Report

Pediction of Ground-level concentration of SO2 and to study the variation of some meterorological parameters in Rayalaseema Thermal Power Plant in Kadapa, Andhra Pradesh using Gaussian Plume Model

06.02.2025

Aayan Angkit Kashyap

Indian Institute of Science, Education and Research (IISER) Kolkata

Contents

1. Abstract

Air pollution from coal-based thermal power plants remains a critical environmental and public health concern, particularly in rapidly industrializing nations such as India. This study investigates the dispersion of sulfur dioxide (SO_2) emissions from the Rayalaseema Thermal Power Plant in Andhra Pradesh using the Gaussian Plume Model (GPM). The model was applied to assess the spatial distribution of SO_2 concentrations under varying meteorological conditions, including wind speed, atmospheric stability, and temperature variations. Key input parameters such as emission rate (1.0944×10^9 µg/s), stack height (220 m), wind profile, and Pasquill-Gifford stability classification were utilized to estimate pollutant concentrations at different downwind distances.

The results indicate that the peak SO_2 concentration of 232.3 µg/m^3 occurs at approximately 3.52 km downwind, with concentrations decreasing progressively at greater distances. The analysis demonstrates that stronger wind speeds enhance pollutant dispersion, reducing ground-level concentrations, whereas stable atmospheric conditions lead to localized pollutant accumulation. A comparison with CPCB and NAAQS standards suggests that while industrial areas experience moderate pollution, residential regions located beyond 9 km remain within acceptable air quality limits. Additionally, a minimum safe distance of 15 km is recommended for sensitive infrastructures such as healthcare facilities to prevent prolonged exposure to elevated SO_2 levels.

The study underscores the importance of regulatory compliance, emission control technologies, and strategic urban planning to minimize air pollution-related risks. It also highlights the need for integrating real-time monitoring systems and more advanced atmospheric dispersion models to enhance the accuracy of pollutant impact assessments. These findings contribute to ongoing efforts in environmental policy-making and sustainable energy management by providing empirical evidence for air quality regulation in industrial zones.

Keywords: Gaussian Plume Model, Atmospheric Stability, Wind Speed and Dispersion, Health Risks of Air Pollution, Sulfur Dioxide (SO_2) Emissions

2. Introduction

India and China are the largest consumers of coal globally, contributing significantly to sulphur dioxide (SO2) emissions. India has become the world's leading emitter, primarily from thermal power stations located in regions such as Rayalaseema, Singrauli, and Mundra. This study focuses on SO2 emissions from coal-based thermal power plants in the Kadapa region of Andhra Pradesh, using the Gaussian Plume Model (GPM). Indian coal has high ash content and low calorific value, leading to significant air pollutants including SO2 and particulate matter.

Understanding the distribution of these pollutants is essential for developing air quality mitigation strategies. The GPM, while simplistic, helps analyze emission patterns and make comparisons across different scenarios, allowing us to assess compliance with air-quality standards and explore alternatives if necessary.

2.1. Air Quality Model

Air quality models use math to simulate how air pollutants move and react in the atmosphere. These models help us understand the relationships between emissions, weather conditions, pollution levels, and other important factors. While measuring air pollution gives important details about its concentration and how it settles, it only provides information from specific places and times. This makes it hard to identify the causes of air quality problems. In contrast, air pollution modeling offers a broader view of these issues by analyzing emission sources, weather influences, and physical and chemical changes. This helps us decide on necessary actions to improve air quality.

Air pollution models are vital for scientific research. They uniquely show the relationship between emissions and pollutant concentrations, including the impacts of past and future situations. Because of this, these models are important for regulatory, research, and industrial purposes.

When modeling air pollution dispersion, we consider four key physical processes:
1. Transport
2. Diffusion
3. Chemical transformation
4. Ground deposition

Transport describes how fast gases move, a topic studied for centuries, like how sailors monitor wind speeds for navigation. The study of diffusion, or how pollutants spread through turbulence, emerged more recently. We also consider chemical transformation, assuming pollutants do not break down or react. Lastly, we often ignore ground deposition, assuming pollutants simply fall to the ground without being absorbed.

