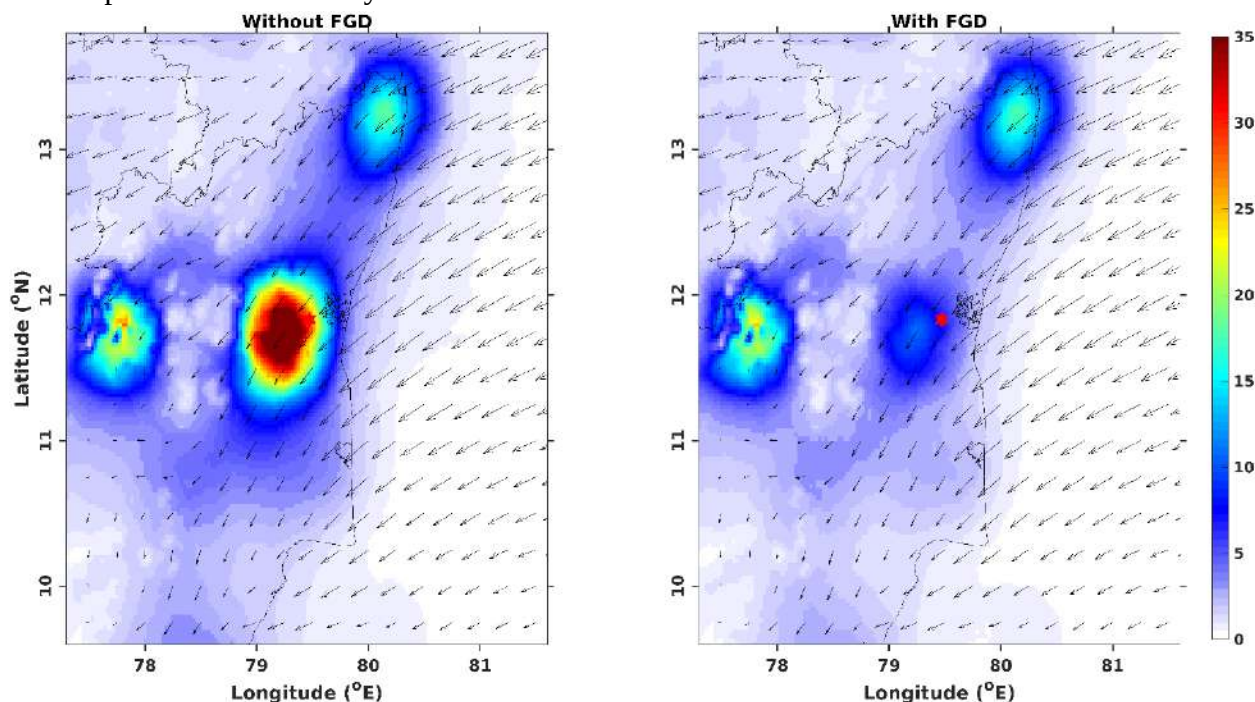


Figure 5.31: : Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO₂ along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for October 2019

It is evident from Figure 5.31 that the WRF-Chem model is able to capture the hotspot regions with higher SO₂ concentrations around the location of TPPs in both the simulations. Comparing the SO₂ concentrations simulated by the model over the study region in July and October, we find that relatively lower concentrations of SO₂ are present across the region during October as compared to July month. This happens due to stronger north-easterly winds (coming from the oceanic region in the north-east) prevalent within the atmospheric boundary layer resulting in faster dispersion of air pollutants as well as more rainfall over the region during October (as compared to south-westerly winds coming from the land regions in July) results in more efficient dispersion and wet scavenging of air pollutants from the atmosphere during October as compared to July month. It is also evident from Figure 5.30 that the surface concentration of SO₂ decreases

significantly (by as much as 20 $\mu\text{g}/\text{m}^3$) in the downwind direction up to a distance of about 60 km from the location of the Neyveli TPP in the simulation which considers reduced SO_2 emissions due to FGD implemented in this power plant.

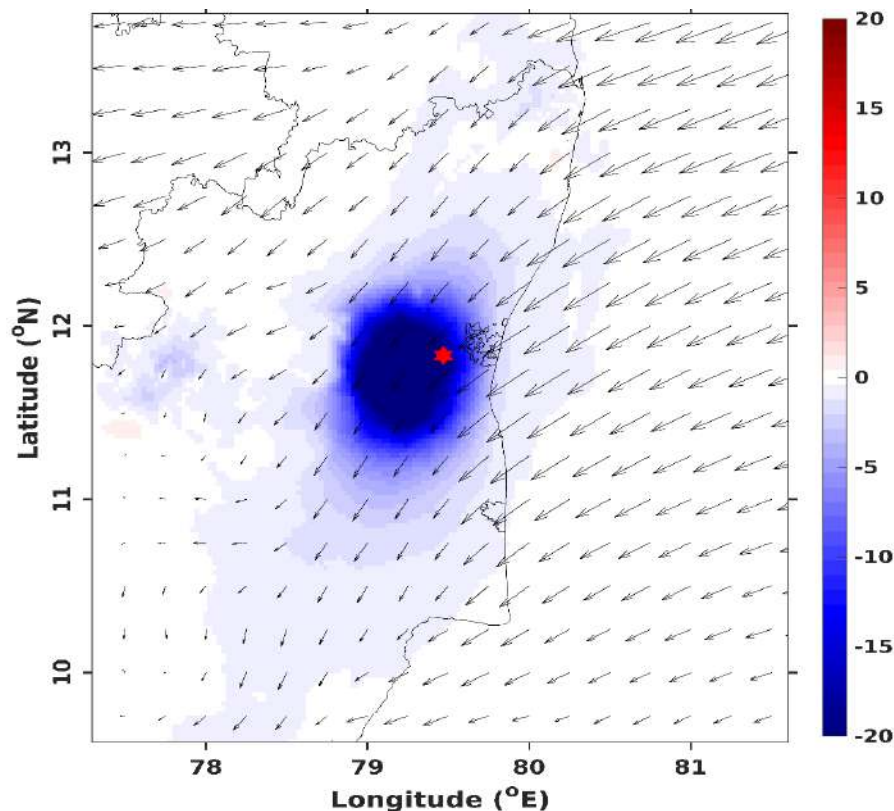


Figure 5.32: Change in monthly mean surface concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for October 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

Nevertheless, in order to understand the impact of FGD implementation in the Neyveli TPP on the changes in surface concentrations of SO_2 in the surrounding region during the month of October in a better way, we plotted the differences in SO_2 concentrations over the surrounding region from simulations conducted with and without FGD implementation in this TPP for October 2019. Figure 5.32 shows the change in monthly mean surface concentration of SO_2 in the surrounding region (over the inner domain of the model setup as shown in Figure 5.25) as simulated by the WRF-Chem model with and without FGD implemented in the Mundra TPP for October 2019. Negative values for the change in surface concentration of SO_2 as noted in Figure 5.32 are exhibiting a decrease in the surface concentrations of SO_2 over the surrounding region that we can expect to see with the implementation of FGD in the Neyveli TPP during the month of October. Results of our simulations show that we can expect to see a decrease in surface concentrations of SO_2 by as much as 20 $\mu\text{g}/\text{m}^3$ (nearly 55% decrease with respect to a no FGD scenario) in the surrounding region and especially in the downwind direction with the implementation of FGD in the Neyveli TPP. It is also evident from Figure 5.32 that although the implementation of FGD or reduced emission of SO_2 from the Neyveli TPP can result in small

decreases (up to $1 \mu\text{g}/\text{m}^3$) in SO_2 concentrations in the ambient atmosphere in the downwind areas as far as 200 Km from the TPP but significant decreases (up to $20 \mu\text{g}/\text{m}^3$) in SO_2 concentrations are likely to occur maximum up to a distance of about 60 km from the location of the Neyveli TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

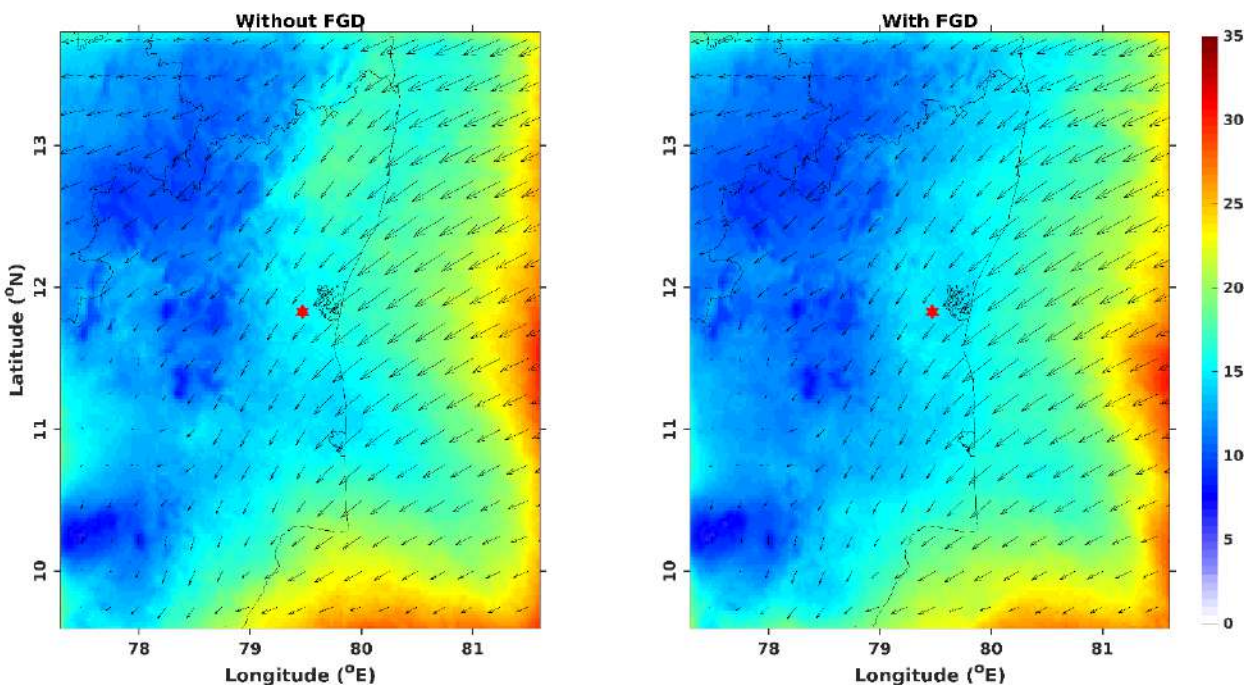


Figure 5.33: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for October 2019

In order to understand the impact of FGD implementation in Neyveli TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of October 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO_2 emitted from coal based TPPs as well as other sources of SO_2 . While the primary oxidant responsible for the gaseous phase oxidation of SO_2 in the atmosphere is OH radical, the aqueous phase oxidation of SO_2 largely happens through its reaction with hydrogen peroxide (H_2O_2). Sulphuric acid (H_2SO_4) molecules which form through the oxidation of SO_2 by various oxidants subsequently reacts with ammonia gas (NH_3) and water (H_2O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.33 shows the monthly mean near surface concentration of sulfate aerosols along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for October 2019. It is evident from Figure 5.33 that sulfate aerosol concentrations across the simulation domain varies in the range $5\text{--}35 \mu\text{g}/\text{m}^3$ with higher values noted in the eastern part of the domain over the Bay of Bengal during the month of October. Wind patterns during October suggest that

the low level (850 hPa and below) winds are predominantly north-easterly over the oceanic regions and easterly over the land areas within the domain. That means air pollutants emitted from the Neyveli TPP are more likely to be dispersed in the downwind direction which are in the western and southern directions of this TPP in the month of October.

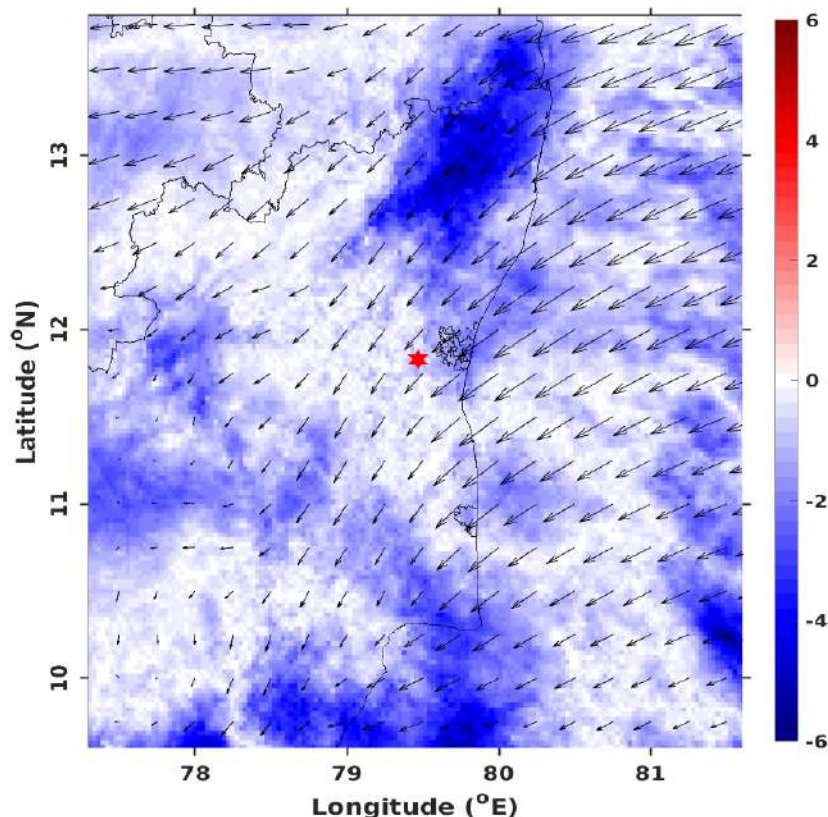


Figure 5.34: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for October 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

Figure 5.34 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Neyveli TPP for the month of October 2019. Negative values for the change in surface concentration of sulfate aerosols across the domain as noticeable in Figure 5.34 suggests that the implementation of FGD in the Neyveli TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Neyveli TPP, monthly mean surface concentrations of sulfate aerosols could decrease by up to $6 \mu\text{g}/\text{m}^3$ at some places which could be as far as 200 Km from this TPP. That means with the implementation of FGD in the Mundra TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols anywhere in the range of 0-10% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are far as 200 Km distant from the location of this TPP. Decreases in sulfate concentrations are noted both in the southern and northern directions of this TPP. As noted earlier for the month of July, decreases in sulfate aerosol concentrations are more widespread across the domain as compared to the decreases in SO_2 concentrations in the month

of October as well. While decreases in SO₂ concentrations are largely restricted up to a distance of about 60-80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are noted as far as 200 km from the TPP. As mentioned earlier, this happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO₂ but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions the atmosphere and differences are noted in most of these factors between the two simulations conducted with and without FGD implemented in this TPP.

4. Panipat TPP (Haryana):

The fourth coal based TPP considered for investigating the impact of FGD implementation and reduced SO₂ emissions from the stacks of the TPP into the ambient atmosphere on the concentrations of SO₂ and sulfate aerosols over the surrounding region is the Panipat thermal power plant located in Haryana, India. This TPP has a power production capacity of 1360 MW and it has geographical co-ordinates of 29.40 °N, 76.87 °E. The selection of Panipat TPP for this study is based on the fact that it is one of the largest coal based TPP in the state of Haryana and this TPP is located in a distinctly different geographical region experiencing different meteorological variations as compared to the previous Vindhyachal TPP, Mundra TPP, and Neyveli TPP. Another reason for choosing Panipat TPP in our study is that it is one of the largest coal based thermal power plants located within 200 km radius from New Delhi. Figure 5.35 shows the double nested domain chosen for the WRF-Chem simulation centred on the Panipat thermal power plant (shown using a red colour star in this figure). The light yellow box in Figure 5.35 shows the outer domain having model grid resolution of 9km x 9km (consisting of 180 × 180 grid cells) and the bright yellow box shows the inner domain having model grid resolution of 3km x 3km (consisting of 166 × 166 grid cells).

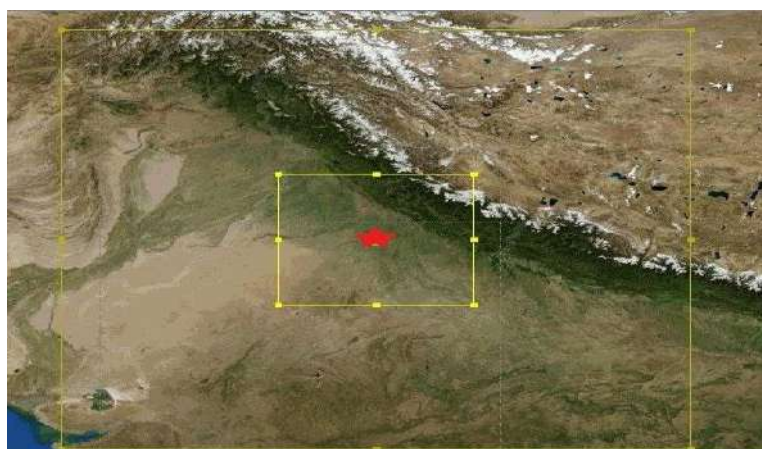


Figure 5.35: Panipat Thermal Power Plant location and model domain for WRF-Chem Simulation

Figure 5.36 shows the gridded SO₂ emission inventory data (CMIP6 + SMOG-v1) for the inner domain of our WRF-Chem simulations conducted with and without FGD system implemented in the Panipat thermal power plant. In the simulation which assumed the FGD system to be implemented in the Panipat thermal power plant, SO₂ emissions from the model

grid represented by the TPP has been reduced by 65%. This reduction in SO₂ emission from the Panipat TPP is estimated after considering FGD efficiency, power production capacity, and age of this particular TPP.

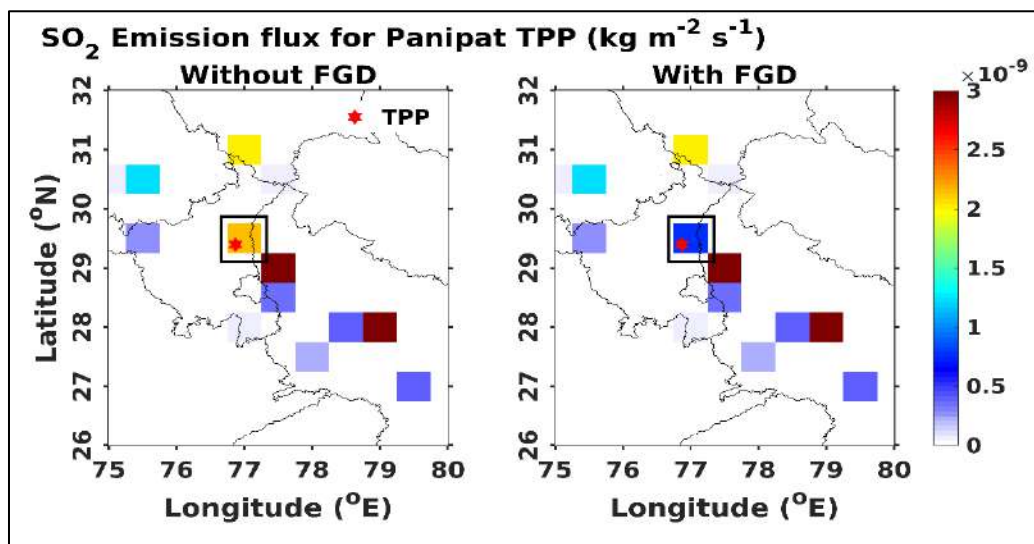


Figure 5.36: Gridded emissions data of SO₂ used in our simulations with and without FGD.

Next we compare the absolute values of monthly mean near surface concentration of SO₂ from the pair of WRF-Chem model simulations conducted with and without FGD implementation in the Panipat TPP for January 2019. For both these experiments, simulations start from 16th December 2018, continue up to 1st February 2019 and the results from the last 31 days of the simulations corresponding to 1-31 January 2019 are analysed for understanding the changes in the surface concentrations of SO₂ and sulfate aerosols. Results from the first fifteen days of model output are excluded from our analyses to allow the model to spin up following the initial conditions. Figure 5.37 shows the monthly mean near surface concentration of SO₂ simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for January 2019. It is evident from Figure 5.37 that the WRF-Chem model is able to capture the hotspot regions with higher SO₂ concentrations around the location of TPPs in both the simulations. It is also evident from Figure 5.37 that the surface concentration of SO₂ decreases significantly by as much as 30 µg/m³ in the neighbourhood of the TPP and up to a distance of about 60 km from the location of the Panipat TPP in the simulation with FGD implemented in this TPP and reduced emission of SO₂ from the grid coinciding with the location of the TPP. Thus results of our WRF-Chem simulations suggest that we can expect to see a decrease in near surface SO₂ concentrations by as much as 30 µg/m³ (or almost up to 25% decrease with respect to without FGD scenario) in the surrounding region especially in the direction of maximum dispersal of the air pollutant and depending upon the wind speed with the implementation of FGD in the Panipat TPP.