3. **Methodology**

3.1. Gaussian Plume Model

3.1.1. Determination of Ground level concentration of the pollutant

The Gaussian Plume Model (GPM) is used as our air pollution model. The Gaussian point-source dispersion equation relates average, steady-state pollutant concentrations to the source strength, windspeed, effective stack height, and atmospheric conditions. It is the simplest model to analyse air pollution and assumes that the three-dimensional (x, y, z) concentration field is generated by a point source under stationary meteorological and emission conditions. In this report, we are concerned with the pollution at the ground level and so we will focus on only a two dimensional (x, y, 0) model of the GPM. The equation is given by:

$$C(x,y,0) = \frac{Q}{\pi u_H \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

where,

- $C(x,y,0)$ = concentration at ground level at the point (x, y, 0) in $\mu\frac{g}{m^3}$
- x = distance directly downwind in m
- y = horizontal distance from the plume centerline in m
- Q = emission rate of pollutants in $\mu\frac{g}{s}$
- u_H = average windspeed at the effective height of the stack in $\frac{m}{s}$
- σ_y = horizontal dispersion coefficient (standard deviation) in m
- σ_z = vertical dispersion coefficient (standard deviation)in m
- H = effective stack height in m

$$(H = h + \Delta h)$$

where,

1. $h =$ actual stack height
2. $\Delta h =$ plume rise

[Inference: What this means is that at a fixed distance x downwind, the concentration along the perpendicular varies with y like a normal distribution.]

3.1.2. Determination of windspeed at the effective stack height elevation

The windspeed to be used in the previous equation u_H, is the windspeed at the effective stack height. Usually windspeed is measured with an anemometer that is set up at a height of 10 meters above the ground, so we need some way to relate windspeed at the anemometer height with windspeed at the effective stack height. The following power law expression is frequently used for elevations less than a few hundred meters above the ground:

$$\left(\frac{u_H}{u_h}\right) = \left(\frac{H}{z_h}\right)^p$$

where,

- u_H = windspeed at the elevation H
- u_h = windspeed at the anemometer height
- H = effective height of the plume
- z_h = anemometer height above ground

- p = a dimensionless parameter that depends on surface roughness and atmospheric stability

3.1.3. Determination of Dispersion Coeffecients σ_y and σ_z

The dispersion coefficients σy and σz are appropriate functions of x, where the coefficients a, b, c, d, f depend on the stability class chosen. These are really just the standard deviations of the horizontal and vertical Gaussian distributions, respectively.
Smaller values for a dispersion coefficient mean the Gaussian curve is narrower, with a higher peak, and larger values mean the opposite. The further downwind we go from the source, the larger these coefficients become. This causes the Gaussian curves to spread further and further. This in turn depends on wind speed, solar insolation, cloud cover and atmospheric stability.

$$\sigma_y = ax^{0.894}$$

$$\sigma_z = cx^d + f$$

- where the constants a, c, d, and f are given in the Pasquill-Gifford Stability Classification Table for each stability classification.

3.1.4. Determination of Plume Rise

The difference between the actual stack height h and the effective height H is called the plume rise Δh. Plume rise is caused by a combination of factors, the most important ones being the buoyancy and momentum of the exhaust gases, and the stability of the atmosphere itself. Buoyancy results when exhaust gases are hotter than the ambient air, or when the molecular weight of the exhaust is lower than that of air (or a combination of both factors). Momentum is caused by the mass and velocity of the gases as they leave the stack.

The following plume rise equation can be used for stable conditions (stability categories E and F):

$$\Delta h = 2.6\left(\frac{F}{u_H S}\right)^{\frac{1}{3}}$$

The quantity F is called the buoyancy flux parameter $(m^4 s^{-3})$

$$F = gr^2 v_s\left(1 - \frac{T_a}{T_s}\right)$$

where,

- Δh = plume rise in m

- g = gravitational acceleration, $9.8ms^{-2}$
- r = inside radius of the stack, m
- u_H = windspeed at the effective height of the stack in ms^{-1}
- v_s = stack gas exit velocity in ms^{-1}
- T_s = stack gas temperature in K
- T_a = ambient temperature in K

The quantity S is a stability parameter with units of s^{-2} given by:

$$S = \frac{g}{T_a}\left(\frac{\Delta T_a}{\Delta z} + 0.01°Cm^{-1}\right)$$

The quantity $\Delta\frac{T_a}{\Delta}z$ represents the actual rate of change of ambient temperature with altitude in °C/m (note that a positive value means the temperature is increasing with altitude).

For neutral or unstable conditions in the atmosphere (stability categories A–D), the following equation can be used to estimate plume rise:

$$\Delta h = \frac{1.6F^{\frac{1}{3}}x_f^{\frac{2}{3}}}{u_H}$$

where, x_f = distance downwind to point of final plume rise in m

Since the previous equation is used when conditions are neutral or unstable, it may be difficult to define the distance downwind at which the plume centerline stops rising. The following is sometimes used:

- $x_f = 120F^{0.4}$ if $F \geq 55m^4s^{-3}$
- $x_f = 50F^{\frac{5}{8}}$ if $F < 55m^4s^{-3}$

3.2. Assumptions

The Gaussian plume model makes the following assumptions:

- The rate of emissions from the source is constant.
- The windspeed is constant both in time and with elevation.
- The pollutant is conservative; that is, it is not lost by decay, chemical reaction, or deposition. When it hits the ground, none is absorbed, and all is reflected.
- The terrain is relatively flat, open country.