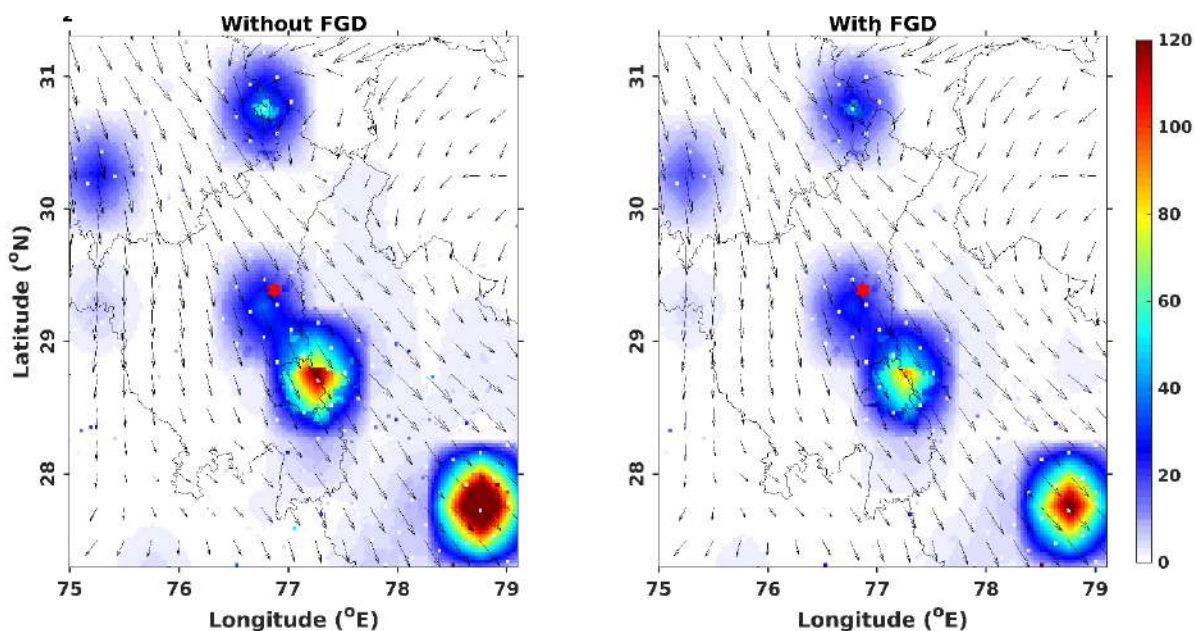


Figure 5.37: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for January 2019

In order to understand the impact of FGD implementation in Panipat TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of January 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO_2 emitted from coal based TPPs as well as other sources of SO_2 . While the primary oxidant responsible for the gaseous phase oxidation of SO_2 in the atmosphere is OH radical, the aqueous phase oxidation of SO_2 largely happens through its reaction with hydrogen peroxide (H_2O_2). Sulphuric acid (H_2SO_4) molecules which form through the oxidation of SO_2 by various oxidants subsequently reacts with ammonia gas (NH_3) and water (H_2O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.38 shows the monthly mean near surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for January 2019. It is evident from Figure 5.38 that sulfate aerosol concentrations are quite high across the inner domain of our WRF-Chem simulation setup with values ranging from 20-40 $\mu\text{g}/\text{m}^3$ during the month of January and higher values are generally noted in the upper half of the simulation domain and upwind direction of the Panipat TPP. Wind patterns during January suggest that the low level (850 hPa and below) winds are predominantly north-westerly or northerly across the model domain. That means air pollution from upwind areas in the north and north-west parts of the Panipat TPP can reach the location of the TPP and air pollutants emitted from this TPP are more likely to be dispersed in the downwind areas which are in the south-eastern and southern directions of the TPP in the month of January.

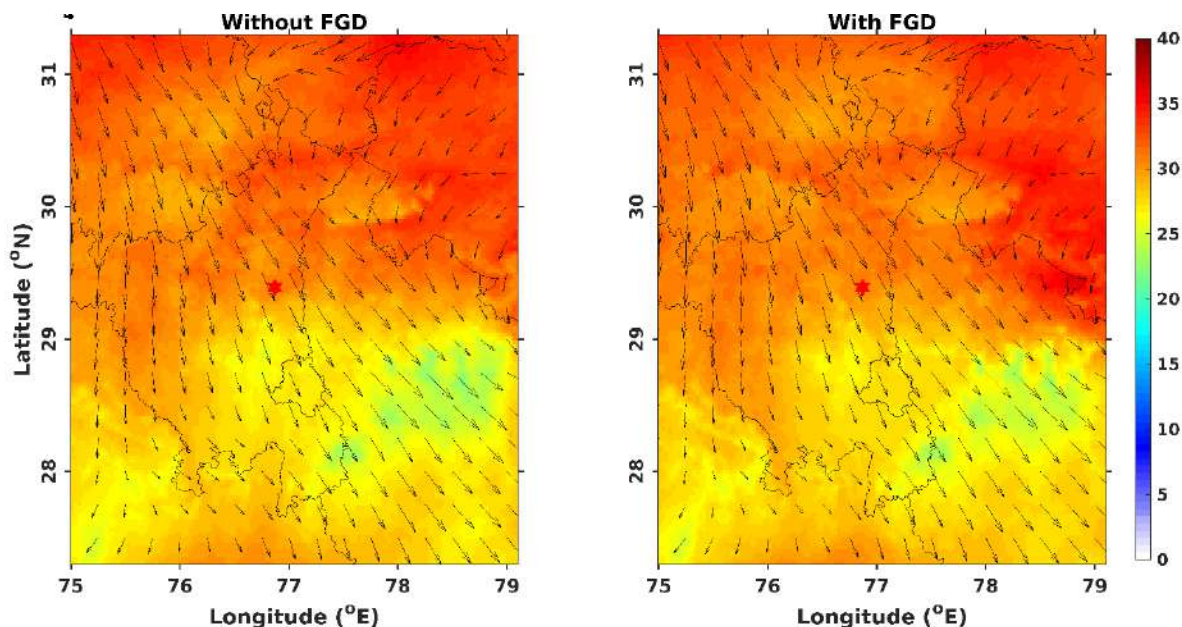


Figure 5.38: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for January 2019

Figure 5.39 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for the month of January 2019. Negative values of change in surface concentration of sulfate aerosols across the domain as shown in Figure 5.39 are suggesting that we can expect to see mostly a decrease in the surface concentrations of sulfate aerosols in the surrounding region with the implementation of FGD in the Panipat TPP. Our results are further suggesting that with the implementation of FGD in the Vindhyachal TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by as much as $5 \mu\text{g}/\text{m}^3$ at some places in the surrounding region of the TPP. In other words, with the implementation of FGD in the Panipat TPP, we can expect to see a decrease in the monthly mean surface concentrations of sulfate aerosols by up to 12% of the climatological values at certain places which are as far as 100-150 Km from the location of this TPP. Thus our results show that with the implementation of FGD in the Panipat TPP, while the significant decreases in SO_2 concentrations are mostly confined in the immediate surrounding areas of the TPP and up to a maximum distance of 60-80 km from the location of the TPP in the direction of maximum dispersal of the air pollutants but, significant decreases in the surface concentrations of sulfate aerosols can be expected at locations which could be as far as 100-150 Km from the location of this TPP. This happens because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants such as OH radical, hydrogen peroxide (H_2O_2), ozone (O_3), water vapor (H_2O), other reactive gases such as NH_3 , meteorological conditions such as wind speed, wind direction, relative humidity, sunlight and clouds. We noted small but finite differences in most of these factors across the region between the two simulations.

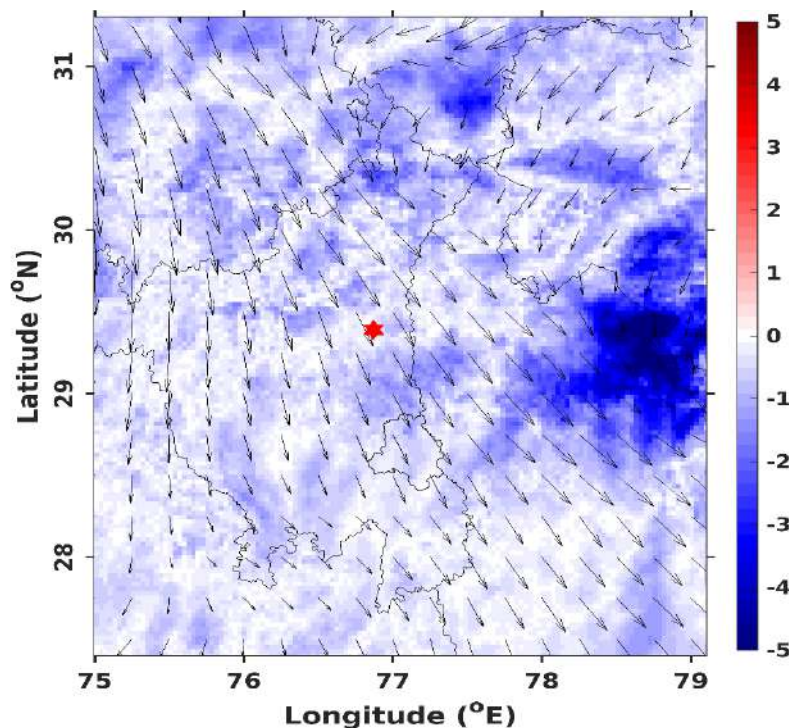


Figure 5.39: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for January 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

In order to understand the impact of FGD implementation and reduced SO_2 emissions from the Panipat TPP on the near surface concentrations of SO_2 and sulfate aerosols over the surrounding region during other times of the year, we conducted additional model simulations for the month October 2019. We decided to carry out these additional simulations because the meteorological conditions over our study region vary greatly with time of the year and the dispersion of air pollutants as well as formation of secondary pollutants in the atmosphere depend on various meteorological conditions which are different during different seasons of the year. Figure 5.40 shows the monthly mean surface concentration of SO_2 inside the inner domain of our model setup (see Figure 5.35) for WRF-Chem simulations conducted with and without FGD implemented in the Panipat TPP for the month of October 2019.

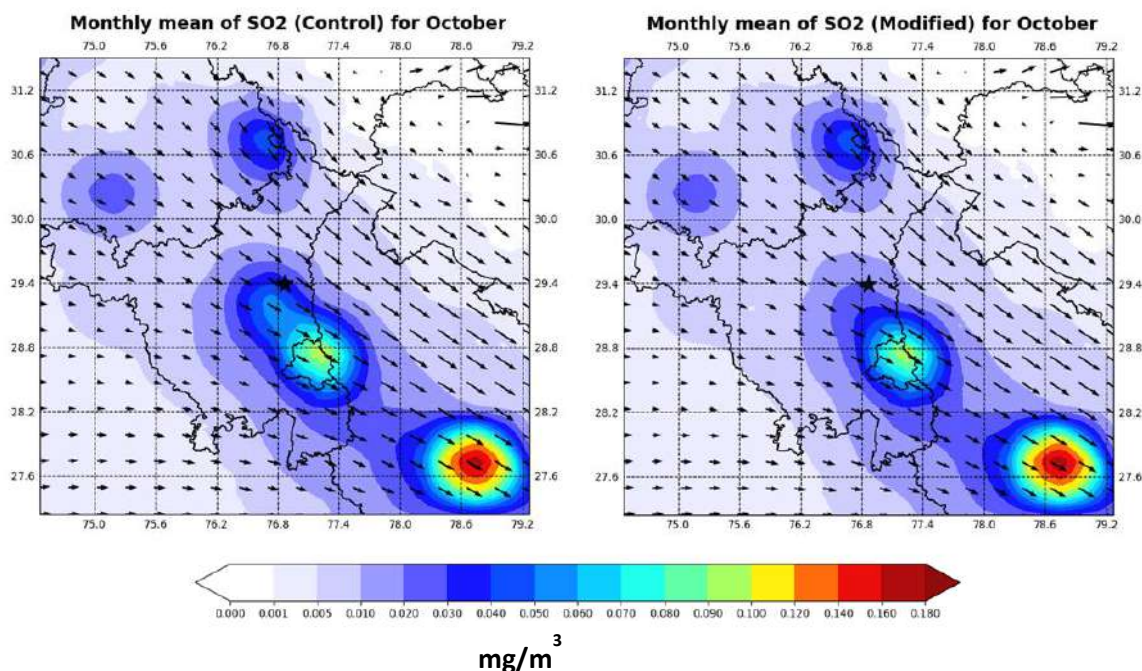


Figure 5.40: Monthly mean near surface concentration (in $\mu\text{g}/\text{m}^3$) of SO_2 along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019

Once again, it is evident from Figure 5.40 that the WRF-Chem model is able to capture the hotspot regions with higher SO_2 concentrations around the location of TPPs in both the simulations. Comparing the SO_2 concentrations simulated by the model in the two months (January and October), we find relatively higher concentrations of SO_2 are present across the region during October as compared to January month. This happens firstly due to relatively higher emissions of SO_2 from other sources such as agricultural waste burning across the northwest India (especially in the states of Punjab and Haryana) during the month of October as compared to January and secondly due to weaker northerly winds prevalent within the atmospheric boundary layer resulting in slow dispersion of air pollutants as well as lesser rainfall during October reduces the wet scavenging of air pollutants from the atmosphere during this month as compared to January month. It is also evident from Figure 5.40 that the surface concentration of SO_2 decreases by as much as $10 \mu\text{g}/\text{m}^3$ up to a distance of 60-80 km from the location of the Panipat TPP in the simulation which considers reduced SO_2 emissions due to FGD implemented in this power plant.

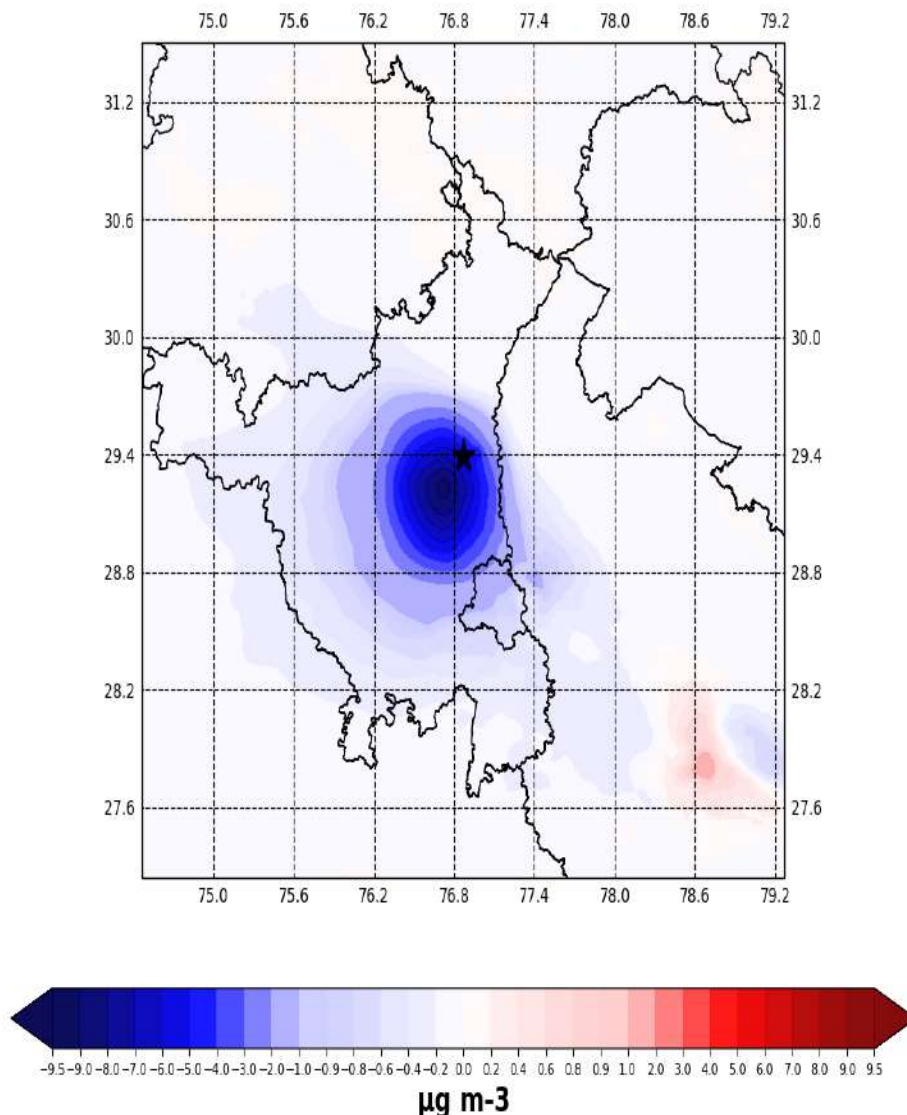


Figure 5.41: Change in monthly mean surface concentration of SO₂ (in µg/m³) simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019. Black arrows represent the wind vector at 850 hPa from the simulation with FGD implemented in this TPP.

Nevertheless, in order to understand the impact of FGD implementation in the Panipat TPP on the changes in surface concentrations of SO₂ in the surrounding region during the month of October in a better way, we plotted the differences in SO₂ concentrations over the surrounding region from simulations conducted with and without FGD implementation in this TPP for October 2019. Figure 5.41 shows the change in monthly mean surface concentration of SO₂ in the surrounding region (over the inner domain of the model setup as shown in Figure 5.35) as simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019. Negative values for the change in surface concentration of SO₂ as noted in Figure 5.41 are exhibiting a decrease in the surface concentrations of SO₂ over the surrounding region that we can expect to see with the implementation of FGD in the Panipat TPP during the month of October. Results of our simulations show that we can expect to see a decrease in surface concentrations of SO₂ by as much as 10 µg/m³ (nearly 6% decrease with respect to a no FGD

scenario) in the surrounding region with the implementation of FGD in the Vindhyachal TPP. It is also evident from Figure 5.41 that although the implementation of FGD or reduced emission of SO₂ from the Panipat TPP can result in small decreases (less than 1 µg/m³) in SO₂ concentrations in the ambient atmosphere in the downwind areas as far as 200 Km from the TPP but significant decreases (up to 10 µg/m³) in SO₂ concentrations are likely to occur maximum up to a distance of about 60 km from the location of the Panipat TPP in the direction of maximum dispersal of the air pollutant and depending upon the wind speed.

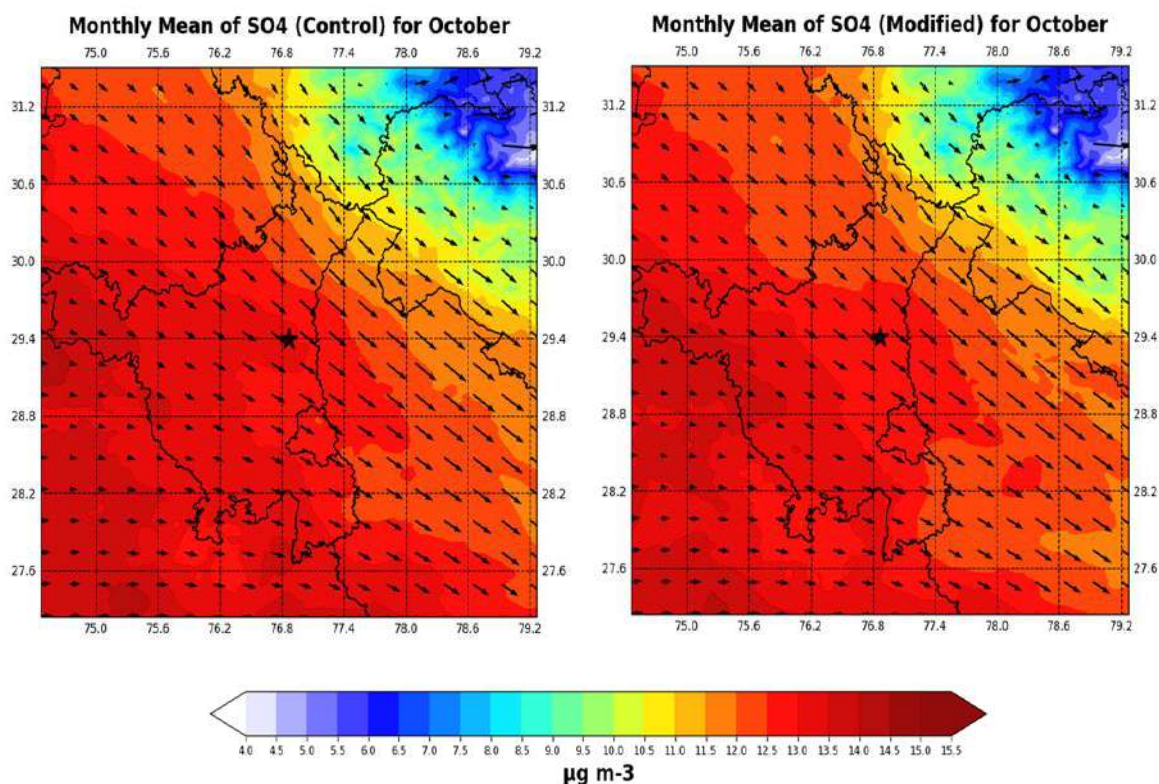


Figure 5.42: Monthly mean near surface concentration (in µg/m³) of Sulfate aerosols along with wind vectors at 850 hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019

In order to understand the impact of FGD implementation in Panipat TPP on the surface concentrations of sulfate aerosols over the surrounding region, first we compare the absolute values of monthly mean near surface concentration of sulfate aerosols from the pair of WRF-Chem simulations conducted with and without FGD implementation in this TPP for the month of October 2019. As we know that sulfate is a secondary aerosol which forms in the atmosphere through oxidation of primary pollutant SO₂ emitted from coal based TPPs as well as other sources of SO₂. While the primary oxidant responsible for the gaseous phase oxidation of SO₂ in the atmosphere is OH radical, the aqueous phase oxidation of SO₂ largely happens through its

reaction with hydrogen peroxide (H_2O_2). Sulphuric acid (H_2SO_4) molecules which form through the oxidation of SO_2 by various oxidants subsequently reacts with ammonia gas (NH_3) and water (H_2O) to form new nanoparticles which further grow through condensation and coagulation processes to form sulfate aerosols in the atmosphere. Figure 5.42 shows the monthly mean near surface concentration of sulfate aerosols along with wind vectors at 850hPa level simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019. It is evident from Figure 5.42 that sulfate aerosol concentrations across the simulation domain varies in the range of 5-16 $\mu\text{g}/\text{m}^3$ with higher values noted in the western part of the domain during the month of October. Wind patterns during October suggest that the low level (850 hPa and below) winds are predominantly north-westerly across the domain. That means air pollutants emitted from the Panipat TPP are more likely to be dispersed in the downwind direction which are in the eastern and south-eastern directions of this TPP in the month of October

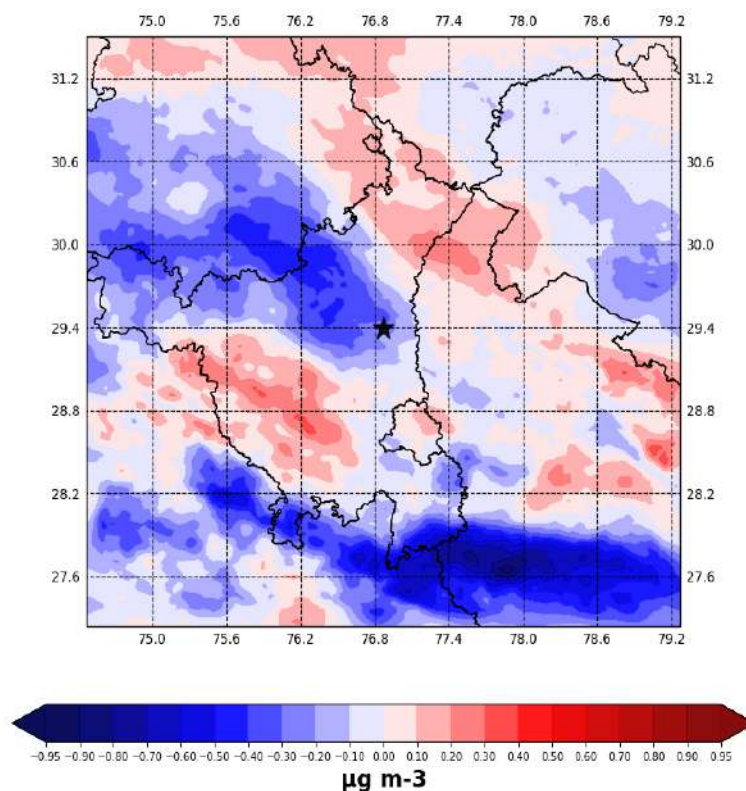


Figure 5.43: Change in monthly mean surface concentration of Sulfate aerosols (in $\mu\text{g}/\text{m}^3$) simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for October 2019. Black arrows represent wind vectors at 850hPa from the simulation with FGD implemented in this TPP.

Figure 5.43 shows the change in monthly mean surface concentration of sulfate aerosols (in $\mu\text{g}/\text{m}^3$) in the surrounding region (over the inner domain of our simulation setup) as simulated by the WRF-Chem model with and without FGD implemented in the Panipat TPP for the month of October 2019. Predominantly negative values for the change in surface concentration of sulfate aerosols across the domain as noticeable in Figure 5.43 suggests that the implementation of FGD in the Panipat TPP is likely to result in a decrease in the surface concentrations of sulfate aerosols in the surrounding region. Our results further suggest that with the implementation of FGD in the Panipat TPP, monthly mean surface concentrations of sulfate aerosols could decrease

by up to 1 $\mu\text{g}/\text{m}^3$ at some places which could be as far as 200 Km from this TPP. That means with the implementation of FGD in the Panipat TPP, we can expect to see a change in the monthly mean surface concentrations of sulfate aerosols anywhere in the range of 0-7% of the climatological values (long term monthly mean concentrations under business as usual scenario) at certain places which are far as 200 Km distant from the location of this TPP. Maximum decreases in sulfate concentrations are noted in the eastern and south eastern directions and at a distance of over 100 km from this TPP.

As noted earlier for the month of January, decreases in sulfate aerosol concentrations are more widespread across the domain as compared to the decreases in SO_2 concentrations in the month of October as well. While decreases in SO_2 concentrations are largely restricted up to a distance of about 60-80 Km from the location of the TPP, significant decreases in sulfate aerosol concentrations are noted as far as 200 km from the TPP. As mentioned earlier, this happened because the changes in the concentrations of sulfate aerosols not only depend on the changes in the concentrations of the precursor gas SO_2 but also on the changes in the concentrations of oxidants, other reactive gases, and meteorological conditions the atmosphere and differences are noted in most of these factors between the two simulations conducted with and without FGD implemented in this TPP.

Summary

We investigated the impact of FGD implementation in individual coal based TPPs in India on the near surface concentrations of two major air pollutants, namely SO_2 and sulfate aerosols in the surrounding region of these TPPs by conducting a series of chemical transport model simulations using the WRF-Chem model. In order to get a comprehensive understanding of the impact of FGD implementation in TPPs on the ambient SO_2 and sulfate aerosol concentrations in the surrounding region, multiple WRF-Chem simulations are conducted in a systematic way by choosing model domains around specific TPPs located in different geographical areas of the country and during different times of the year.

We conducted these multiple simulations because the transport and removal of air pollutants as well as formation of secondary pollutants in the atmosphere depend on meteorological conditions and presence of various oxidants in the atmosphere which vary greatly across India and during different times of the year. Results of our chemical transport model simulations suggest that with the implementation of FGD in any of the major coal based TPPs in India, we can expect to see a decrease in near surface concentrations of SO_2 in the surrounding region of the TPP (within a distance of 100 km from the location of the TPP) by an amount which may vary anywhere between 5 to 30% of the climatological values under business as usual scenario (that means without FGD implementation in the TPP).

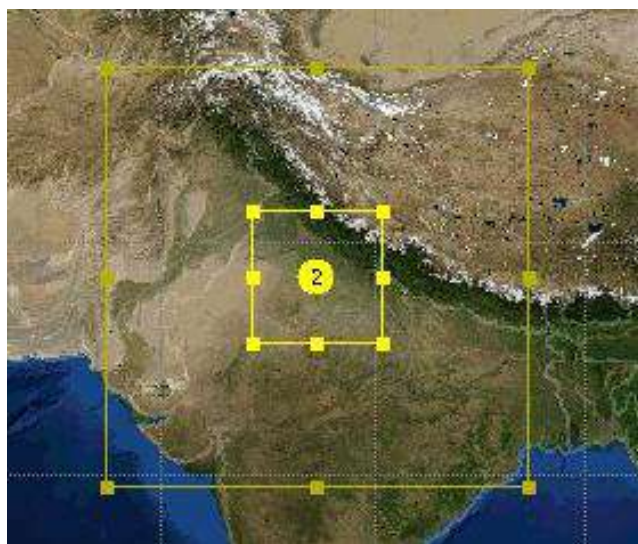
Our results further show that although the implementation of FGD or reduced emission of SO₂ from the coal based TPP can result in small decreases (up to 1% change) in SO₂ concentrations in the ambient atmosphere in the downwind areas as far as 200km from the location of the TPP but significant decreases (in the range of 5 to 30%) in SO₂ concentrations are likely to occur up to a maximum distance of about 60-80 km from the location of the TPP in the direction of maximum dispersal of the air pollutant and also depending upon the wind speed.

CHAPTER 6: SOURCE APPORTIONMENT OF AIR POLLUTANTS FOR DELHI NATIONAL CAPITAL REGION (NCR)

A series of systematically designed WRF-Chem model simulations are performed to carry out source apportionment of air pollutants for Delhi National Capital Region (NCR). Here we try understanding the contribution of different emissions sectors along with contributions of local versus remote emission contributions towards the air pollutant levels within Delhi National Capital Region (NCR) for the month of December 2018.

Model and Simulation Details

The Weather Research and Forecasting model coupled with chemistry (WRF-Chem) is a fully coupled regional weather-chemistry-climate prediction system that is designed to serve both operational forecasting and atmospheric research needs (Skamarock, 2008; Powers et al., 2017). WRF-Chem version 3.8.1 has been used in this study to simulate the atmospheric chemistry over the entire North India region for December 2018. For this study, the model domain is centered at IIT Delhi (77.19° E and 28.55° N) and covers approximately the entire North India Region at a horizontal resolution of 9 km, with 210×112 grid cells. We have used a nested domain simulation setup with the inner domain resolution of 3 km, with 198×197 grid cells. For this study, model vertical grid is composed of 37 vertical levels from the surface to ~ 10 hPa. The ERA-Interim data (available at 6 hourly intervals) with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ has been used to provide meteorological initial and lateral boundary conditions to the model.



The Model of Emissions of Gases and Aerosols from Nature (MEGAN) is used for online calculation of biogenic emissions, the Community Emissions Data System (CEDS, for use in CMIP6) is used for Anthropogenic and Biomass Burning emissions except for Black Carbon (BC) on Organic Carbon (OC) in the model simulations. The BC & OC emissions are considered from the Speciated Multipollutant Generator emission inventory for India (SMOG – v1). Model for Ozone and Related Chemical Tracers – version 4 (MOZART-4) results have been used to

provide the lateral and initial chemical boundary condition to the model, (<http://www.acom.ucar.edu/wrf-chem/mozart.shtml>) (Emmons et al., 2010). Different physical and chemical parameterization schemes used in this study are mentioned in **Table 6.1**.

Table 6.1: *Major Physics and Chemistry schemes used in this study.*

Model Resolution	2 Nested domain setup with 3 km x 3 km inner domain and 9 km x 9 km outer domain. Centered over IIT Delhi.
Meteorology	ERA-Interim meteorology.
Simulation Period	20 th Nov 2018 to 2 nd Jan 2019
Microphysics Scheme	Lin scheme
Longwave Radiation Scheme	Rapid Radiative Transfer Model new version (RRTMG) Scheme
Shortwave Radiation Scheme	Rapid Radiative Transfer Model new version (RRTMG) Scheme
Surface Layer Scheme	Revised MM5 Monin-Obukhov Scheme
Boundary-Layer Scheme	Yonsei University Scheme (YSU)
Cumulus Parameterization Scheme	Grell 3-D Scheme
Gas-phase chemical mechanism & Aerosol module Scheme	MOZART & MOSAIC (4 Bin) + VBS (Volatility Basis Set) for organic aerosol evolution

In the present study, we try to understand the contribution of different emissions sectors along with contributions of local versus remote emission contributions towards the air pollutant levels within Delhi National Capital Region (NCR) for the month of December 2018. Emissions of primary air pollutants as well as precursors to various secondary air pollutants are provided as input to the model for following sectors: **Energy** sector (mostly power plants), **Residential and Commercial** (fossil and biofuel use for cooking and heating), **Industry** (combustion and production processes, solvent use losses from production and end-use), **Land Transportation** (road and off-road vehicles), **Agriculture** (livestock and crop production), **Waste management** (solid waste, including landfills and open trash burning, residential and industrial wastewater), **Forest Fire and Grass Fire** (natural burning of forest and grassland). To estimate the sectoral emission contribution to the air pollutant levels over Delhi, A series of systematically designed WRF-Chem model simulations as listed in Table 6.2 are performed. Our control simulation is based on a business-as-usual scenario with emissions from all sectors and from across the model domain switched on. In the successive model sensitivity simulations, we either switched off the emissions from a particular emission sector or all emissions from within Delhi NCR. Difference in model output between the control simulation and various sensitivity simulations are used to quantify the contribution of individual sectors or local vs remote contributions.

Table 6.2: List of various WRF-Chem simulations performed for this study.

Model Run	Local (Delhi)	Rest of the World	Simulation Name
RUN – 01	Control	Control	CNTL
RUN – 02	All Emission (0%)	Control	NoDelhi
RUN – 03	Industrial Emission Sector (0%)		NoIND
RUN – 04	Power Emission Sector (0%)		NoENE
RUN – 05	Transport Emission Sector (0%)		NoTRA
RUN – 06	Residential Emission Sector (0%)		NoRES
RUN – 07	Agriculture Emission Sector (0%)		NoAGR
RUN – 08	Waste Burning Emission Sector (0%)		NoTRB
RUN – 09	Biogenic Emission (0%)		NoBio
RUN – 10	Biomass Burning Emission (0%)		NoBB

Results and Discussion

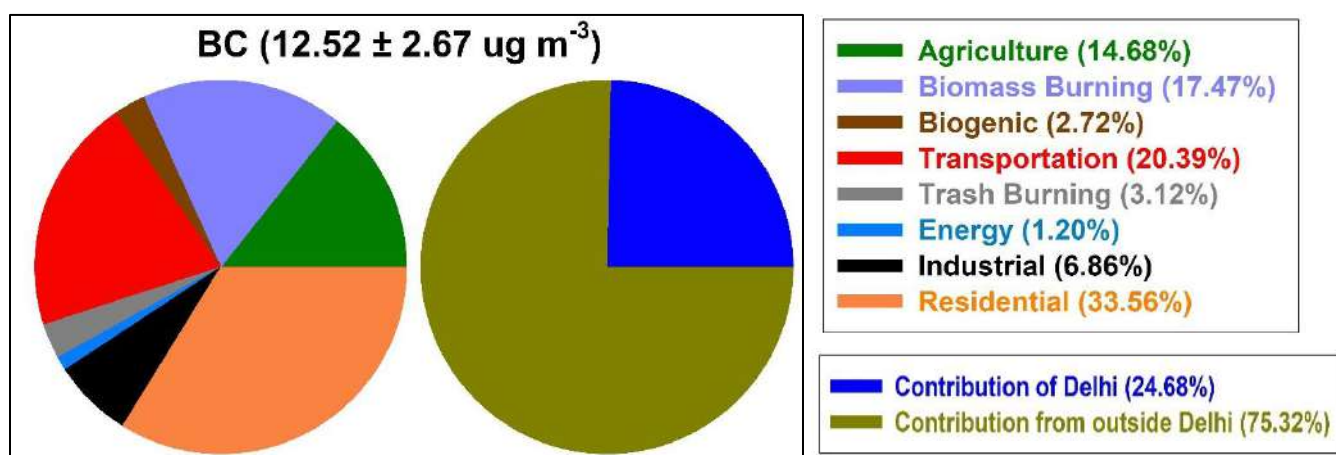


Figure 6.1: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean Black Carbon (BC) aerosol surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of BC over Delhi is mentioned in the parenthesis.

Our results suggest that maximum contribution to Black Carbon (BC) aerosol surface mass concentration over Delhi NCR for December 2018 came from the Residential sector emissions ($\sim 34\%$). Energy sector ($\sim 1\%$) has minimum contribution to Black Carbon (BC)

aerosol surface concentration over Delhi NCR for December month. Other sectors contributing significantly to Black Carbon (BC) aerosol surface concentration over Delhi NCR during December month include Transportation sector (20%), Agriculture (15%) and Biomass Burning (17%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute more (75%) than local emissions from within Delhi NCR (25%) towards the total Black Carbon (BC) aerosol surface mass concentration over Delhi NCR during the month of December.

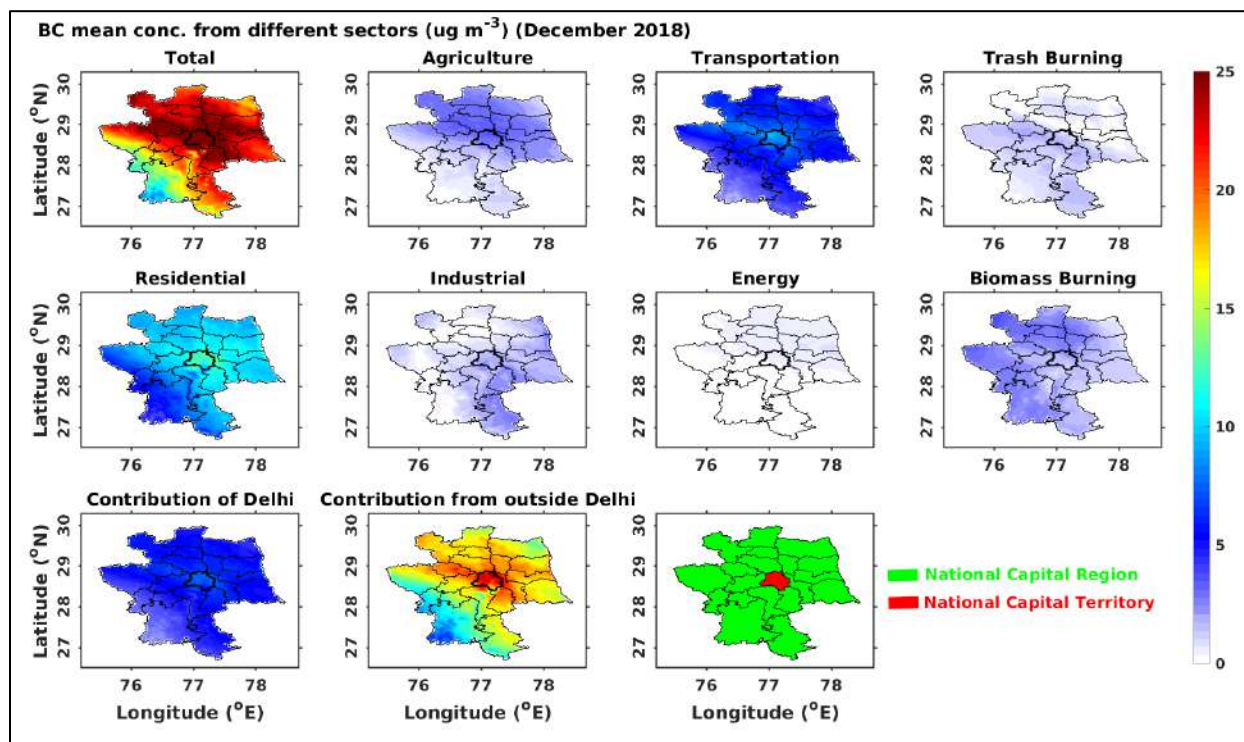


Figure 6.2: Spatial distribution of monthly mean surface mass concentration of BC (in $\mu\text{g/m}^3$) from different emission sectors over Delh NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

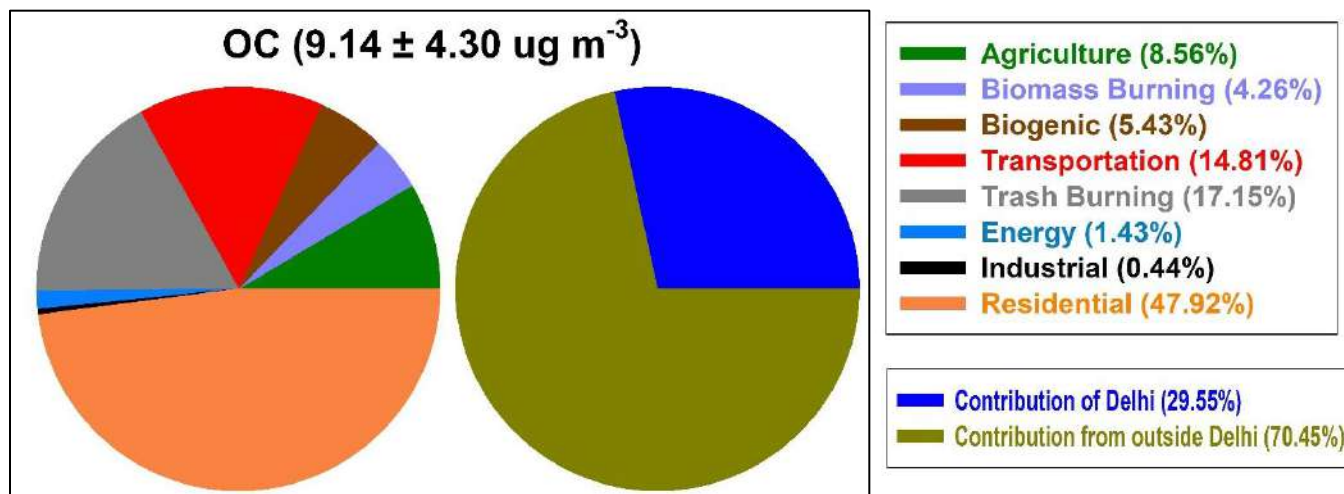


Figure 6.3: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean Organic Carbon (OC) aerosol surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of OC over Delhi is mentioned in the parenthesis.

Our results suggest that maximum contribution to Organic Carbon (OC) aerosol surface mass concentration over Delhi NCR for December 2018 came from the Residential sector emissions ($\sim 48\%$). Industrial sector and energy sector both have minimum contribution ($\sim 1\%$) to Organic Carbon (OC) aerosol surface concentration over Delhi NCR for December month. Other sectors contributing significantly to Organic Carbon (OC) aerosol surface concentration over Delhi NCR during December month include Trash burning (17%), Transportation (15%), and Agriculture (9%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute $\sim 70\%$ while local emissions from within Delhi NCR contribute $\sim 30\%$ towards the total Organic Carbon (OC) aerosol surface mass concentration over Delhi NCR during the month of December.

Our results suggest that maximum contribution to sulfur dioxide (SO_2) surface mass concentration over Delhi NCR for December 2018 came from the energy sector emissions ($\sim 63\%$). Biomass burning and agriculture sector both have minimum contribution ($<1\%$) to SO_2 surface concentration over Delhi NCR for December month. Other sectors contributing significantly to SO_2 surface concentration over Delhi NCR during December month include Industrial (19%), and Transportation (9%) sectors. Our results further suggest that remote

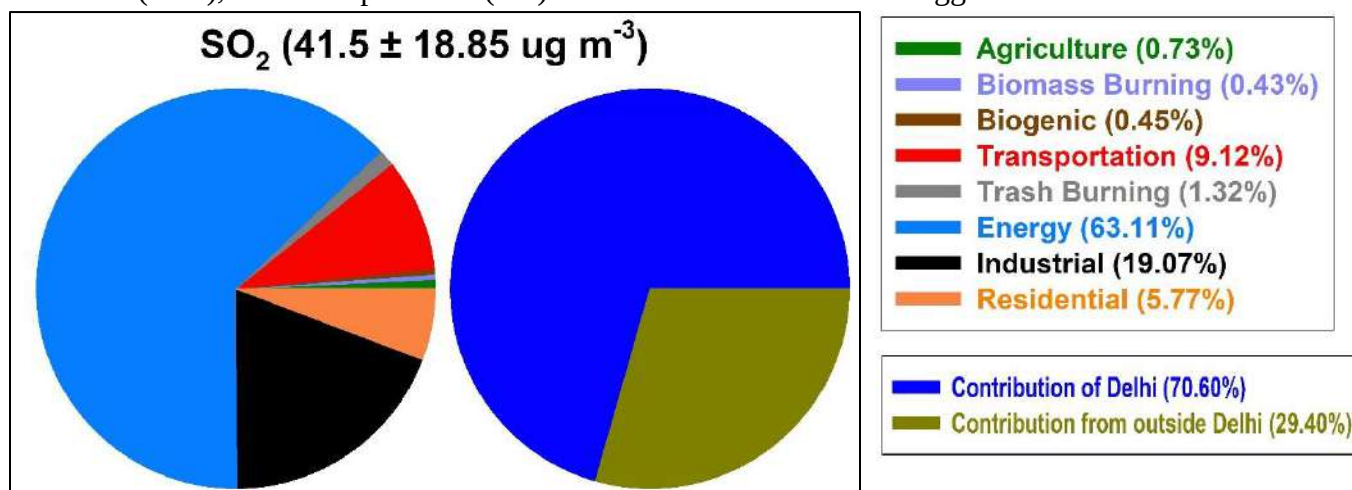


Figure 6.4: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean sulfur dioxide (SO_2) surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of SO_2 over Delhi NCR is mentioned in the parenthesis.

Emission from outside Delhi NCR contribute $\sim 29\%$ while local emissions from within Delhi NCR contribute $\sim 71\%$ towards the total SO_2 surface mass concentration over Delhi NCR during the month of December.