4. Area of Interest (AOI)

Rayalaseema Thermal Power Project of Andhra Pradesh State Electricity Board is at Kalamala of Kadapa district, Andhra Pradesh, with an installed capacity of 1050MW in five units under three stages. Five stacks are provided in three chimneys with inter stack distance of 70 meters whose coal consumption is 137

Tph. Coal consumption for 5 units is 685 Tph. The coordinates for this Thermal Power Station are approximately $14.70°N$ $78.46°E$.

Rayalaseema Thermal Power Plant was developed under 3 stages namely stage I, II, III and IV. The station is performing well in the recent years by achieving high plant load factor. It stood first in country during 1998– 99, 2002– 03, 2003– 04 and second during 1999– 2000, 2001– 02. The station has received Meritorious productivity awards for six consecutive years and Incentive award for seven consecutive years. BHEL commissioned stage IV unit 1X600MW in March 2018 leading to total installed capacity of RTPP to 1650MW.

Figure 1: *SOURCE*: Google Earth (3D View)

Figure 2: *SOURCE*: Pinterest

4.1. Input Parameters

4.1.1. Power Plant Data

Parameter	Interpretation	Value	Unit
Q	Rate of Emission of SO_2	$1.0944X10^9$	μgs^{-1}
h	Stack height for release of pollutant	220	m
H	Effective stack height (i.e., stack height + plume rise)	270	m
u_h	Average Wind Speed at ground level (10 m)	4.68	ms^{-1}
u_H	Wind speed at elevation H	9.05	ms^{-1}
σ_y	Horizontal dispersion coefficient	-	m
σ_z	vertical dispersion coefficient	-	m
r	Radius of the stack	2	m
v_s	Exit velocity of pollutant from stack	28.7	ms^{-1}
g	Acceleration due to gravity	9.8	ms^{-2}
T_a	Average Ambient temperature	307.34	K
T_s	Stack Exit Temperature	413.15	K

Parameter	Interpretation	Value	Unit
x_f	Distance downwind to the point of plume rise	5000	m
F	Flux buoyancy parameter	288.134	$m^4 s^{-3}$

4.1.2. Meteorological Data

Ambient Temperature of the surroundings:
- Summer: $312.28K$
- Monsoon: $307.97K$
- Autumn: $304.50K$
- Winter: $304.58K$

So, the average ambient temperature should be: $307.34K$

Windspeed at the ground level measured by anemometer:
- Summer: $3.889ms^{-1}$
- Monsoon: $8.527ms^{-1}$
- Autumn: $4.251ms^{-1}$
- Winter: $2.055ms^{-1}$

So, the average windspeed should be: $4.68ms^{-1}$

4.1.3. Wind Profile Exponent p, for Rough Terrain

Pasquill-Gifford Stability Classification

Stability Class	Description	Exponent p
A	Very Unstable	0.15
B	Moderately Unstable	0.15
C	Slightly Unstable	0.20
D	Neutral	0.25
E	Slightly Stable	0.40
F	Stable	0.60

- **Stability Class for Rayalaseema Thermal Power Plant**: Class C (in general)

4.1.4. Value of the constants a, c, d, and f to find the values of σ_y and σ_z

		$x \leq 1$ km			$x \geq 1$ km		
Stability	a	c	d	f	c	d	f
A	213	440.8	1.941	9.27	459.7	2.094	−9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
C	104	61.0	0.911	0	61.0	0.911	0
D	68	33.2	0.725	−1.7	44.5	0.516	−13.0
E	50.5	22.8	0.678	−1.3	55.4	0.305	−34.0
F	34	14.35	0.740	−0.35	62.6	0.180	−48.6

5. Observation

We will study the model for Sulphur Dioxide (SO^2):