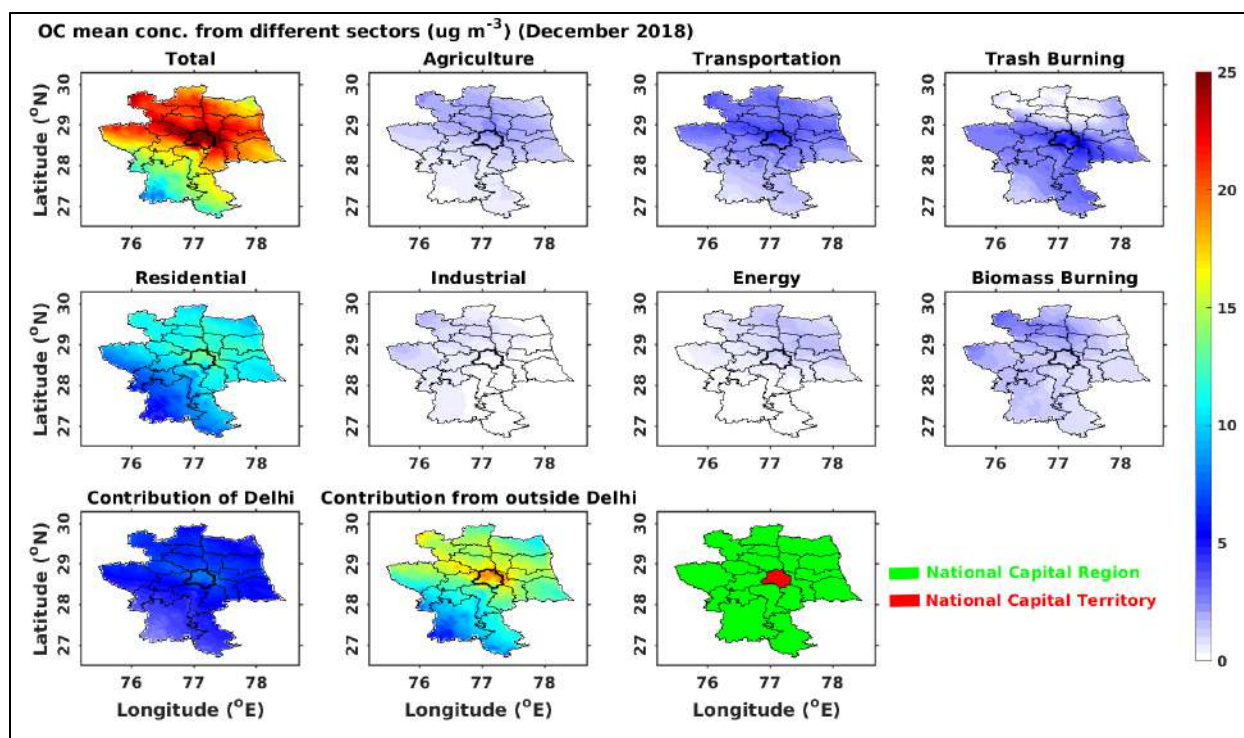


Figure 6.5: Spatial distribution of monthly mean surface mass concentration of OC (in $\mu\text{g}/\text{m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

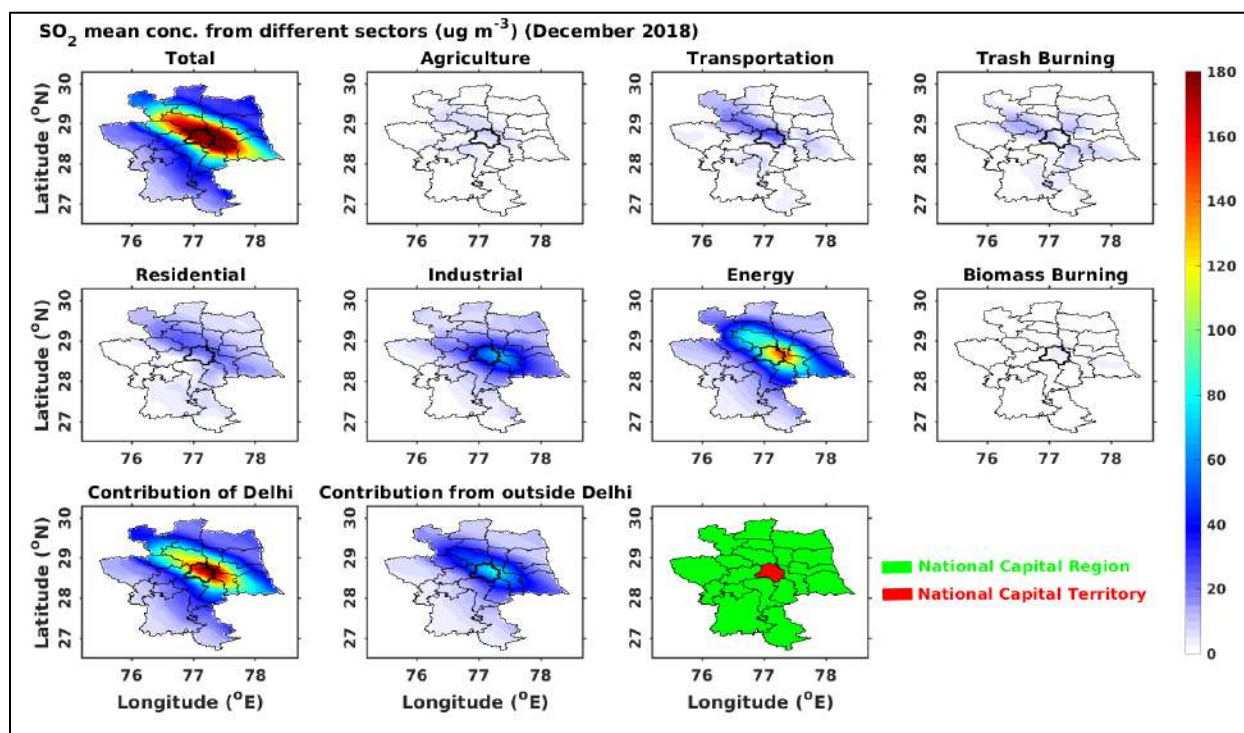


Figure 6.6: Spatial distribution of monthly mean surface mass concentration of SO_2 (in $\mu\text{g}/\text{m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

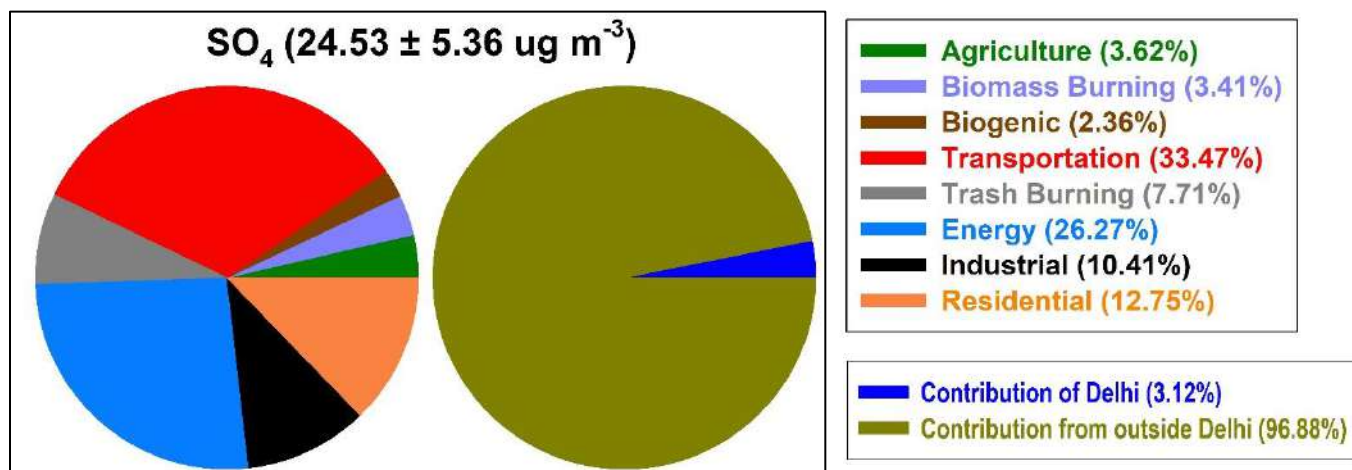


Figure 6.7: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean sulfate (SO₄) aerosol surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of sulfate (SO₄) aerosol over Delhi is mentioned in the parenthesis.

Our results suggest that maximum contribution to sulfate (SO₄) aerosol surface mass concentration over Delhi NCR for December 2018 came from the transportation sector emissions (~33%). Biogenic emissions (2%) and biomass burning (3%) both have minimum contribution towards sulfate (SO₄) aerosol surface concentrations over Delhi NCR for December month. Other sectors contributing significantly to sulfate (SO₄) aerosol surface concentration over Delhi NCR during December month include energy (26%), residential (13%) and industrial (10%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute ~97% while local emissions from within Delhi NCR contribute ~3% towards the total sulfate (SO₄) aerosol surface mass concentration over Delhi NCR during the month of December.

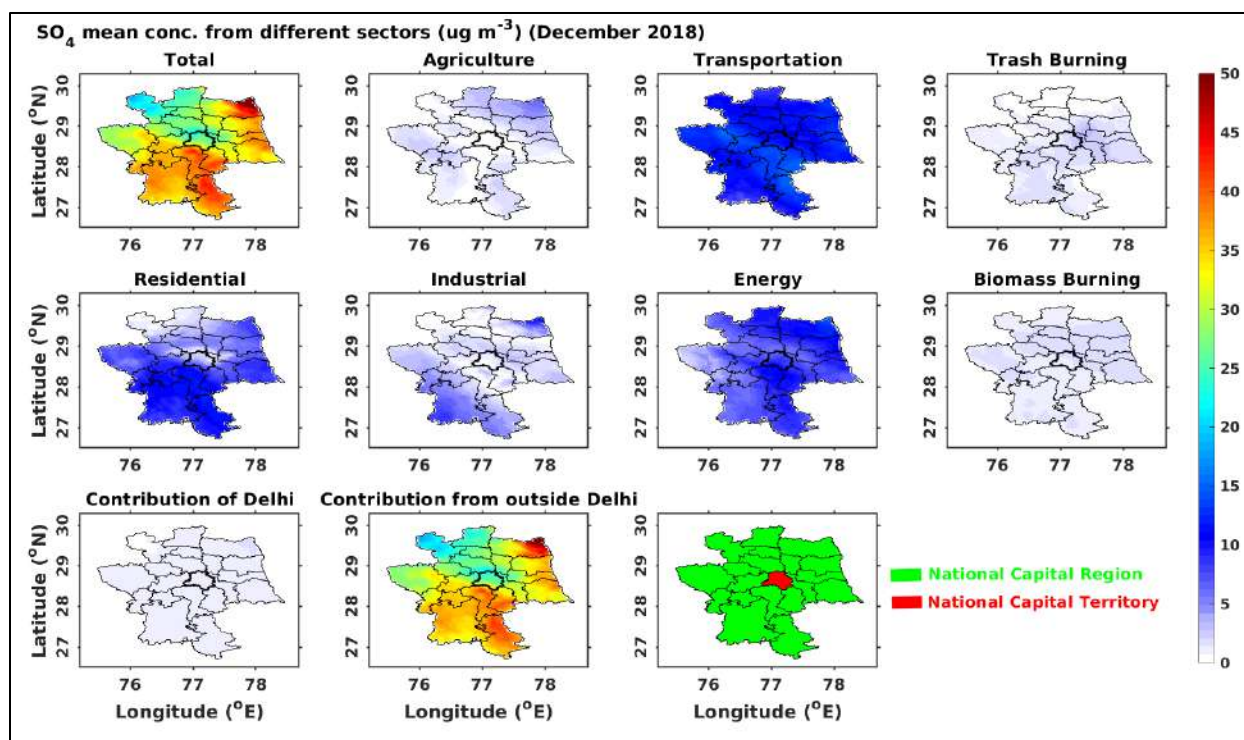
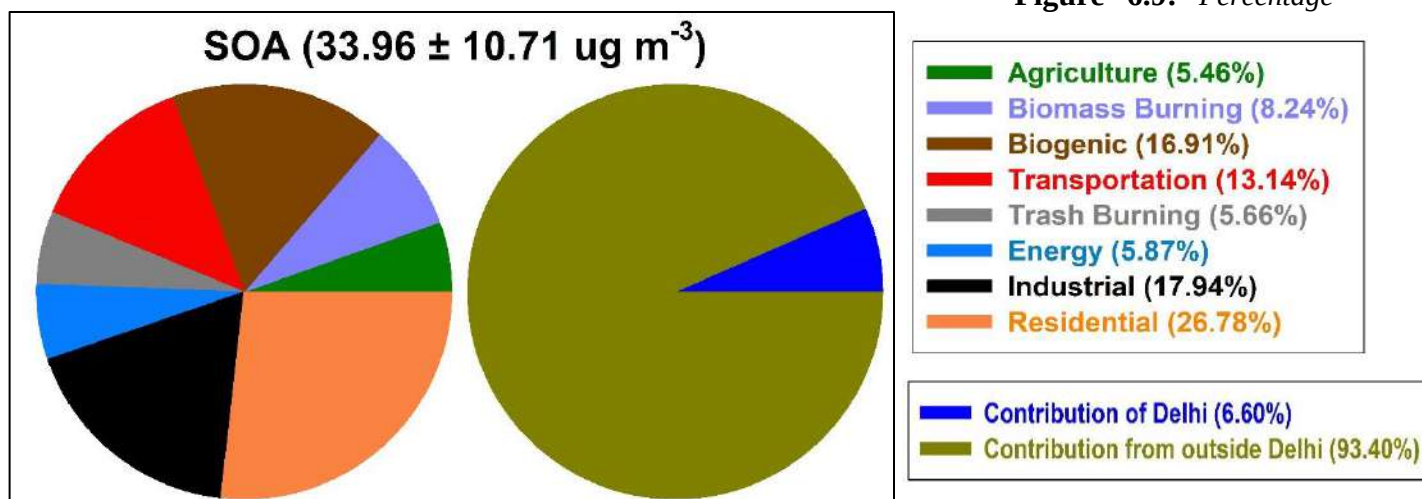


Figure 6.8: Spatial distribution of monthly mean surface mass concentration of sulfate (SO_4) aerosol (in $\mu\text{g}/\text{m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.



contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean secondary organic aerosol (SOA) surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of secondary organic aerosol (SOA) over Delhi is mentioned in the parenthesis.

Our results suggest that maximum contribution to secondary organic aerosol (SOA) surface mass concentration over Delhi NCR for December 2018 came from the residential sector emissions (~27%). Agriculture (5%) and energy sector (6%) both have minimum contribution towards secondary organic aerosol (SOA) surface concentrations over Delhi NCR for December month. Other sectors contributing significantly to secondary organic aerosol (SOA) surface concentration over Delhi NCR during December month include industrial (18%), biogenic emissions (17%) and transportation (13%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute ~93% while local emissions from within Delhi NCR contribute ~7% towards the total secondary organic aerosol (SOA) surface mass concentration over Delhi NCR during the month of December.

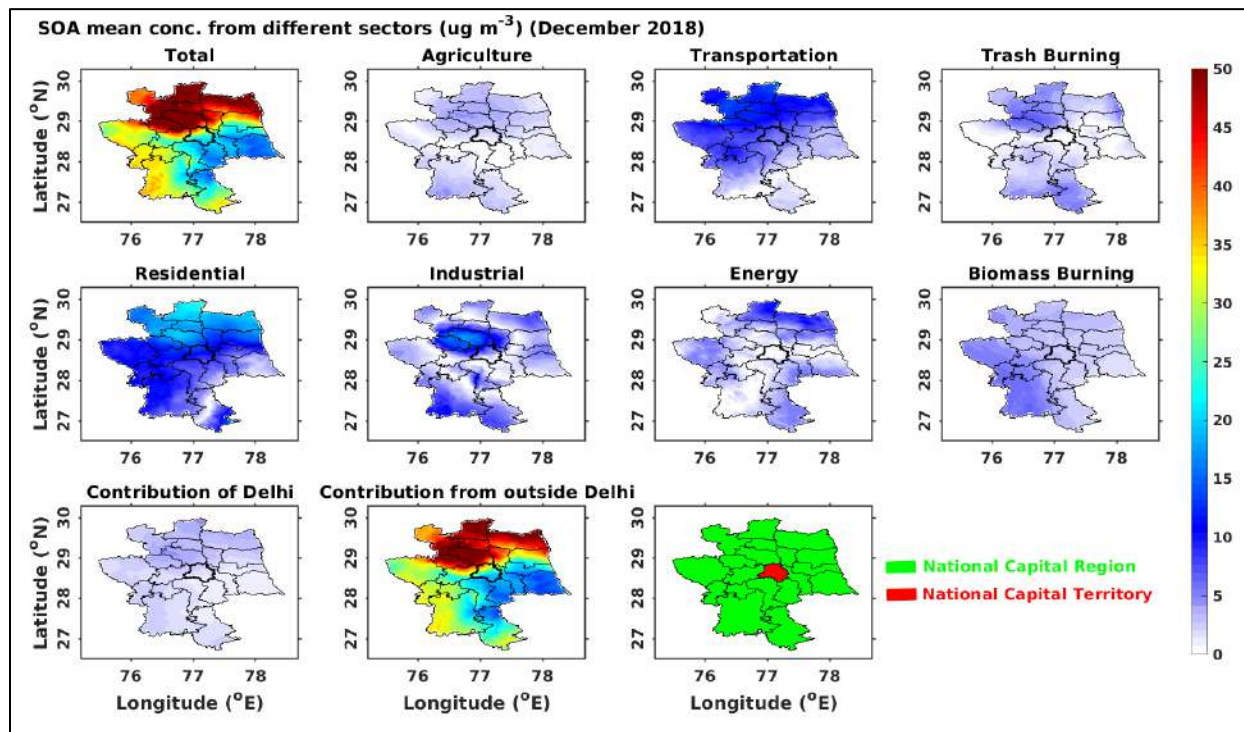


Figure 6.10: Spatial distribution of monthly mean surface mass concentration of secondary organic aerosol (SOA) (in $\mu\text{g/m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

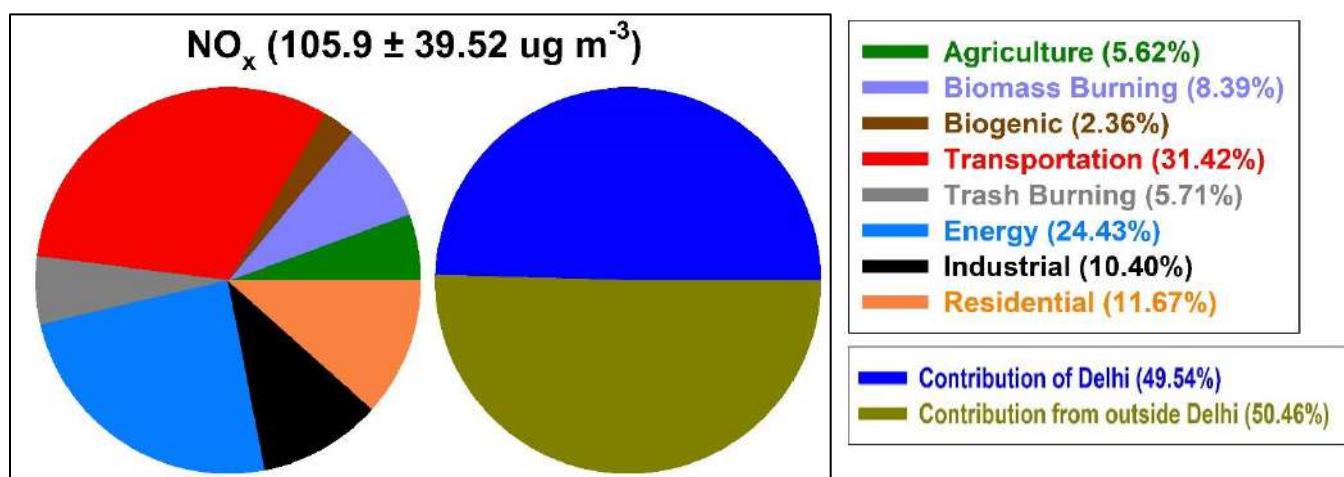


Figure 6.11: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean NO_x ($\text{NO} + \text{NO}_2$) surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of NO_x over Delhi NCR is mentioned in the parenthesis.

Our results suggest that maximum contribution to NO_x ($\text{NO} + \text{NO}_2$) surface mass concentration over Delhi NCR for December 2018 came from the transportation sector emissions (~31%). Biogenic emissions (2%) and trash burning (6%) both have minimum contribution to NO_x surface concentration over Delhi NCR for December month. Other sectors contributing significantly to NO_x surface concentration over Delhi NCR during December month include energy (24%), residential (12%), and industrial (10%) sectors. Our results further suggest that remote emissions from outside Delhi NCR and local emissions from within Delhi NCR contribute almost equally (~50% each) towards the total NO_x surface mass concentration over Delhi NCR during the month of December.

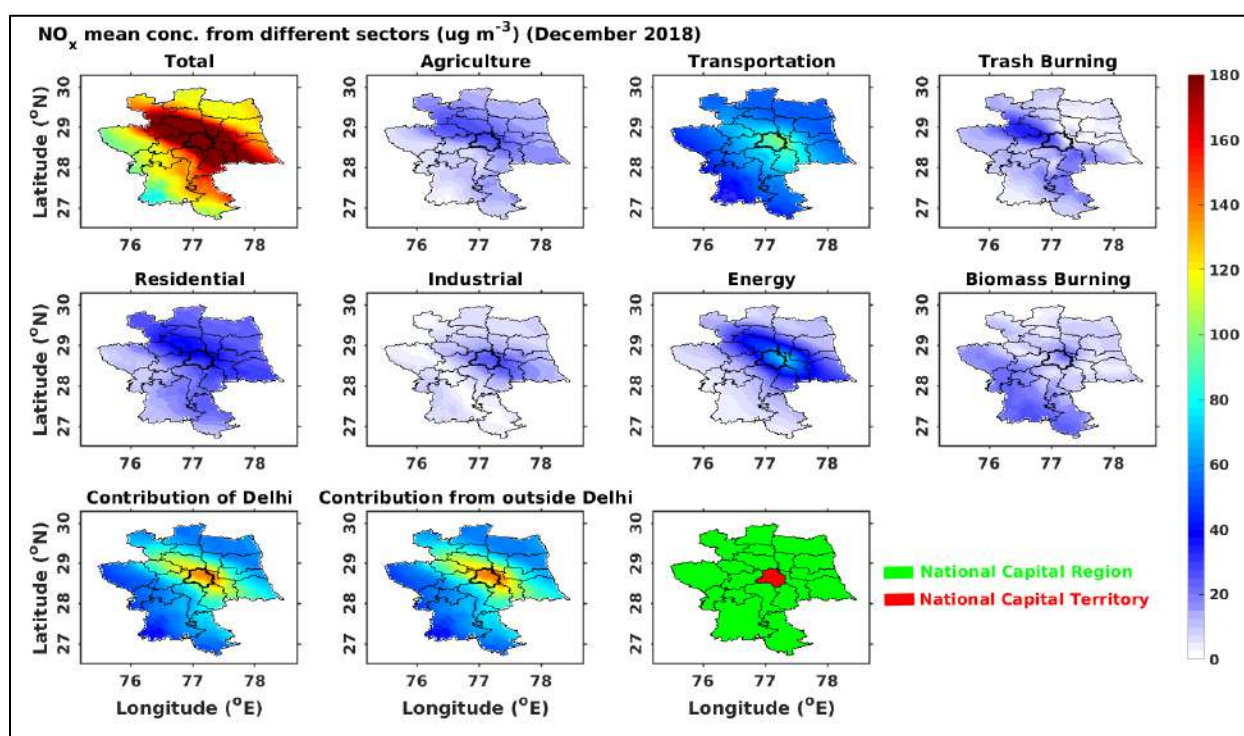


Figure 6.12: Spatial distribution of monthly mean surface mass concentration of NO_x (in $\mu\text{g}/\text{m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

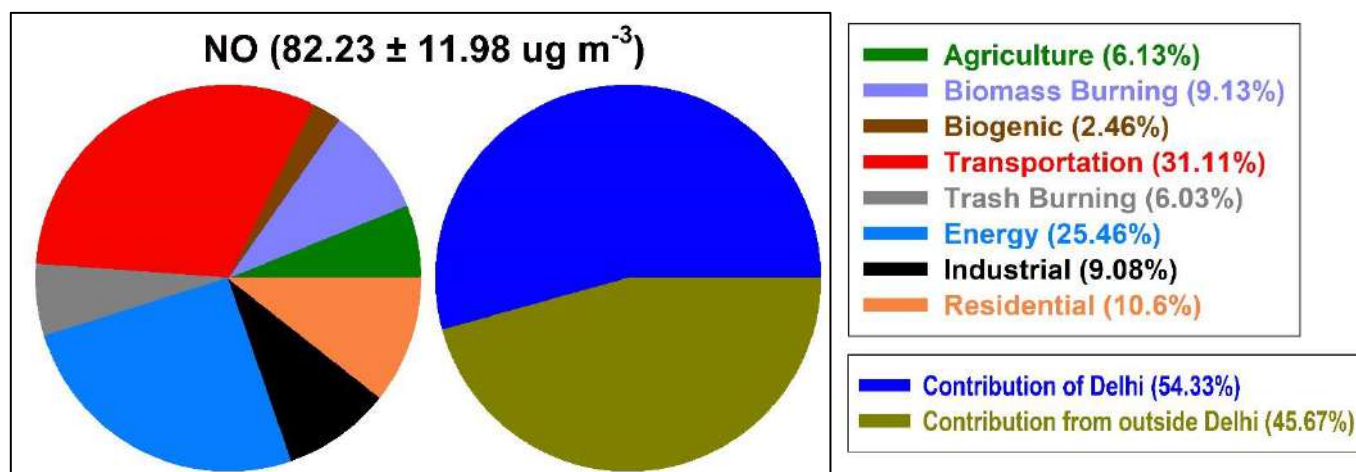


Figure 6.13: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean NO surface concentration (in $\mu\text{g/m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of NO over Delhi NCR is mentioned in the parenthesis.