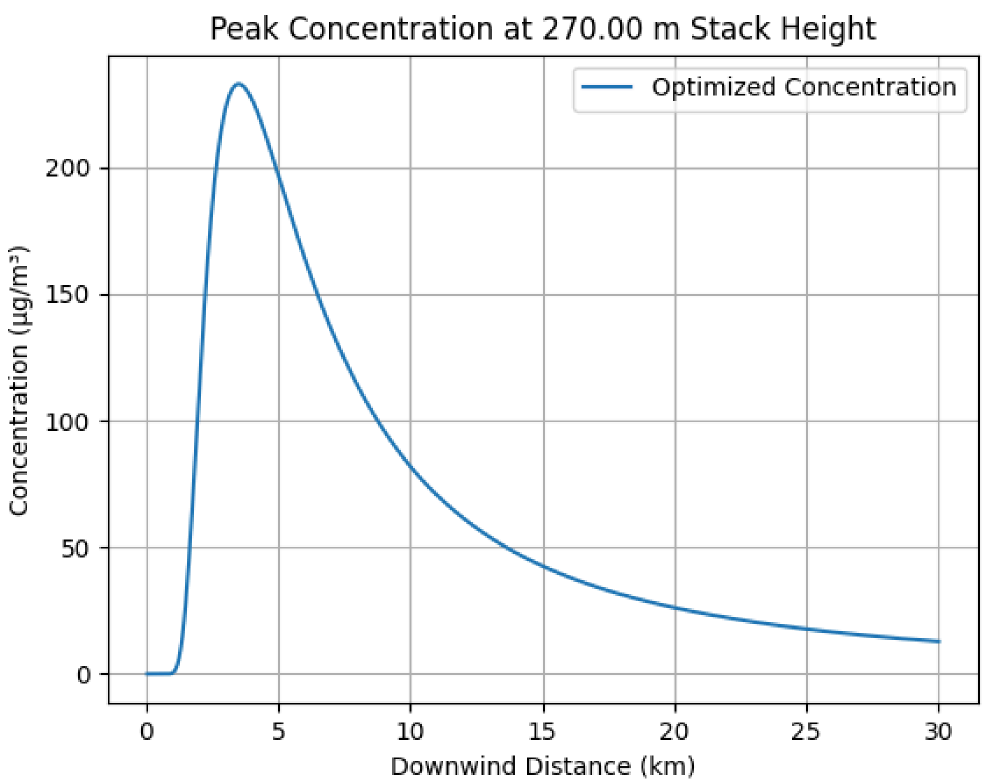

Figure 4: Downwind Concentration Plot in 2-D

- **Inference:**

From the above plot, we have got the peak concentration of SO_2 which is $232.3 \mu g m^{-3}$ at a downwind distance of $3.52 km$

The highest peak downwind concentration occurs when the atmosphere is very unstable rather than stable. The turbulence in an unstable atmosphere brings the looping plume to Earth very quickly, resulting in high peak values near the stack. Downwind, however, concentrations drop off very quickly. Having a high peak concentration near the stack may be a satisfactory situation as long as any populations or ecosystems that might be damaged by the pollution are more than a few kilometers away.