The oxides of nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$) are generated by combustion activities. Generally, tailpipe emissions of NO_x contain 10-20% NO_2 , and 90-80% NO. NO can be oxidized to NO_2 by chemical species such as O_3 , HO_2 and RO_2 species. In the present study, we also wanted to know the contribution of various emission sectors as well as local versus remote emission contribution towards NO and NO_2 separately in addition to understanding the contribution of various sources towards NO_x concentration. Our results suggest that maximum contribution to NO surface mass concentration over Delhi NCR for December 2018 came from the transportation sector emissions (~31%). Biogenic emissions (2%), trash burning (6%) and agriculture (6%) sector have minimum contribution to NO surface concentration over Delhi NCR for the December month. Other sectors contributing significantly to NO surface concentration over Delhi NCR during December month include energy (25%), residential (11%), and industrial (9%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute nearly 46% while local emissions from within Delhi NCR contribute the remaining 54% towards surface mass concentration of NO over Delhi NCR during the month of December.

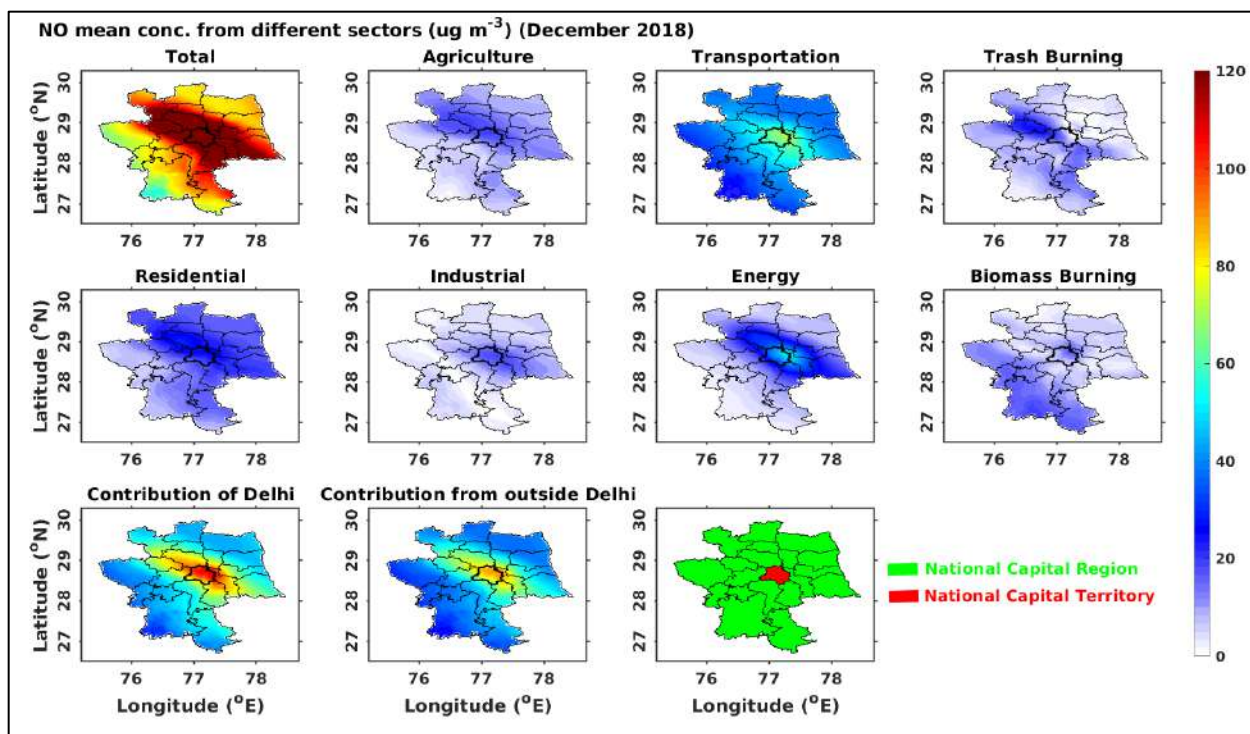


Figure 6.14: Spatial distribution of monthly mean surface mass concentration of NO (in $\mu\text{g/m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

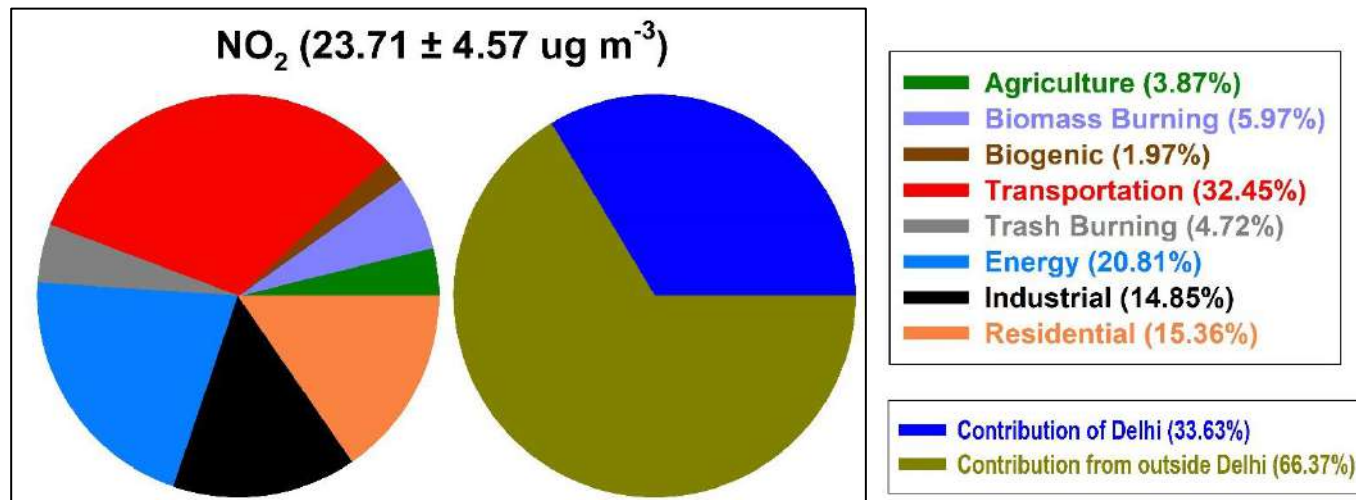


Figure 6.15: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean NO_2 surface concentration (in $\mu\text{g/m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of NO_2 over Delhi NCR is mentioned in the parenthesis.

Our results suggest that maximum contribution to PM_{10} (Particulate Matter having aerodynamic diameters as 10mm or less) surface mass concentration over Delhi NCR for December 2018 came from the residential sector emissions (~39%). Biogenic emissions (2%) and biomass burning (3%) sectors have minimum contribution towards PM_{10} surface concentrations over Delhi NCR for December month. Other sectors contributing significantly to PM_{10} surface concentration over Delhi NCR during December month include industrial (15%), transportation (10%) sectors and other sources (9%) such as wind-blown sand grains and transported dust. Our results further suggest that remote emissions from outside Delhi NCR contribute ~46% while local emissions from within Delhi NCR contribute ~54% towards the total PM_{10} surface mass concentration over Delhi NCR during the month of December

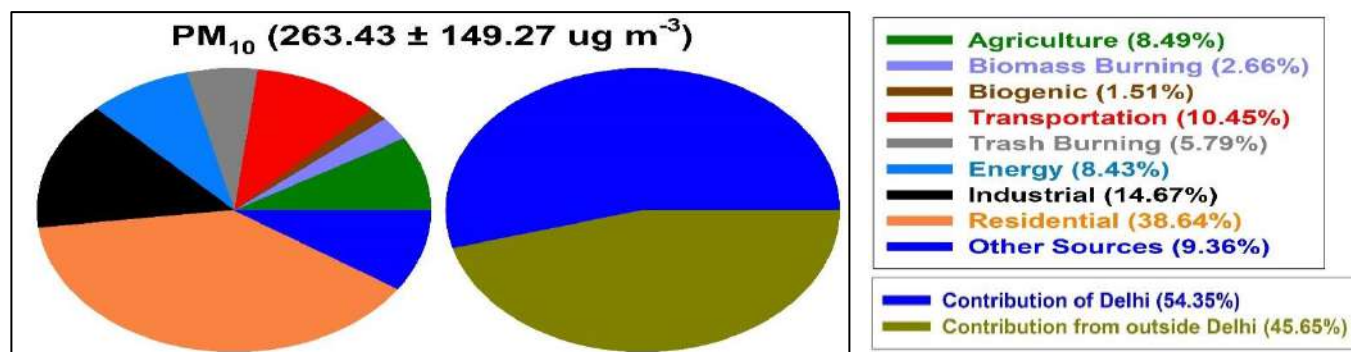


Figure 6.16: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean PM_{10} surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of PM_{10} over Delhi is mentioned in the parenthesis.

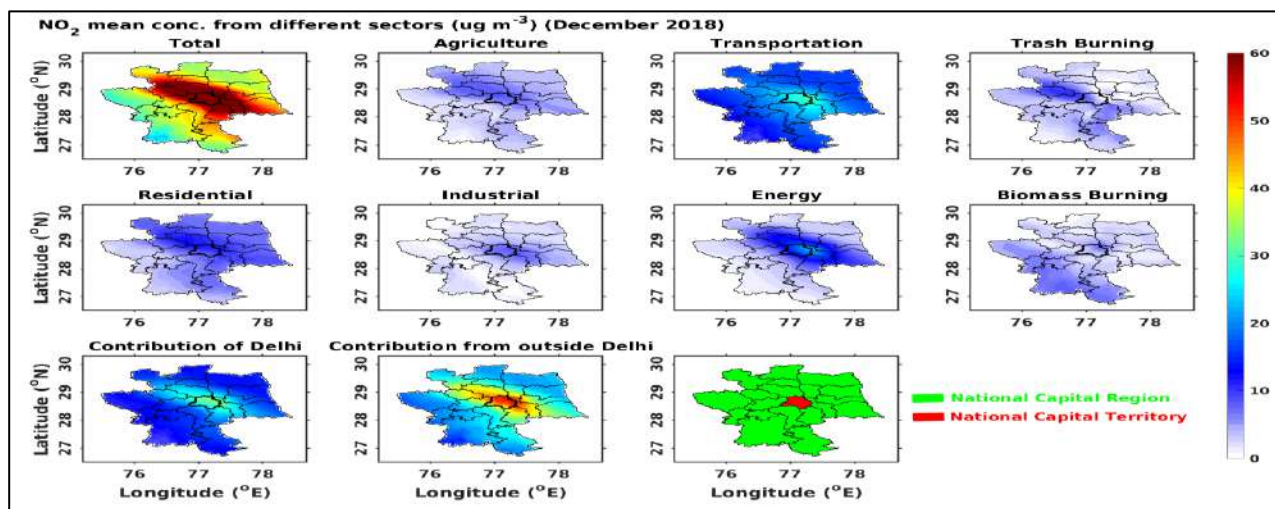


Figure 6.17: Spatial distribution of monthly mean surface mass concentration of NO_2 (in $\mu\text{g}/\text{m}^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

Our results suggest that just as in the cases of NO_x and NO , maximum contribution to NO_2 surface mass concentration over Delhi NCR for December 2018 also came from the transportation sector emissions ($\sim 32\%$). Biogenic emissions (2%), trash burning (5%) and agriculture (6%) sector have minimum contribution to NO_2 surface concentration over Delhi NCR for the December month. Other sectors contributing significantly to NO_2 surface concentration over Delhi NCR during December month include energy (21%), residential (15%), and industrial (15%) sectors. Our results further suggest that remote emissions from outside Delhi NCR contribute more (66%) as compared to local emissions from within Delhi NCR (34%) towards surface mass concentration of NO_2 over Delhi NCR during the month of December.

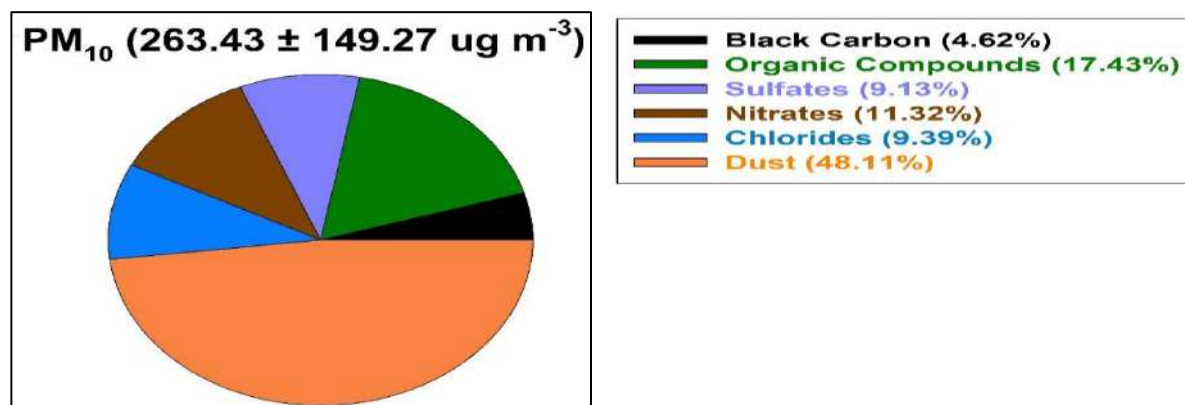


Figure 6.18: Percentage contribution of various aerosol types towards the monthly mean PM_{10} surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018.

We also estimated percentage contribution of various aerosol types towards the monthly mean PM_{10} surface concentration (in $\mu g/m^3$) over Delhi NCR for December 2018. Our results suggest that maximum contribution to PM_{10} surface mass concentration over Delhi NCR for December 2018 came from dust (naturally emitted wind-blown sand grains, transported dust as well as mineral matter and dust emitted due to various anthropogenic activities) emissions (~48%). Our results further suggest that organic compounds, nitrates, sulfates, chlorides, and BC contribute approximately 17%, 11%, 9%, 9%, and 5% respectively towards total PM_{10} surface concentrations over Delhi NCR for December month.

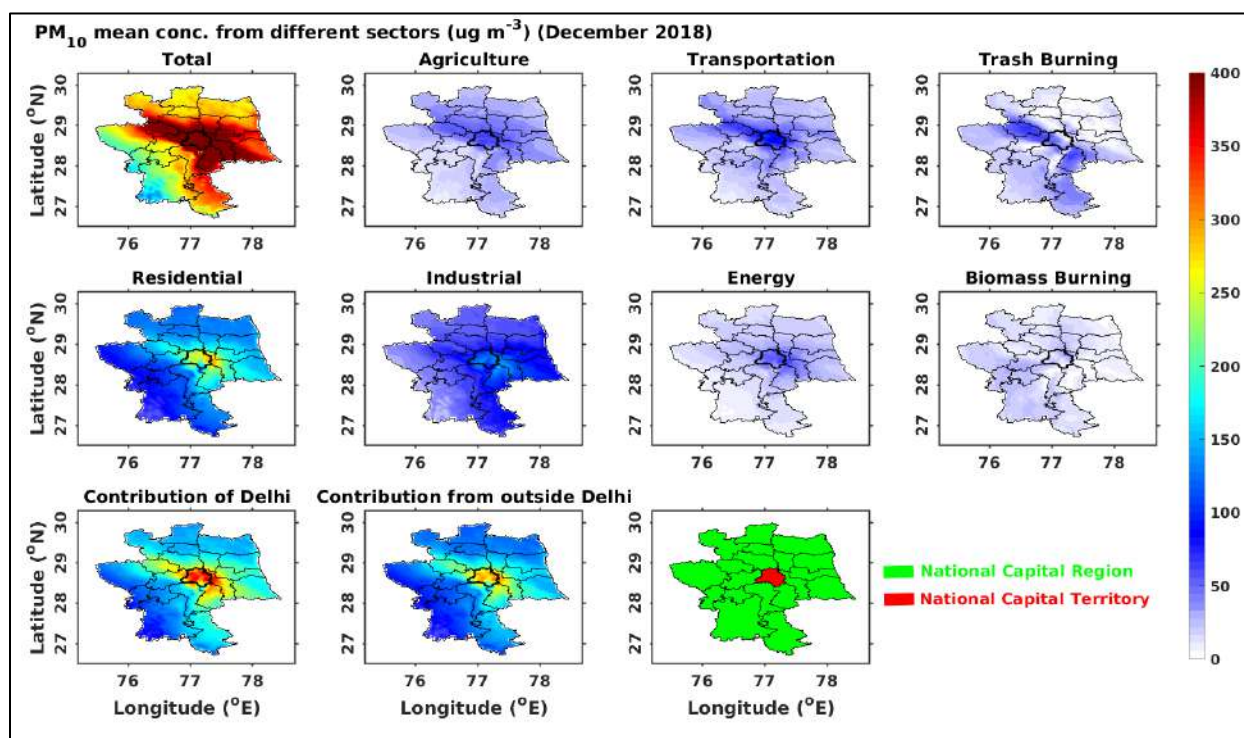


Figure 6.19: Spatial distribution of monthly mean surface mass concentration of PM_{10} (in $\mu g/m^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

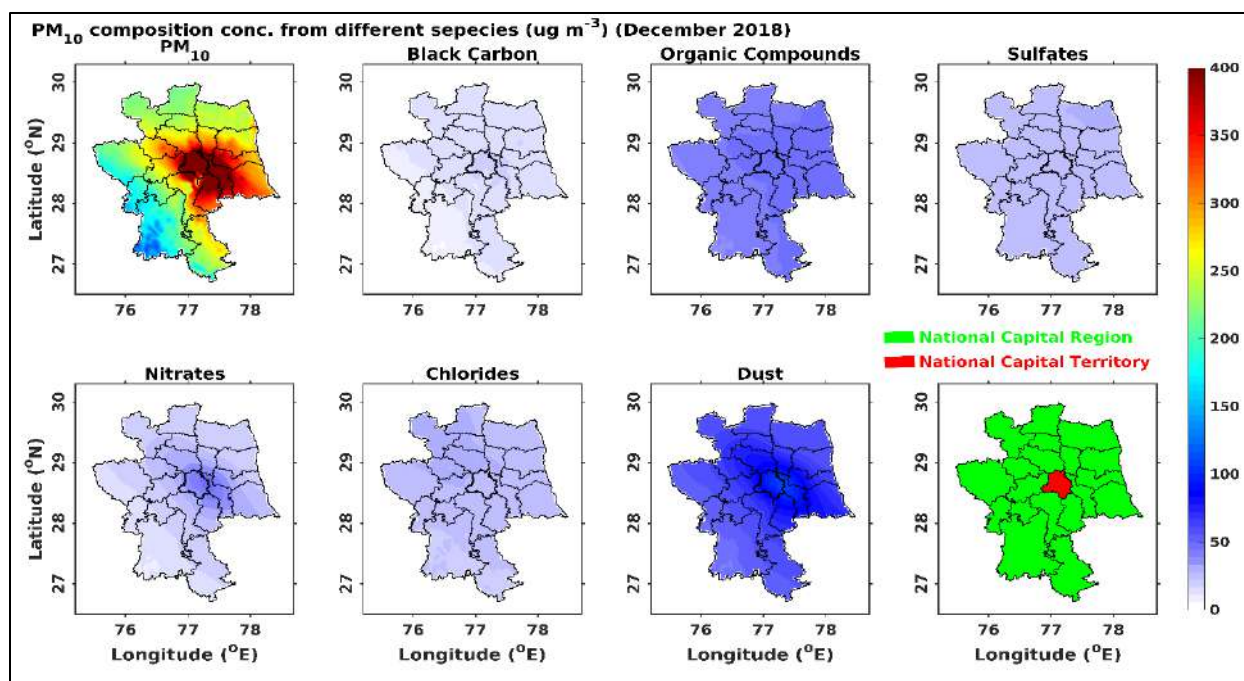


Figure 6.20: Spatial distribution of monthly mean surface mass concentration of PM₁₀ (in $\mu\text{g}/\text{m}^3$) from different aerosol types over Delhi NCR for December 2018.