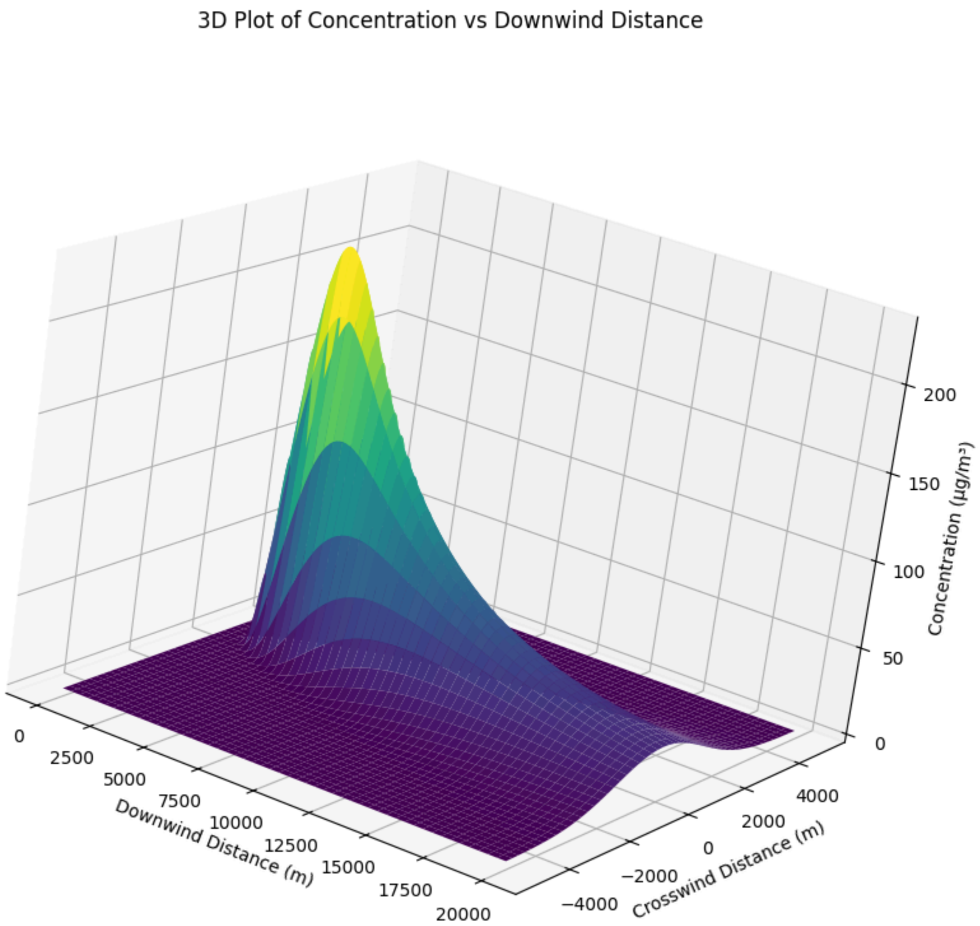

Figure 5: Downwind Concentration Plot in 3-D

- **Inference:**

Here, the given surface plot represents the ground-level of the air pollutant concentration variation along with both the downwind distance and the crosswind distance.

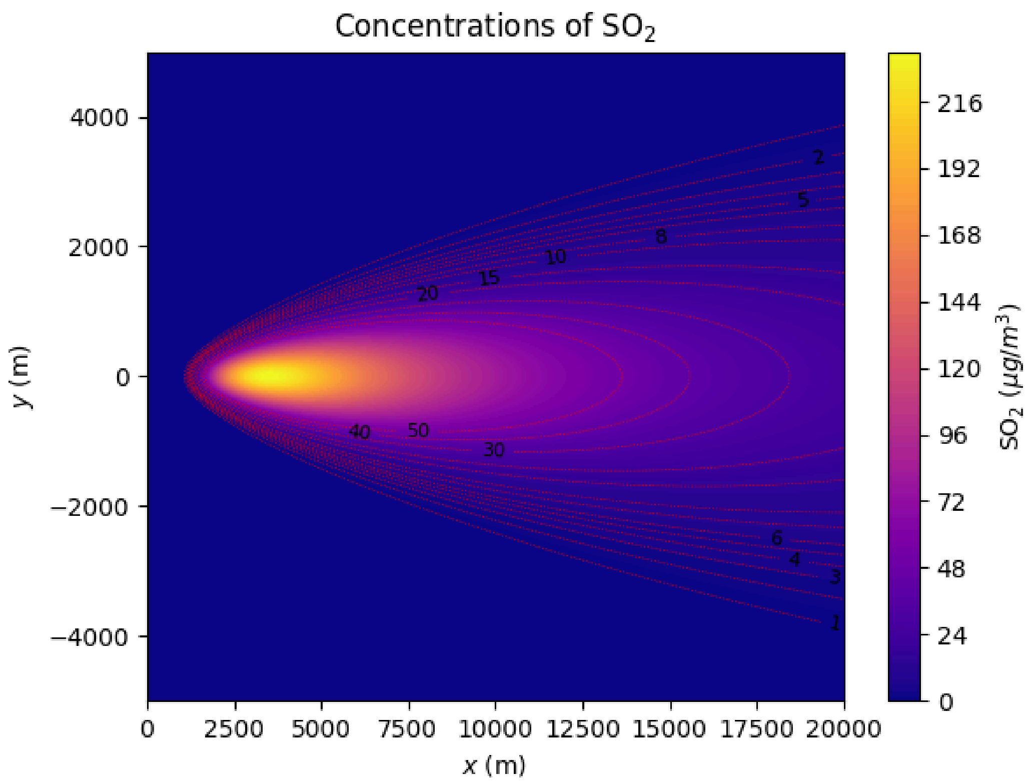

Figure 6: Contour Plot

- **Inference:**

This countour plot represents the modeled SO_2 concentrations at the ground level. The contour lines give the pollutant concentration in μg/m^3 . Note that axes do not have the same scale – distances on the y axis have been exaggerated for visibility.