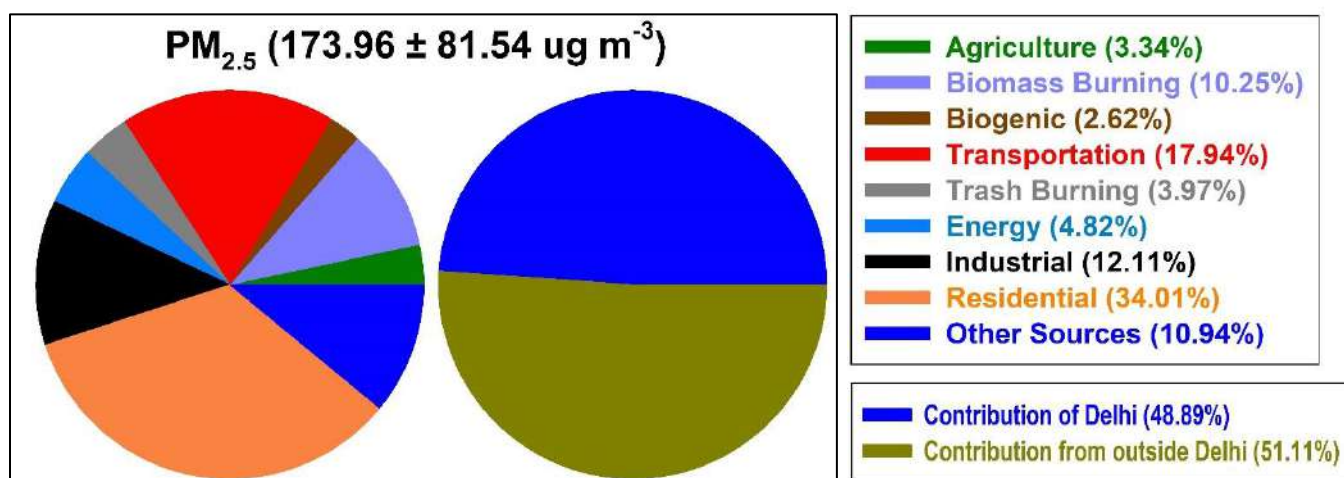


Figure 6.21: Percentage contribution of various emission sectors as well as local versus remote emission contributions towards the monthly mean PM_{2.5} surface concentration (in $\mu\text{g}/\text{m}^3$) over Delhi NCR for December 2018. Monthly mean surface concentration of PM_{2.5} over Delhi is mentioned in the parenthesis.

Our results suggest that maximum contribution to PM_{2.5} (Particulate Matter having aerodynamic diameters as 2.5mm or less) surface mass concentration over Delhi NCR for December 2018 came from the residential sector emissions (~34%). Our results further suggest that transportation sector, industrial sector, biomass burning, other sources (such as wind-blown sand grains and transported dust), energy sector, trash burning, and biogenic emissions

contribute approximately 18%, 12%, 10%, 10%, 5%, 4%, and 3% respectively towards total $PM_{2.5}$ surface concentrations over Delhi NCR for December month.

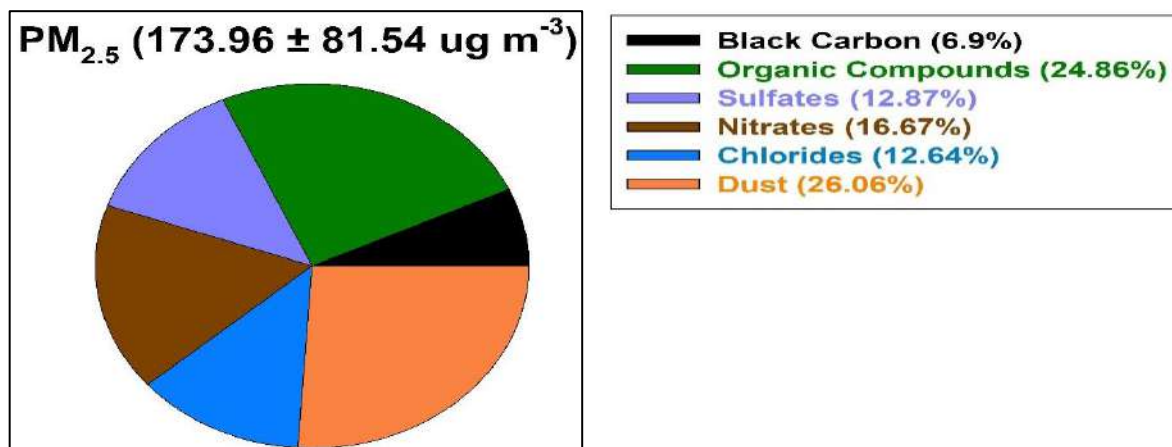


Figure 6.22: *Percentage contribution of various aerosol types towards the monthly mean $PM_{2.5}$ surface concentration (in $\mu g/m^3$) over Delhi NCR for December 2018.*

We also estimated percentage contribution of various aerosol types towards the monthly mean $PM_{2.5}$ surface concentration (in $\mu g/m^3$) over Delhi NCR for December 2018. Our results suggest that maximum contribution to $PM_{2.5}$ surface mass concentration over Delhi NCR for December 2018 came from dust (naturally emitted wind-blown sand grains, transported dust as well as mineral matter and dust emitted due to various anthropogenic activities) emissions (26%). Our results further suggest that organic compounds, nitrates, sulfates, chlorides, and BC contribute approximately 25%, 17%, 13%, 13%, and 7% respectively towards total $PM_{2.5}$ surface concentrations over Delhi NCR for December month.

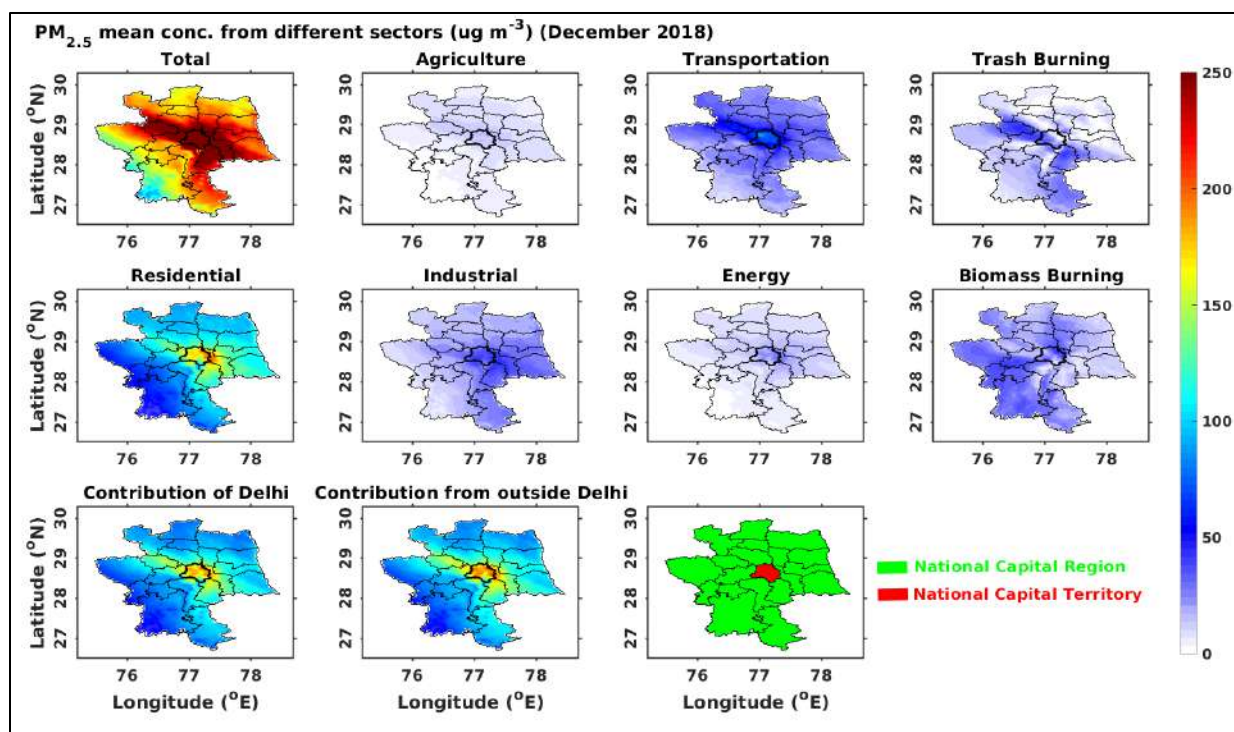


Figure 6.23: Spatial distribution of monthly mean surface mass concentration of $PM_{2.5}$ (in $\mu g/m^3$) from different emission sectors over Delhi NCR for December 2018. Contribution of emissions from remote and local sources are also shown.

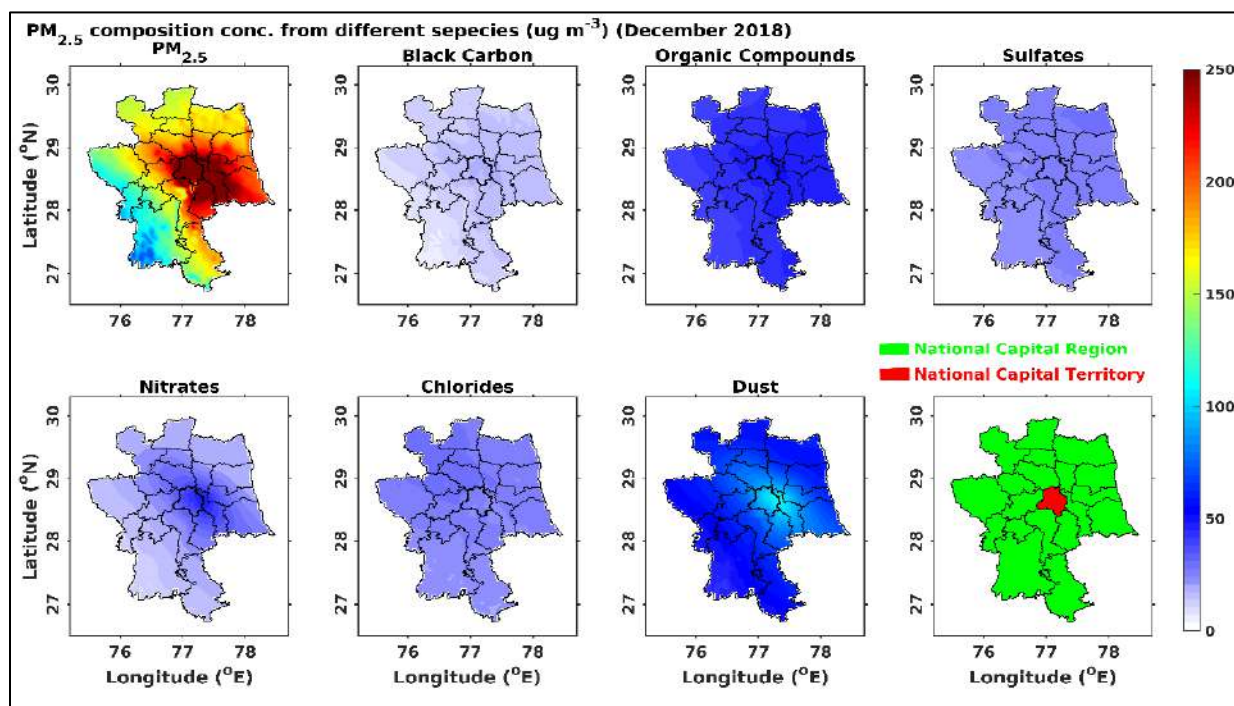


Figure 6.24: Spatial distribution of monthly mean surface mass concentration of $PM_{2.5}$ (in $\mu g/m^3$) from different aerosol types over Delhi NCR for December 2018.

References

- Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., Coen, J. L., Gochis, D. J., Ahmadov, R., Peckham, S. E., Grell, G. A., Michalakes, J., Trahan, S., Benjamin, S. G., Alexander, C. R., Dimego, G. J., Wang, W., Schwartz, C. S., Romine, G. S., ... Duda, M. G. (2017). The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions. *Bulletin of the American Meteorological Society*, 98(8), 1717–1737. <https://doi.org/10.1175/BAMS-D-15-00308.1>
- Skamarock WC, et al. (2008). A description of the advanced research WRF version 3, NCAR Tech. Note, NCAR/TN-468+STR. *Natl. Cent. for Atmos. Res. Boulder, Colorado, June*, 408. <https://doi.org/10.5065/D68S4MVH>

CHAPTER 7: ACTION PLAN FOR PHASED IMPLEMENTATION OF FGD AT ALL COAL BASED THERMAL POWER PLANTS ACROSS THE COUNTRY

Background

Ministry of Environment, Forest, and Climate Change (MOEF&CC) has issued notification no. S.O.3305 (E) titled 'Environmental (Protection) Amendment rules, 2015 dated 7.12.2015. The said notification has brought out amendments to Schedule - I of Environment (Protection) Rules, 1986 for the water consumption and emission norms applicable to thermal power stations. As per the amendment, the new emission norms that are applicable to the thermal power plants are listed in Table 7.1

Table 7.1: New (2015) regulation on emissions from TPPs in India

Emission Parameter	TPSs (Units) Installed		
	Before 31.12.03	After 31.12.03 to 31.12.16	From 01.01.17
Particulate Matter (PM)	100 mg/Nm ³	50 mg/Nm ³	30 mg/Nm ³
Sulphur Dioxide (SO ₂)	600 mg/Nm ³ for <500 MW 200 mg/Nm ³ for ≥500 MW	600 mg/Nm ³ for <500 MW 200 mg/Nm ³ for ≥500 MW	100 mg/Nm ³
Nitrogen oxides (NO _x)	600 mg/Nm ³	300 mg/Nm ³	100 mg/Nm ³

After notification of new emission norms, it has become necessary for several thermal power plants across the country to install Flue gas desulfurization (FGD) units to ensure that the emission of SO₂ from the stacks satisfy the above stipulated SO₂ emission limits.

Hence, the Central Electricity Authority (CEA) in consultation with various stakeholders prepared a detailed plan for installation of FGD in various thermal power plants across the country in a phased manner by the end of the year 2024. CEA submitted this FGD installation plan to MoEF&CC in June 2017. However, subsequently, the timeline for installation of FGD in TPPs was squeezed by MoEF&CC to December 2022. In its notification regarding standard technical specification for retrofit of Wet Limestone Based FGD system in a typical TPP, CEA made it mandatory for all supplier/manufacture of the FGD that to meet any specific level of SO₂ emission as stipulated by the MoEF&CC, the manufacturer must guarantee that the maximum SO₂ emissions level that will be achieved in the treated flue gas after the installation of the FGD in the TPP under full Turbine maximum continuous rating (TCMR) load will always

maintain some margin below the maximum limit specified by the MoEF&CC. The following table 7.1 mentions the maximum SO₂ emission level in the treated flue gas that must be guaranteed by the supplier/manufacturer of the FGD:

Table 7.2: Guaranteed maximum SO₂ level that needs to be maintained after FGD installation

SO ₂ level stipulated by MoEF&CC	Guaranteed SO ₂ level in the treated flue gas under guarantee condition (100% TMCR load)
600 mg/Nm ³	500 mg/Nm ³
200 mg/Nm ³	150 mg/Nm ³
100 mg/Nm ³	70 mg/Nm ³

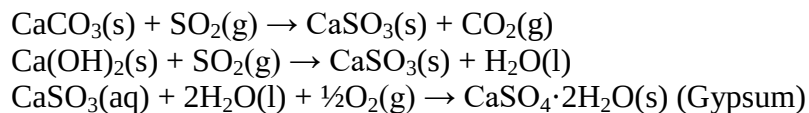
As per the CEA notification published in December 2017, the compliance of emission norms of 100 mg/Nm³ and 200 mg/Nm³, the required SO₂ removal efficiency of the installed FGD system should be in the range of 90- 95%. Similarly, for compliance of emission norms of 600 mg/Nm³, the required SO₂ removal efficiency of the installed FGD system should be in the range of 60-70%.

Flue Gas Desulfurization Technologies

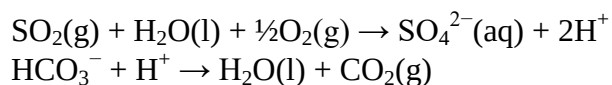
Flue gas desulfurization (FGD) is an effective method of removing sulfur dioxide (SO₂) from thermal power plant emissions through treatment of flue gases by a suitable SO₂ absorber. To curtail SO₂ emission from coal based thermal power plants, FGD units are being installed before the inlet of power plant stack in TPPs across the world. FGD removes SO₂ content from flue gas using various chemical processes. For a typical coal fired TPP, FGD may remove anywhere between 50% to 99.8% of the SO₂ in the flue gases depending upon the age of the TPP, sulfur content in coal burnt in the TPP, and type of chemical absorbers used in the FGD system. Various types of FGD technologies involving different chemical processes are available in the market. Some of the popular FGD technologies include Wet scrubbers (Limestone scrubbing, Seawater scrubbing), Spray dry scrubbers, Sorbent injection, Regenerable processes, etc. Each FGD technology requires some raw materials and leads to certain byproducts. The selection of appropriate FGD technology for a given TPP generally depends on the following major factors: (1) The cost and availability of raw materials or reagents, (2) Utilization and disposal of byproducts, (3) sulfur content in coal burnt and SO₂ content in exhaust gas, (4) Requirement of SO₂ emission reduction based on the emission norms, (5) Size or capacity of the power plant.

The chemical reactions involved in some of the most prevalent FGD technologies are mentioned below:

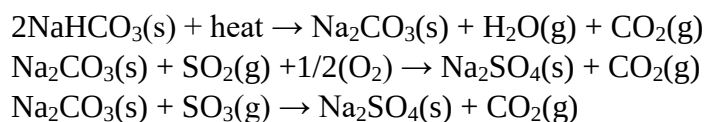
Wet limestone scrubbing FGD technology



Seawater scrubbing FGD technology



Dry Sorbent Injection (DSI) FGD technology



In the FGD market around the world, wet limestone scrubbing is the most prominent and widely used technology because of lower capital and operating expenditure involved in this and it leads to a byproduct which is marketable gypsum.

FGD manufacturing in India

To understand the indigenous FGD manufacturing capacity available within India, various private and public sector companies including international companies operating from India were approached and asked to share information regarding the FGD technologies, source of raw materials used in FGD manufacturing, cost of FGD, and timeframe for manufacturing FGD. Table 7.3 provides a list of some companies which are involved in FGD manufacturing in India. We received responses to our queries from only three FGD manufacturers, namely Bharat Heavy Electricals Limited (BHEL), GE India Pvt. Ltd., and Doosan Lentjes.

Doosan Lentjes:

Doosan Lentjes is offering 3 different FGD technologies with SO₂ removal efficiencies up to 99% and above. The three FGD technologies offered by Doosan Lentjes are Wet Limestone scrubbing FGD technology, Seawater FGD, and Circoclean FGD (a semidry process based on circulation fluidised bed for smaller applications). Low-cost desulphurisation (DSI, limestone direct injection) for plants with limited remaining lifetime is not offered by Doosan Lentjes.

According to Doosan Lentjes, a realistic time-period for implementation of a small size semidry FGD is about 24 months and for wet limestone scrubbing FGD, it is about 30-36 months after receiving the contract. Doosan Lentjes suggested the price of a wet limestone scrubbing FGD system to be around 50-60 US dollars/KW. Circoclean FGD system would cost around 35-42 US dollars/kW, and Sea Water FGD would cost around 25-30 US dollars/kW. Doosan Lentjes are currently executing the contract for installation of FGD in Mejia TPP (DVC). Doosan Lentjes is

acting as a technology provider. According to Doosan Lentjes, they are involved in implementing FGDs in about 200 TPPs across the world.

Table 7.3: List of FGD manufacturers in India

S. No.	FGD Manufacturer	S. No.	FGD Manufacturer
1	Transparent Technologies Private Ltd	15	Ducon Technologies India Pvt Ltd
2	EnviroPol Engineers Private Limited	16	McNally Bharat Engineering Co. Limited
3	K C Cottrell	17	Nalern Technologies Pvt. Ltd.
4	Rohan Engineering Enterprise	18	IDE Technologies India Pvt. Ltd.
5	UK engineering	19	Lockheed Engineering Works
6	RIECO Industries Limited	20	Technithon Technologies Private Limited
7	VS Enviro	21	Mechwell Industries Ltd
8	Whizz Engineering Service Pvt. Ltd.	22	Chanderpur Works Private Limited
9	Wintech Supply	23	Bharat Heavy Electricals Limited (BHEL)
10	Ojas Enterprise	24	GE India Pvt. Ltd
11	Awasthi Industries Ltd.	25	Doosan Lentjes
12	Green Force Engineer Pvt Ltd	26	L&T
13	Clar Aqua Private Limited	29	Thermax
14	Ferrum technologies India Pvt. Ltd.	30	S&P

Bharat Heavy Electricals Limited (BHEL)

Bharat Heavy Electricals Limited (BHEL) effectively contributes to the prevention of air pollution through its Double Contact Flow Scrubber (DCFS) for Wet limestone FGD or Sea Water based FGD, a patented technology of MHPS Japan. The Efficiency of the FGD depends on the project requirement. However, BHEL offers SO₂ reduction efficiency up to ~99%. According to BHEL, the Timeline for manufacturing and implementation of FGD is dependent on variables like Project scope, layout, configuration/sizing of FGD, other Contractual requirements etc., the estimated FGD implementation period may range from 30-42 months. FGD system comprises of various equipment's/ subsystems, including agitators, gypsum dewatering system (vacuum belt filter), Oxidation blowers, slurry recirculation pumps, wet ball mill, mist eliminator, etc. apart from civil & structural works. Adequate domestic manufacturing capacity exists for major FGD components/subsystems; with BHEL being capable of manufacturing most of the FGD equipment's in-house. However, due to factors like customer requirements (incl. DJU requirements) or to ensure cost-competitiveness, some of the equipment's/ subsystems are procured indigenously or through imports. The level of imports may vary on case-to-case basis.

According to BHEL, the Per MW cost of setting up a FGD system varies on case-to-case basis, based on various factors, like project layout, available land, Sulphur content in input fuel, soil conditions and civil works requirement, local labor availability, multiplicity of units (project configuration), etc. However, usually the per MW cost of FGD packages may vary from Rs. 0.50

to Rs.1.20 Crore/MW. The cost of the FGD implementation doesn't depend on the age of the thermal power plant as it is dependent on factors such as project scope, layout, configuration/sizing of FGD, other Contractual requirements etc.

Sufficient domestic manufacturing capacity exists in the nation for catering to current as well as future requirements of FGD implementation in the country. According to BHEL, sometimes factors like customers insistence on criteria/DJUs, availability of raw materials as well as cost differential between local and imported raw materials compel manufacturers to import FGDs or FGD components. As per BHEL, major FGD system suppliers in India are BHEL, L&T, GE, ISGEC, Techno-electric, Thermax, PES, S&P, etc. BHEL has received orders for approximately 32 GW (66 Sets) FGD units for various TPPs across India. All orders received by the BHEL are currently under execution stage.

GE Power India Ltd.

GE Power India Ltd. offers Wet scrubbing FGD based on Limestone & Sea Water, Semi Dry FGD based on lime. GE Power India Ltd. offers 99 % reductions in SO₂ emissions if limestone based wet FGD are being used and 98 % reduction in emissions if Wet scrubbing FGD based on Sea Water or Semi Dry FGD are being used. The realistic time-period required by GE Power India Ltd for FGD manufacturing and implementation in thermal power plant is at least 30 months for one wet scrubbing FGD unit, at-least 24 months for one semi dry FGD unit with phase gap of 2 months for subsequent units. According to GE Power India Ltd., since FGD does not comprise of a single manufactured item instead it is a system comprising of multiple sub-systems which are designed, engineered, and procured from various vendors for installation & commissioning at plant site, it often takes longer than anticipated time-periods (24 to 30 months) for completing the FGD installation in any TPP.

Further, according to GE Power India Ltd., as current commodity market is quite unstable and also due to covid-19 pandemic there are impacts which cannot be ascertained, however a tentative price for Limestone based wet FGD is approximately 65 Lacs / MW (excluding GST) for a minimum 2-unit configuration (Full EPC with civil, chimney, C276 absorber lining) for units up to 500 MW and above and for units 300 MW and below is approximately 110 Lacs per MW (excluding GST) for a minimum 2-unit configuration (Full EPC with civil, chimney, C276 absorber lining). However, according to GE Power India Ltd., the cost will finally depend on the technical specifications desired by the end user or consultant. Besides this, the cost of FGD is not depended on the age of TPPs whereas it is more depended on the flue gas flow, inlet SO₂ and outlet emission requirement, plant layout and civil conditions of the TPP.

Challenges involved in installation of FGDs in all TPPs by December 2022

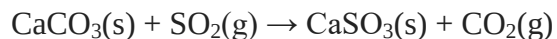
CEA has started planning for implementation of measures to comply with new emission norms issued by the MoEF&CC. More than 90% TPPs in India are suitable for installation of wet limestone based FGD system as it is economical. However, there are several genuine challenges and complex issues experienced by the CEA for the implementation of FGD system in thermal power plants across the country. For example, till the end of the year 2015 no SO₂ norms were

applicable, thus FGD manufacturing capacity was almost nonexistent in the country prior to 2015. FGD technology being new to our country, there are at present limited vendors with limited capacity to supply FGD components. Hence, there are genuine availability constraint for raw materials and components of FGD systems in the country. There has been a sudden surge of demand for FGD implementation in the country as all thermal generating units, about 470 running units of 180 GW capacity, must implement FGD system in one go to meet the timeframe given by the MoEF&CC. Proper planning was not there for development of infrastructure to meet this sudden surge in demand for FGD. Although India has the manufacturing capability of nearly 70% FGD components, it still depends on the imports from other country as manufacturing capacity is insufficient to cater to huge surge in demand in a short period of time. To boost up the indigenous production of FGD systems for meeting such huge demand as per required specifications of the TPP developers, more time (at least another 2-3 years) is required. Remaining 30% of FGD components that are not manufactured in India must be imported from other countries because to create a manufacturing capability of these items in India, it would take at least another 2-3 years. A huge foreign exchange is required for importing technology, equipment, and skilled manpower from other FGD manufacturing countries. As per CEA, placing a single order of worth nearly one lakh thirty thousand crore rupees that is required for installation of FGDs in all TPPs across the country simultaneously without ascertaining the performance of these FGDs in Indian condition may not be a correct decision. As the manufacturers of FGDs will take at least 36 months to implement the FGD in any TPP, all FGD orders are being placed in one go, targeting December 2022 deadline. However, as the timeframe for installation of FGDs instructed by the MoEF&CC is very short, there is insufficient time for fine tuning the specifications of the FGDs according to the requirement and infrastructure conditions prevailing in each individual TPPs. Moreover, due to huge gap in demand and slow supply of FGD equipment, prices of raw materials and FGD components are escalating exorbitantly, and it can also lead to market manipulation by FGD manufacturers. Impact of Covid-19 pandemic on planning, placing of order, supply chain of equipment and installation of FGD is quite severe. All these factors are likely to ultimately lead to increasing cost of electricity in the country.

In addition to the genuine concerns of CEA, we believe that although there is no doubt about the fact that FGD implementation will bring down the SO₂ emissions from the TPPs in a significant way, however, to the best of our knowledge, indeed there are no credible studies available which has quantified the overall life-cycle cost and benefits of FGD implementation in coal based TPPs, especially in the Indian context. Here are some points which demand further study to be undertaken to understand quantify the overall cost and benefits of FGD implementation in coal based thermal power plants.

Based on the most prevalent FGD technologies that are available today, it is clear that CO₂ emissions per unit power generated by coal based thermal power plants are likely to increase with FGD implemented in these thermal power plants. Primary reason for this increase in CO₂ emissions with the implementation of FGD in a coal based thermal power plants 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. For example, in wet lime FGD technology the following reaction occurs



Other FGD technologies like Dry Sorbent Injection (DSI) FGD technology and the Seawater FGD technology also involve emission of extra CO_2 into the atmosphere in addition to the CO_2 that is anyway going to be emitted due to combustion of coal in the TPPs. Thus, if the sulfur content in coal used in the TPP is about 0.5% then at least an additional 0.5% CO_2 will be emitted into the atmosphere in the process of neutralizing SO_2 by the FGD implemented in the TPP. Although Indian coal has a relatively low sulfur content in the range of 0.3 - 0.8% but, due to continuous growth in power demand and occasional shortages of domestic coal supply in the country, various developers of TPPs in the country are compelled to import coal from foreign countries to keep with the rapidly increasing power demand in India. However, sulfur content in coal imported from several foreign countries can go up to 3.5%. Hence, the quantities of additional CO_2 emitted into the atmosphere due to FGD implementation and usage of coal with high sulfur content cannot be ignored in addition to the CO_2 released by the TPPs from the combustion of coal itself. Moreover, previous studies suggest that the coal consumption in TPPs are likely to increase by at least 1 % due to increases in Auxiliary Power Consumption (APC) depending on the FGD technology implemented in the TPP and thereby result in more greenhouse gas or CO_2 emission into the atmosphere due to increased coal consumption in the TPP. Hence there is an urgent need to quantify the increases in greenhouse gas emissions (especially CO_2) with the implementation of FGD in all coal based thermal power plants in India as India has committed in the UN Climate Change Conference (COP26) held in Glasgow, U.K. in November 2021 to decrease the carbon intensity of its economy by less than 45 per cent as compared to year 2005 levels by the end of the year 2030.

Secondly, although SO_2 and sulfate aerosols which form in the atmosphere from the emissions of SO_2 are air pollutants, but numerous studies have shown that sulfate aerosols are very efficient in blocking the solar radiation from reaching the surface of the earth and hence they have contributed towards partially suppressing or offsetting the adverse impacts of global warming caused by rapid increases in emissions of greenhouse gases such as CO_2 . Since coal based thermal power plants are a major emitters of SO_2 and the implementation of FGD in thermal power plants will bring down the level of sulfate aerosols in the atmosphere, it is likely that the sudden reduction in sulfate aerosols from the atmosphere with FGD implementation in TPPs will accelerate the adverse impacts of global warming and result in faster increases in atmospheric temperature. Consequences of such rapid increases in temperature on the regional climate of India including the Indian monsoon system and extreme weather events such as floods and droughts are unknown and needs to be explored. The accelerated warming is also likely to increase the adverse impacts of heat-stress on human health. This also needs to be quantified.

Thirdly, out of the various technologies available for FGD implementation in thermal power plants in India, Wet limestone scrubbing FGD technology is the most suitable one for

implementation in the Indian context due to easy availability of limestone in India as well as lower operating expenditure involved. However, in addition to requirement of limestone, wet limestone scrubbing FGD technology also requires large supplies of water, and we have a genuine scarcity of fresh drinking water across the country. Hence, a study must be conducted to quantify the cost of additional water required by the TPPs to support the FGD systems, extra emissions of greenhouse gases and other air pollutants such as dust that are likely to happen during the extraction of limestone from the mines, including additional electricity required for limestone mining, emissions from the operation of diesel fueled trucks involved in limestone mining and transporting them to various coal based thermal power plants spread across the country.

Hence it is imperative to carry out a thorough investigation keeping in view of the above points to truly quantify the socio-economic cost and benefits of FGD implementation in coal based thermal power plants across India. Reduction in SO₂ emissions from TPPs by FGD implementation is desirable but, it is also equally important to understand if this benefit of SO₂ emission reduction is coming at a cost of increased emission of greenhouse gases which could potentially lead to accelerated global warming, and various other problems associated with it. It is crucial to understand and quantify the tangible benefits of installation of FGD in TPPs by considering its impact on extra CO₂ emission, accelerated warming of the regional climate, extra water consumption, limestone mining, transportation of limestone from the mines to the TPPs, and disposal of byproducts like gypsum etc.

Action Plan for Phased Implementation of FGD

India is committed to create a clean environment and pollution free air and water. India's commitments and obligations to environmental conservation and protection within the ambit of the targeted goals on environmental sustainability under the Sustainable Development Goals (SDGs) is manifested in several administrative and regulatory measures, including a separate statute on air and water pollution are under implementation since long by the MoEF&CC. The Air (Prevention and Control of Pollution) Act, 1981, was enacted under Art. 253 of the Constitution to implement the decisions taken at the United Nations Conference on Human Environment held at Stockholm in June 1972, in which India participated. Sustainable development, in terms of enhancement of human well-being, is an integral part of India's development philosophy.

There are multiple ways for phased implementation of FGDs in TPPs across the country. In recent years, medium and small towns and cities have also witnessed an increase in pollution, thus being fast reflected in the non-attainment cities of India. Air pollution has increasingly become a serious concern, predominantly because of its health impacts. The CPCB has identified

a list of polluted cities in which the prescribed National Ambient Air Quality Standards (NAAQS) are violated. These cities have been identified based on the ambient air quality data obtained (2011–2015) under the National Air Quality Monitoring Programme (NAMP). PM₁₀ has been found to be exceeding in 94 cities consecutively for five years and NO_x is exceeding the limits in five cities. According to the Central Pollution Control Board (CPCB) NAMP data there are currently a total of 132 non-attainment cities with million plus population in India under India National Clean Air Programme (NCAP). Based on our government's commitment to improve the air quality of all non-attainment cities in the country the following thermal power plants may be selected for the FGD implementation on the highest priority. This is one way of phased implementation of FGDs in TPPs across the country.

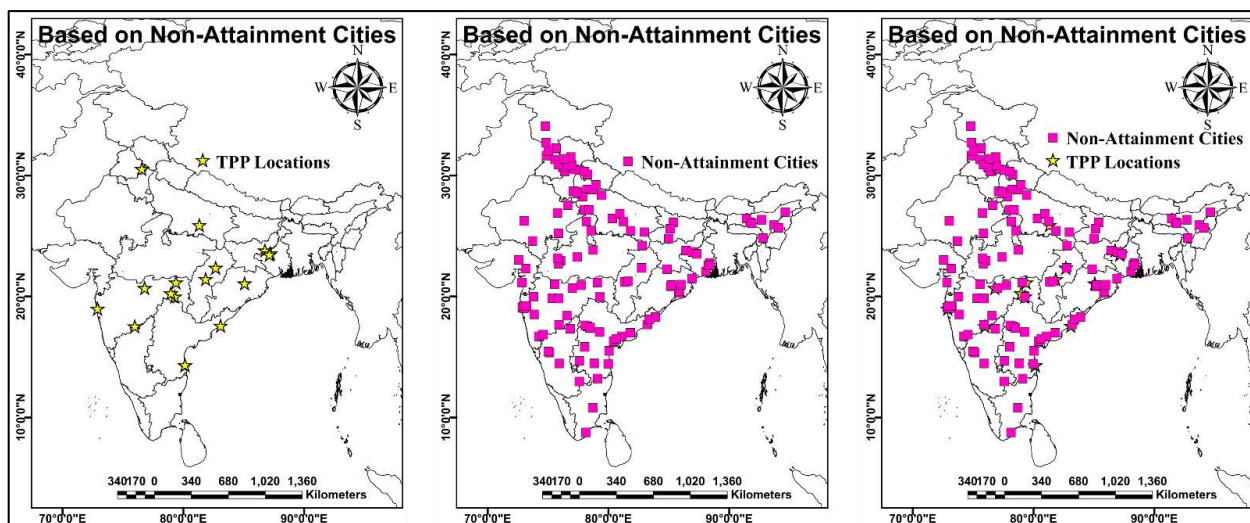


Figure 7.1: Location of all non-attainment cities across India and location of coal based TPPs present in these non-attainment cities or within a distance of 15 km from these TPPs.

Table 7.4: List of TPPs present in any of the non-attainment cities or within a distance of 15 km from these TPPs across India.

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	MAITHON RB TPP	1050	10	NABHA TPP (RAJPURA TPP)	1400
2	TALCHER STPS	3000	11	SIMHADRI TPP	2000
3	DURGAPUR STEEL TPS	1000	12	MOUDA TPS	2320
4	MEJIA TPS	2340	13	CHANDRAPUR STPS	2920
5	RAIKHEDA TPP	1370	14	WARDHA WARORA TPP	540

6	KORBA STPS	2600	15	SEMBICORP GAYATRI P.LTD.	1320
7	UNCHAHAR TPS	1550	16	PAINAMPURAM TPP	1320
8	TROMBAY TPS	930	17	SOLAPUR TPP	660
9	PARAS TPP	500			

Based on our analysis of stack emissions of SO₂ data provided by various developers of TPPs as discussed in Chapter 2 of this report, following 66 TPPs may be preferred for FGD implementation

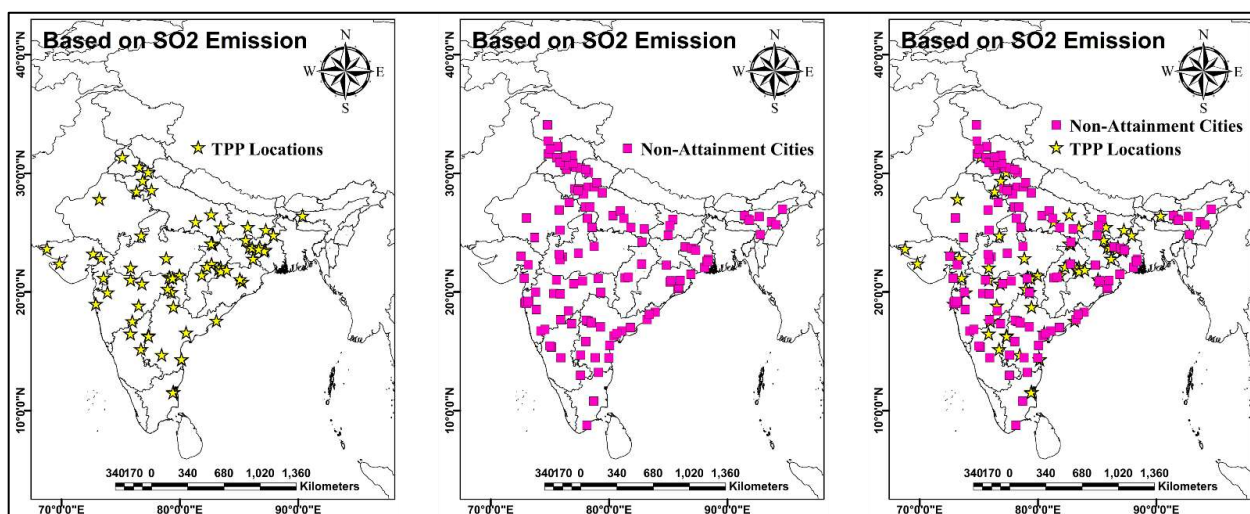


Figure 7.2: Location of all 66 TPPs across India with stack emissions of SO₂ exceeding the maximum limits as per the Environment (Protection) Amendment Rules, 2015 and non-attainment cities within a distance of 60 km from these TPPs across India.

Table 7.5: List of all 66 TPPs across India with stack emissions of SO₂ exceeding the maximum limits as per the Environment (Protection) Amendment Rules, 2015

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	BARH TPP	1320	34	FARAKKA STPS	2100
2	BOKARO TPS	500	35	YAMUNA NAGAR TPS	600
3	CHANDRAPURA TPS	500	36	NABHA TPP (RAJPURA TPP)	1400
4	KODARMA TPS	1000	37	SIMHADRI TPP	2000

5	JOJOBERA TPP	240	38	RAMAGUNDAM STPS	2600
6	MAITHON RB TPP	1050	39	GANDHI NAGAR TPS	630
7	KAMALANGA TPP	1050	40	UKAI TPS	1110
8	TALCHER STPS	3000	41	WANAKBORI TPS	1470
9	DURGAPUR STEEL TPS	1000	42	TIRORA TPS	3300
10	MEJIA TPS	2340	43	KHAPERKHEDA TPS	1340
11	RAGHUNATHPUR TPP	1200	44	KORADI TPS	2400
12	PANIPAT TPS	710	45	MOUDA TPS	2320
13	DADRI (NCTPP)	1820	46	NASIK (P) TPS	1350
14	RIHAND STPS	3000	47	CHANDRAPUR STPS	2920
15	SINGRAULI STPS	2000	48	WARDHA WARORA TPP	540
16	NEYVELI TPS	1890	49	MAHATMA GANDHI TPS	1320
17	TAQA, NEYVELI	250	50	GOINDWAL SAHIB	540
18	RAIKHEDA TPP	1370	51	DR. N. TATA RAO TPS	500
19	RAIGARH TPS	1000	52	RAICHUR TPS	1090
20	TAMNAR TPP	2400	53	YERMARUS TPP	1600
21	KORBA STPS	2600	54	SIKKA REP. TPS	500
22	SIPAT STPS	2980	55	BHUSAWAL TPS	1210
23	VINDHYACHAL STPS	4260	56	BONGAIGAON	750
24	LARA STPP	800	57	KAWAI TPS	1320
25	BARAUNI TPS EXTN.	500	58	RAYALASEEMA TPS	1050
26	UNCHAHAHAR TPS	1550	59	SEMBICORP GAYATRI P.LTD.	1320
27	TROMBAY TPS	930	60	PAINAMPURAM TPP	1320
28	PARAS TPP	500	61	BELLARY TPS	1700

29	GADARWARA STPS	1600	62	KUDGI TPP	1600
30	DARLIPALI STPS	1600	63	KUTCH LIG. TPS	215
31	TANDA TPP	1760	64	PARLI TPS	750
32	BARSINGSAR TPS	250	65	SOLAPUR TPP	660
33	KAHALGAON TPS	2590	66	KHARGONE STPP	660

However, our preferred criteria for phased implementation of FGDs across the country is based on SO₂ surface concentration (in µg/m³) climatology obtained from AURA (OMI) satellite observations and MERRA2 reanalysis data for the last five years, that is 2015-2019.

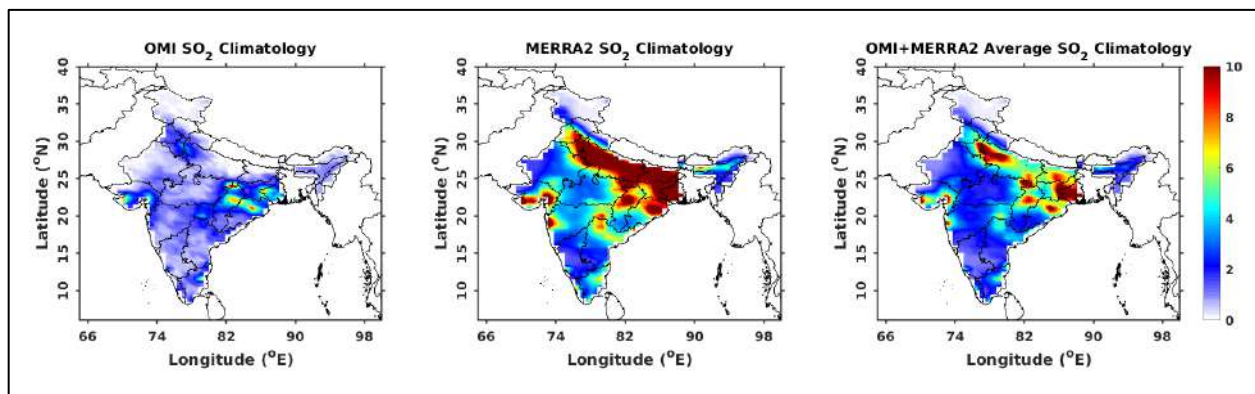


Figure 7.3: Annual mean SO₂ surface concentration (in µg/m³) climatology obtained from AURA (OMI) satellite observations, MERRA2 reanalysis data, and average of AURA(OMI) and MERRA2 data for the last five years, that is 2015-2019.

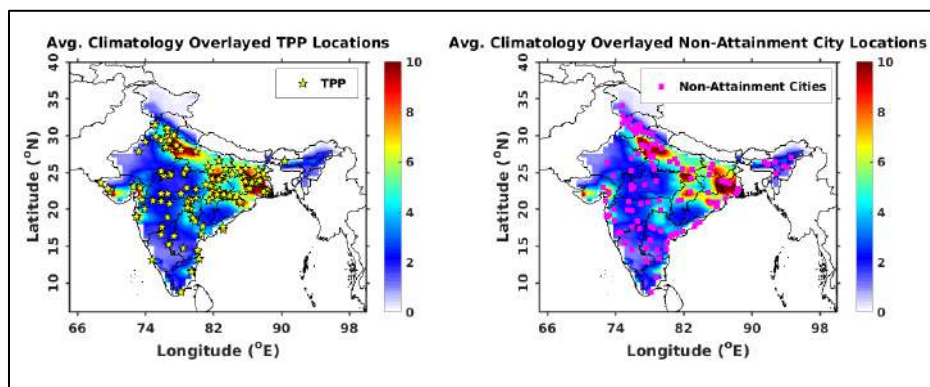


Figure 7.4: Annual mean SO₂ surface concentration (in µg/m³) climatology obtained as average of AURA(OMI) and MERRA2 data for the last five years, that is 2015-2019. Locations of various TPPs and non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration climatology.

In order to suggest a graded action plan for phased implementation of FGDs across the country based on SO₂ surface concentration climatology obtained from AURA (OMI) satellite observations and MERRA2 reanalysis, we regirded these data into five intervals as shown in Figure 7.5

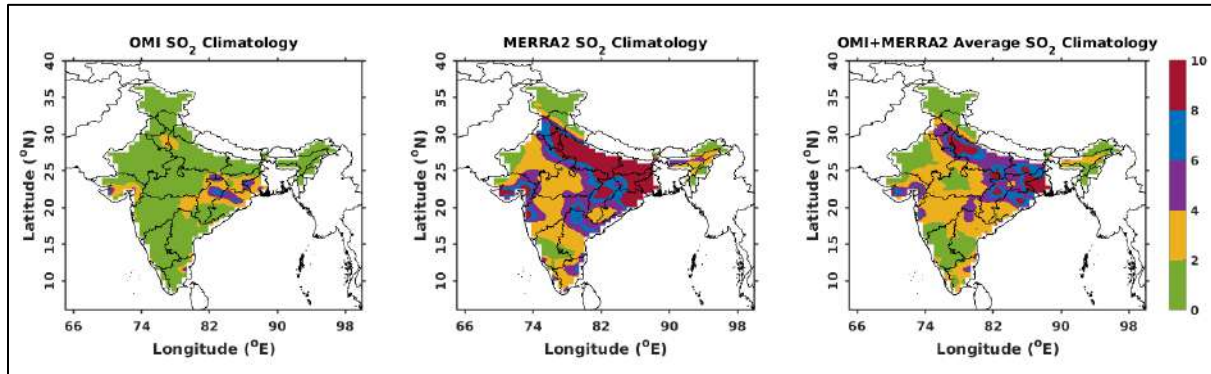


Figure 7.5: Annual mean SO₂ surface concentration (in µg/m³) climatology obtained from AURA (OMI) satellite observations, MERRA2 reanalysis data, and average of AURA(OMI) and MERRA2 data for the last five years, that is 2015-2019, regirded into five intervals.