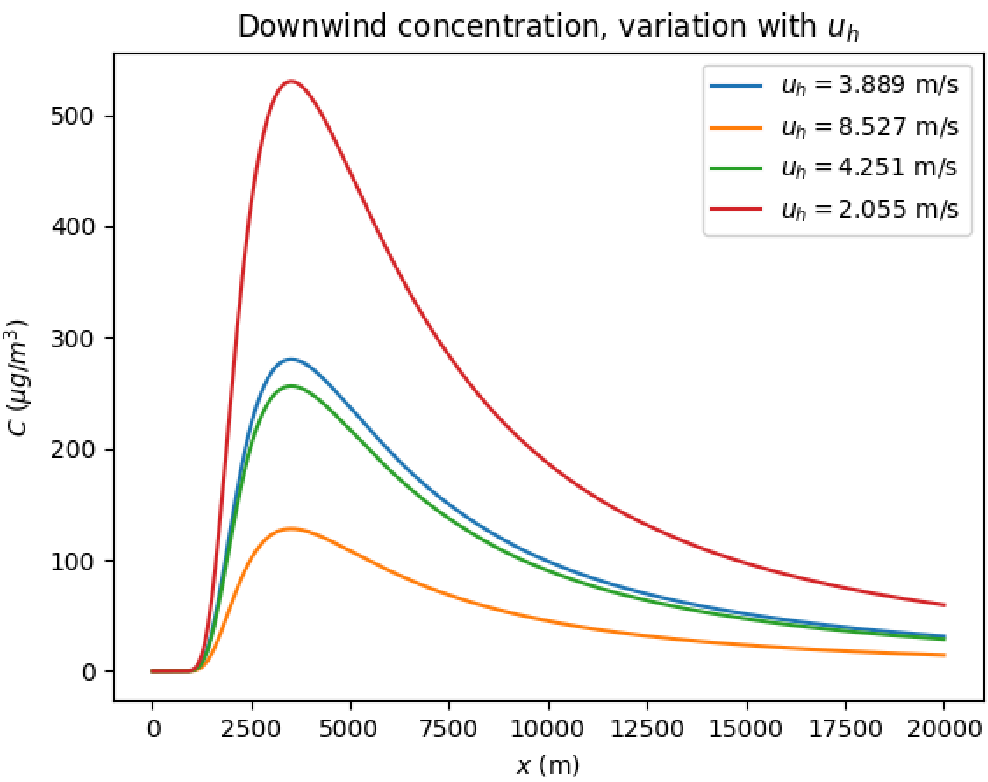

Figure 7: Variation of downwind concentration with windspeed at the stack height elevation

- **Inference:**

Here, we have studied how the downwind concentration changes when we vary the wind speed at the stack height elevation. From this plot, we infer that the peak concentration becomes higher and closer to the origin as we decrease the wind speed. This means that stronger winds are able to carry and distribute the air pollutant which in this case is SO_2 more effectively.

Higher wind speeds dilute the plume by quickly dispersing pollutants over a larger area, this results in a more stretched-out, lower-concentration plume over a larger area. On the other hand, at lower wind speeds, pollutants remain near the source for longer, allowing vertical and lateral dispersion to take effect before they are transported further downwind. This leads to higher concentrations near the source and a peak that is closer to the origin.