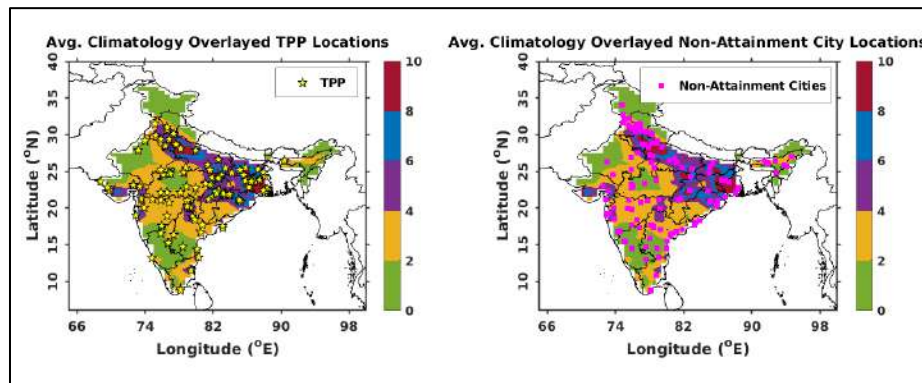


Figure 7.6: Annual mean SO₂ surface concentration (in µg/m³) climatology obtained as average of AURA(OMI) and MERRA2 data for the last five years, that is 2015-2019, regirded into five intervals. Locations of various TPPs and non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration climatology.

Considering the challenges involved in implementing FGDs in all TPPs across the country simultaneously as discussed in the previous section, it is recommended to adopt a graded action plan for phased implementation of FGDs by giving preference to areas which have highest surface concentration of SO₂ as per our analysis of satellite observations and MERRA2 reanalysis data.

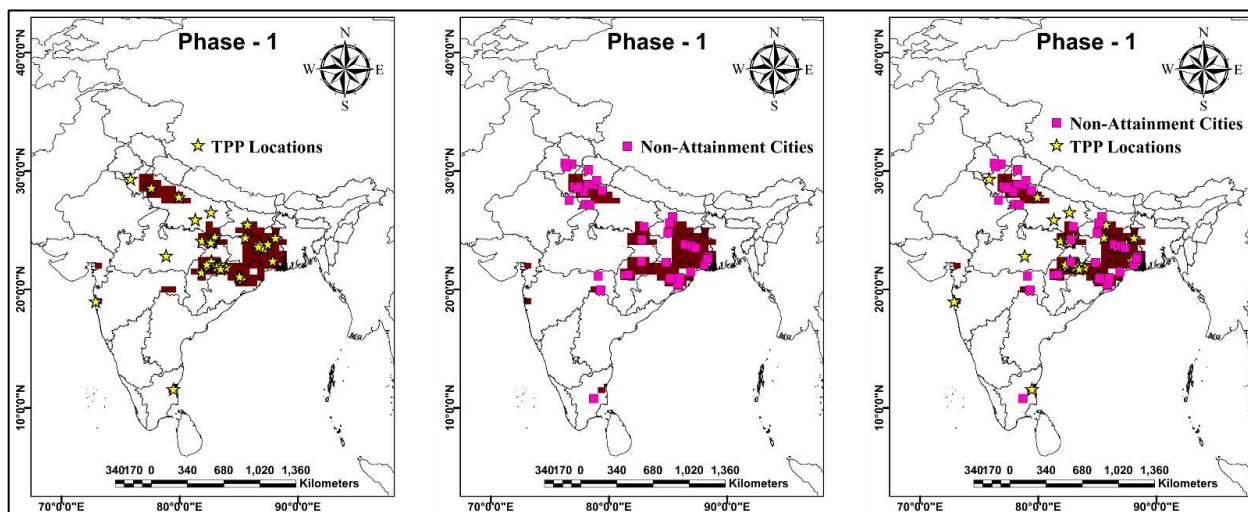


Figure 7.7: Areas with highest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. Locations of various TPPs for Phase-1 implementation of FGDs during July 2022 to July 2025 and beneficiary non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration.

Figure 7.7 shows area with highest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. It also shows the locations of various TPPs with power production capacity greater than 750MW for implementation of FGDs in Phase-1 of the graded action plan. Figure 7.7 also shows the locations of beneficiary non-attainment cities across India with Phase-1 implementation of FGDs. Since any manufacturer of FGD will likely take approximately 30-36 months to implement FGD in a typical power plant with two units of 500MW each, it is recommended that the Phase-1 of FGD implementation must be 3 years period from July 2022 to July 2025.

Table 7.6: List of TPPs with power production capacity greater than 750MW chosen for implementation of FGDs in Phase-1 of the graded action plan during July 2022 to July 2025.

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	BARH TPP	1320	21	NEYVELI TPS	1890

2	KODARMA TPS	1000	22	MARWA TPS	1000
3	MAITHON RB TPP	1050	23	DSPM TPS	1000
4	KAMALANGA TPP	1050	24	BARADARHA TPS	1200
5	DERANG TPP	1200	25	RAIKHEDA TPP	1370
6	TALCHER STPS	3000	26	AKALTARA TPS	1200
7	DURGAPUR STEEL TPS	1000	27	RAIGARH TPS	1000
8	MEJIA TPS	2340	28	TAMNAR TPP	2400
9	RAGHUNATHPUR TPP	1200	29	KORBA STPS	2600
10	KOLAGHAT TPS	1260	30	SIPAT STPS	2980
11	BAKRESWAR TPS	1050	31	UCHPINDA TPP	1080
12	SAGARDIGHI TPS	1600	32	NIGRI TPP	1320
13	RAJIV GANDHI TPS	1200	33	VINDHYACHAL STPS	4260
14	ANPARA C TPS	1200	34	SASAN UMTTP	3960
15	DADRI (NCTPP)	1820	35	LARA STPP	800
16	RIHAND STPS	3000	36	GADARWARA STPS	1600
17	SINGRAULI STPS	2000	37	DARLIPALI STPS	1600
18	ROSA TPP PH-I	1200	38	TANDA TPP	1760
19	ANPARA TPS	2630	39	UNCHAHAR TPS	1550
20	OBRA TPS	1000	40	TROMBAY TPS	930

After Phase-1 of FGD implementation in around 40 TPPs, a study must be conducted to ascertain the performance of these FGDs at least over a period of next one year and confirm the benefits of FGD implemented in these TPPs vis-a-vis impact of increased emission of greenhouse gases and its consequences in terms of extreme weather events such as floods and droughts.

Next, Phase-2 of FGD implementation should happen in around 49 TPPs should start from July 2026 and completed by July 2029. The list of FGDs selected for Phase-2 implementation of

FGDs not only include TPPs located in areas with second highest annual mean SO₂ surface concentration values but also remaining TPPs from areas with highest annual mean SO₂ surface concentration but having the power production capacity less than 750MW. A four-year time period between start of the Phase-1 and Phase-2 of FGD implementation will also allow us to see the emergence of new FGD technologies which could possibly consume less water, avoid any extra emission of greenhouse gases such as CO₂ with FGD implementation. This time gap between Phase-1 and Phase-2 of FGD implementation will also allow local Indian domestic companies to improve their FGD manufacturing capabilities with minimum or zero imports of FGD raw materials and components (promote “Atma-Nirbhar Bharat” mission of the Government of India). In order to ensure tangible benefits of installation of FGD units in TPPs, it is important to take advantage of any new and upcoming innovative technology of SO₂ emission control without extra CO₂ emission into the atmosphere and hence go for a phased implementation of FGDs.

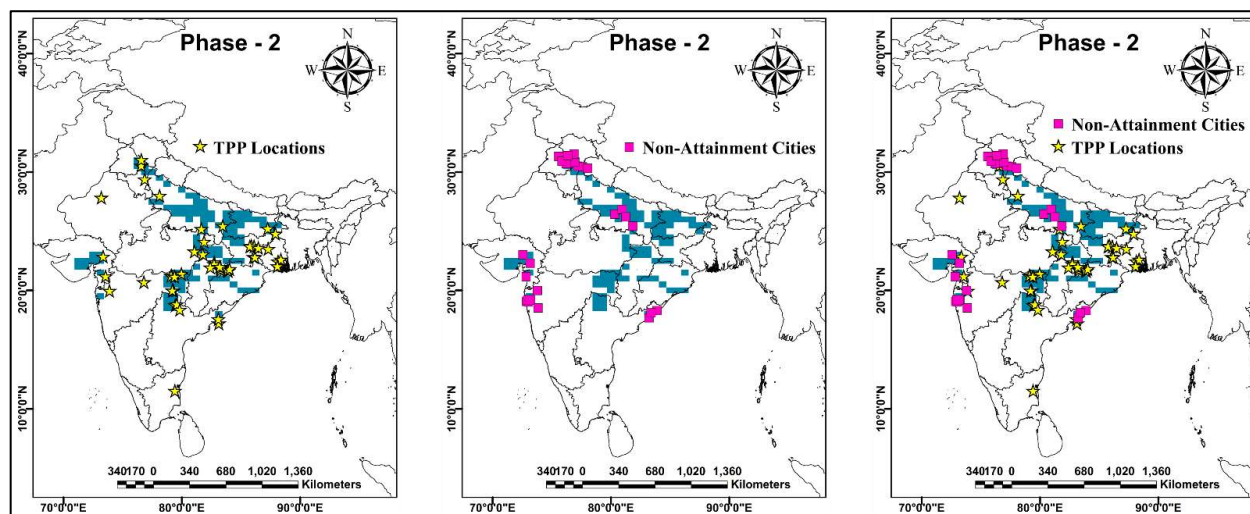


Figure 7.7: Areas with second highest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. Locations of various TPPs for Phase-2 implementation of FGDs during July 2026 to July 2029 and beneficiary non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration.

Table 7.7: List of TPPs chosen for implementation of FGDs in Phase-2 of the graded action plan during July 2026 to July 2029.

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	KAHALGAON TPS	2590	26	CHANDRAPURA TPS	500
2	FARAKKA STPS	2100	27	IB VALLEY TPS	420
3	NABHA TPP (RAJPURA	1400	28	STERLITE TPP	600

	TPP)				
4	PRAYAGRAJ TPP	1980	29	BUDGE BUDGE TPS	750
5	VIZAG TPP	1040	30	SOUTHERN REPL. TPS	136
6	SIMHADRI TPP	2000	31	D. P. L. TPS	300
7	RAMAGUNDAM STPS	2600	32	HALDIA TPP	600
8	SINGARENI TPP	1200	33	INDIA POWER TPP	150
9	KAKATIYA TPS	1100	34	SANTALDIH TPS	500
10	UKAI TPS	1110	35	PANIPAT TPS	710
11	WANAKBORI TPS	1470	36	HARDUAGANJ TPS	500
12	ANUPPUR TPP	1200	37	TAQA, NEYVELI	250
13	SANJAY GANDHI TPS	1340	38	BALCO TPS	600
14	TIRORA TPS	3300	39	AVANTHA BHANDAR	600
15	KHAPERKHEDA TPS	1340	40	PATHADI TPP	600
16	KORADI TPS	2400	41	BINJKOTE TPP	300
17	MOUDA TPS	2320	42	NAWAPARA TPP	300
18	NASIK (P) TPS	1350	43	MAHAN TPP	600
19	ROPAR TPS	840	44	DHARIWAL TPP	600
20	CHANDRAPUR STPS	2920	45	BARAUNI TPS EXTN.	500
21	IND BARATH TPP	350	46	AKALTARA TPS	600
22	TENUGHAT TPS	420	47	BINJKOTE TPP	300
23	JOJOBERA TPP	240	48	PARAS TPP	500
24	MAHADEV PRASAD STPP	540	49	BARSINGSAR TPS	250
25	BOKARO TPS	500			

Hoping that the indigenous capacity of FGD manufacturing in India to grow significantly by the year 2029 and also new and better FGD technologies to be available in the market by then, it might take lesser time (maximum 24 months) to implement FGDs in rest of the TPPs from Phase-3 onward. Phase-3 of FGD implementation should happen in around 27 TPPs and it can start from July 2029 and completed by July 2031. Figure 7.8 shows area with third highest annual mean SO₂ surface concentration data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. It also shows the locations of various TPPs identified for implementation of FGDs in Phase-3 of the graded action plan. Figure 7.8 also shows the locations of beneficiary non-attainment cities across India with Phase-3 implementation of FGDs.

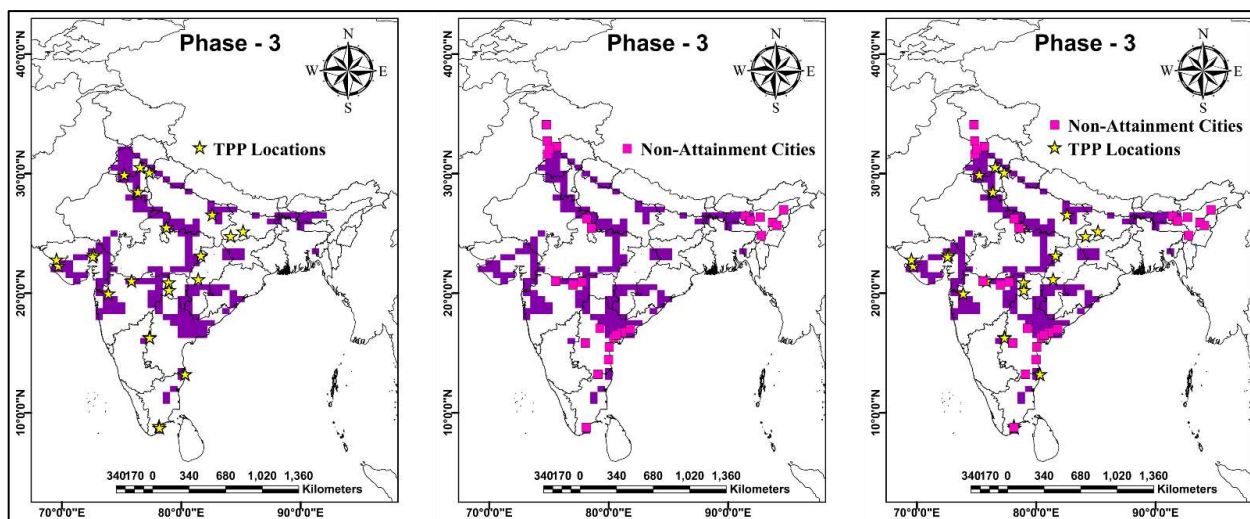


Figure 7.8: Areas with third highest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. Locations of various TPPs for Phase-3 implementation of FGDs during July 2029 to July 2031 and beneficiary non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration.

Table 7.8: List of TPPs chosen for implementation of FGDs in Phase-3 of the graded action plan during July 2029 to July 2031.

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	MAHATMA GANDHI TPS	1320	15	YAMUNA NAGAR TPS	600
2	INDIRA GANDHI STPP	1500	16	GH TPS (LEH.MOH.)	670
3	TALWANDI SABO TPP	1980	17	BHILAI TPS	500

4	PARICHHA TPS	920	18	GANDHI NAGAR TPS	630
5	RAICHUR TPS	1090	19	SABARMATI	120
6	YERMARUS TPP	1600	20	AMARKANTAK EXT TPS	210
7	MUTHIARA TPP	1200	21	EMCO WARORA TPS	600
8	VALLUR TPP	1500	22	NASIK TPS	630
9	TUTICORIN (JV) TPP	1000	23	WARDHA WARORA TPP	540
10	NORTH CHENNAI TPS	1830	24	BUTIBORI TPP	600
11	MUNDRA UMTTP	5000	25	TADA TPS	440
12	MUNDRA TPS	2640	26	NABI NAGAR TPP	250
13	SALAYA TPP	1200	27	MUZAFFARPUR TPS	630
14	BHUSAWAL TPS	1210			

Along with the Phase-3 of FGD implementation, CEA must conduct another study to ascertain the performance of the FGDs installed in Phase-1 and Phase-2 and confirm the benefits of FGD implemented in these TPPs. Phase-4 of FGD implementation should happen in around 21 TPPs and it can start from July 2031 and completed by July 2033. Figure 7.9 shows area with fourth highest annual mean SO₂ surface concentration data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. It also shows the locations of various TPPs identified for implementation of FGDs in Phase-4 of the graded action plan. Figure 7.9 also shows the locations of beneficiary non-attainment cities across India with Phase-4 implementation of FGDs.

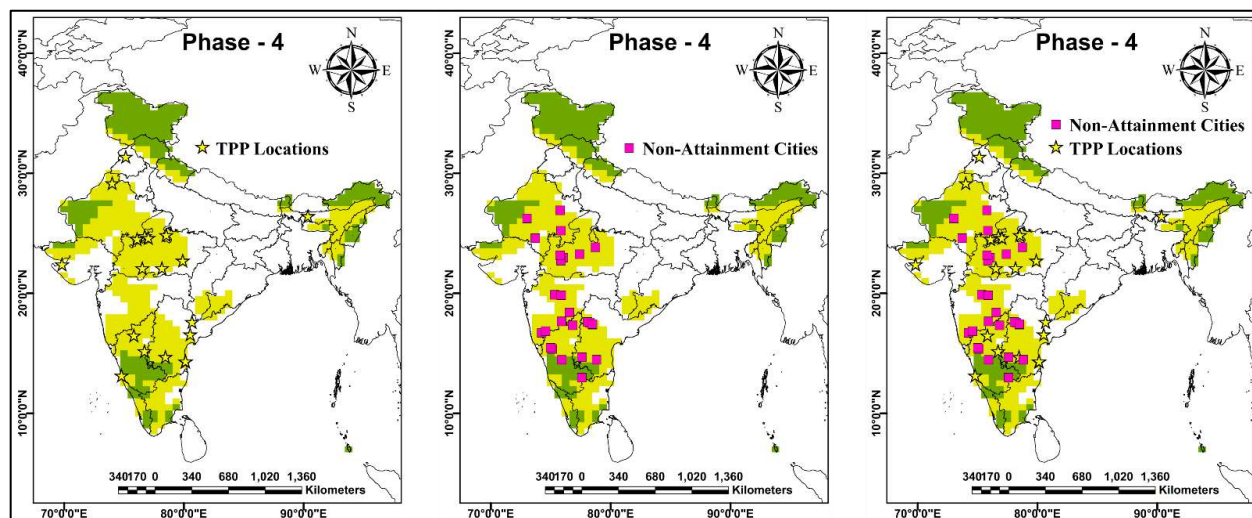


Figure 7.9: Areas with fourth highest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019. Locations of various TPPs for Phase-4 implementation of FGDs during July 2031 to July 2033 and beneficiary non-attainment cities across India are overlayed on the annual mean SO₂ surface concentration.

Table 7.9: List of TPPs chosen for implementation of FGDs in Phase-4 of the graded action plan during July 2031 to July 2033.

No.	TPP Name	Capacity (MW)	No.	TPP Name	Capacity (MW)
1	KAWAI TPS	1320	12	KUDGI TPP	1600
2	CHHABRA TPP	760	13	KUDGI	800
3	KALISINDH TPS	1200	14	SHRI SINGHAJI TPP	2520
4	SURATGARH TPS	1500	15	BONGAIGAON	750
5	LALITPUR TPS	1980	16	GOINDWAL SAHIB	540
6	RAYALASEEMA TPS	1050	17	SEIONI TPP	600
7	DAMODARAM SANJEEVAIAH TPS	1600	18	SATPURA TPS	500
8	SEMBCORP GAYATRI P.LTD.	1320	19	DR. N. TATA RAO TPS	500
9	PAINAMPURAM TPP	1320	20	KOTHAGUDEM TPS (NEW)	500
10	UDUPI TPP	1200	21	SIKKA REP. TPS	500
11	BELLARY TPS	1700			

Finally, Phase-5 of FGD implementation should happen for the remaining 7 TPPs and it can start from July 2033 and completed in one year by July 2034. Considering the small capacities of these remaining TPPs and hoping that the indigenous capacity of FGD manufacturing in India to grow even further by the year 2033 with availability of newer and better FGD technologies in the market by then, it should not take more than 12 months to implement FGDs in these 7 TPPs in the last Phase-5 of the graded action plan. Figure 7.10 shows area with lowest annual mean SO₂ surface concentration data as per AURA(OMI) observations and MERRA2 data in the last five

years, that is 2015-2019 and shows the locations of various TPPs identified for implementation of FGDs in Phase-5 of the graded action plan.

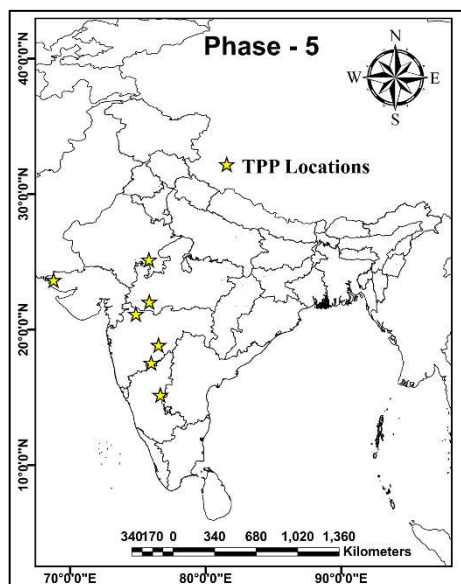


Figure 7.10: Areas with lowest annual mean SO₂ surface concentration (in µg/m³) data as per AURA(OMI) observations and MERRA2 data in the last five years, that is 2015-2019 along with locations of various TPPs for Phase-5 implementation of FGDs during July 2033 to July 2034.

Table 7.10: List of TPPs chosen for implementation of FGDs in Phase-5 of the graded action plan during July 2033 to July 2034.

No.	TPP Name	Capacity (MW)
1	TORANGALLU TPS EXT	600
2	KUTCH LIG. TPS	215
3	PARLI TPS	750
4	SOLAPUR TPP	660
5	SHIRPUR TPP	150
6	KHARGONE STPP	660
7	KOTA TPS	600