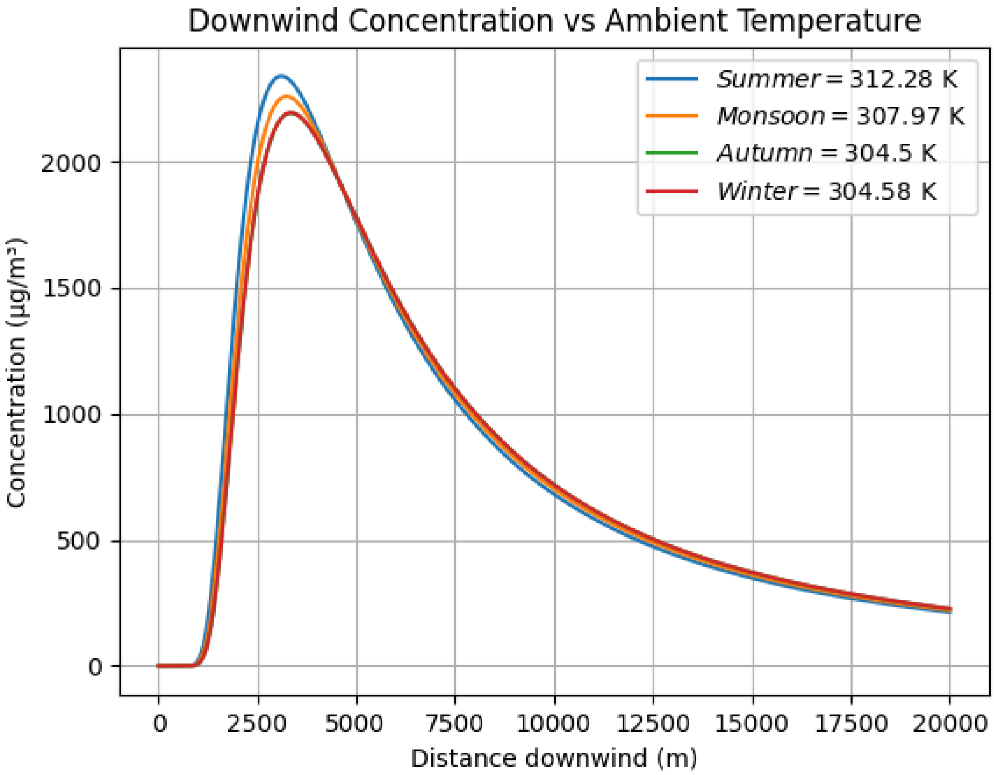

Figure 8: Variation of downwind concentration with Ambient Temperature taken from the 4 major seasons.

- **Inference:**

From the above figure, we plot the seasonal variation with the downwind concentration. Here, there is almost no such variation of the ground-level concentration with the four ambient temperatures. We witness that the four curves coincide with each other almost everywhere. Only, the peak of curves is the unique feature where the higher ambient temperatures give higher peaks. This indicates that temperature changes do not significantly affect pollutant dispersion at most locations, except at the centerline where the peak concentration occurs. This suggests that temperature influences vertical dispersion, causing pollutants to stay more concentrated near the plume centerline.

From the plot, the blue curve gives the highest peak. It implies that when the ambient temperature is higher (hotter i.e., $312.28K$), the air pollutant is more concentrated.

Higher temperatures generally lead to greater atmospheric stability, which results in less vertical mixing and therefore a more concentrated pollutant plume near the ground level at the centerline of the plume, where most receptors are located; essentially, the pollutant is trapped within a smaller vertical space due to reduced turbulence.

Downwind Distance (m)	Concentration($\mu gm^{-}3$) of $SO2$ at slightly unstable condition (class C)	concentration($\mu gm^{-}3$) of $SO2$ at neutral condition (class D)
5000	197.189	12.962
10000	82.044	58.707
15000	42.626	69.118
20000	26.101	65.095
25000	17.692	57.998
30000	12.831	51.021

- **Inference:**

In this table, we have taken two different stability classes C and D to see the variation of the ground-level concentration of the air pollutant with the atmospheric stability.

From the Pasquill-Gifford Stability Classification Table, we know that class C represents moderate turbulence, and decent vertical mixing, and class D represents minimal turbulence, and less vertical dispersion compared to unstable conditions.

We observe that the concentration is higher when the stability class is C. It infers that this class allows pollutants to stay near the ground due to moderate turbulence, leading to higher ground-level concentrations. On the other hand, class D (neutral stability) spreads pollutants horizontally with less vertical mixing, lowering peak concentrations near the surface, which is why leads to lower in concentration relatively.

6. Results

6.1. Distribution of SO_2

The spreading distribution of SO_2 concentrations due to a point emitting source has been represented in Figure. 4, where the origin is the location of emission and the positive x-axis is in the direction of the downwind.

Figure. 4 shows that the pollutant concentration peaks around $3.52km$ downwind, with values as high as $232.3\mu gm^{-3}$. From then on, the concentration drops off sharply $82.044\mu gm^{-3}$ at $10km$ and $26.101\mu gm^{-3}$ at $20km$. Furthermore, the spread of pollutants is highly directional.

Figure. 6 shows that the contours are confined to a narrow region. It justifies the scale over which we have run our model.

6.2. Air Quality of the Region

From the graphical representation, we saw that the maximum concentrations of SO_2 near the stack or point source are in the range of $(200 - 250)\mu g$ (located in a downwind range of $2 - 3.7km$). We have chosen a coal-based thermal power plant having a net capacity of $1050MW$. Hence, the range should lie from 200 to $600MW$ according to CPBC (Central Pollution Control Board)

According to the CPBC, the level of air quality with an adequate margin of safety is $200\mu gm^{-3}$ in the thermal power plant region. Our predicted value for the peak concentration is $232.3\mu gm^{--3}$. We, therefore, can say that our predicted value almost fits the standard value given by CPBC. So, the industrial region is moderately polluted and slightly not good for the workers of the plant.

Moreover, we also observe from our prediction that the concentration near the locality which is located around $9.1km$ from the main stack is approximately a range of $50 - 78\mu gm^{-3}$. According to NAAQS(National Ambient Air Quality Standards), the safe level of $S0_2$ concentration in residential areas is near $80\mu gm^{-3}$. So the air quality of the locality near the factory is good for living.

6.3. Safe Distance for Health Care Center:

We have to measure the air quality before constructing a Health Care Center. That is why we have to ensure that the concentration of SO_2 is lower than $40\mu gm^{-3}$ (Very Good air quality). For the stability class of the C,the minimum safe distance for Heatlh care is $15km$ from the main stack (from observing the Figure: 4) where the concentration is below $40\mu gm^{-3}$.

7. Conclusion

In this this study, we have used the Gaussian Plume Model (GPM) to analyze the dispersion of sulfur dioxide (SO_2) emissions from the Rayalaseema Thermal Power Plant, providing a quantitative assessment of air pollution levels in the region. The results indicate that SO_2 concentrations peak at approximately 3.52 km downwind with a maximum concentration of 232.3 µg/m^3, slightly exceeding the 200 µg/m^3 threshold set by the Central Pollution Control Board (CPCB) for industrial areas. Furthermore, the analysis of meteorological influences reveals that wind speed plays a crucial role in pollutant dispersion, with higher wind speeds leading to greater dilution and lower ground-level concentrations. Conversely, under stable atmospheric conditions, pollutants accumulate near the source, increasing exposure risks.

Comparisons with National Ambient Air Quality Standards (NAAQS) indicate that residential areas located beyond 9 km from the emission source experience relatively lower SO_2 levels, remaining within safe limits for human habitation. However, the study identifies a safe distance of at least 15 km for establishing healthcare centers and other sensitive infrastructure to ensure that air quality remains within the "Very Good" category ($< 40\mu gm^{-3}$). The findings of this study highlight the necessity of continuous air quality monitoring, stricter emission control measures, and the adoption of cleaner energy alternatives to mitigate the long-term environmental and health impacts of thermal power plant emissions. Further research incorporating real-time pollutant monitoring and advanced dispersion models could enhance predictive accuracy and inform more effective regulatory policies.

8. Bibliography

1. [Gilbert M. Masters, Wendell P . Ela . : **Introduction to Environmental Engineering and science**, $3rd$ edition.]

2. [Anand Kumar Varma Sibyala, S. Vijayakumar Varma, Muduru Srimurali . **Prediction of Ground Level Concentrations of Air Pollutants Using Gaussian Model, Rayalaseema Thermal Power Project, Kadapa, A.P., India**. link: https://www.researchgate.net/publication/314838346_Prediction_of_Ground_Level_Concentrations_of_Air_Pollutants_Using_Gaussian_Model_Rayalaseema_Thermal_Power_Project_Kadapa_AP_India]

3. [Central Pollution Control Board (CPBC): **thermal_power_plant_overview.pdf** Link: https://cpcb.nic.in/uploads/thermal_power_plant_overview.pdf]

4. [United States Environmental Protection Agency. **NAAQS Table** Link: https://www.epa.gov/criteria-air-pollutants/naaqs-table]

5. [Wikipedia: **Rayalaseema Thermal Power Station** Link: https://en.wikipedia.org/wiki/Rayalaseema_Thermal_Power_Station]

9. Code

```
#CODE FOR THE GAUSSIAN PLUME MODEL:

import numpy as np
import matplotlib.pyplot as plt

# Set up stability parameters
a = { 'A': 213, 'B': 156, 'C': 104, 'D': 68, 'E': 50.5, 'F': 34 }
c_0 = { 'A': 440.8, 'B': 106.6, 'C': 61.0, 'D': 33.2, 'E': 22.8, 'F': 14.35 }
d_0 = { 'A': 1.941, 'B': 1.149, 'C': 0.911, 'D': 0.725, 'E': 0.678,
'F': 0.740 }
f_0 = { 'A': 9.27, 'B': 3.3, 'C': 0, 'D': -1.7, 'E': -1.3, 'F': -0.35 }
c_1 = { 'A': 459.7, 'B': 108.2, 'C': 61.0, 'D': 44.5, 'E': 55.4, 'F': 62.6 }
d_1 = { 'A': 2.094, 'B': 1.098, 'C': 0.911, 'D': 0.516, 'E': 0.305,
'F': 0.180 }
```

```
f_1 = { 'A': -9.6, 'B': 2.0, 'C': 0, 'D': -13.0, 'E': -34.0, 'F': -48.6 }
p = { 'A': 0.15, 'B': 0.15, 'C': 0.20, 'D': 0.25, 'E': 0.40, 'F': 0.60 }

class GPM:
    def __init__(self, Q, stability):
        self.Q = Q
        self.a = a[stability]
        self.c_0 = c_0[stability]
        self.d_0 = d_0[stability]
        self.f_0 = f_0[stability]
        self.c_1 = c_1[stability]
        self.d_1 = d_1[stability]
        self.f_1 = f_1[stability]
        self.p = p[stability]

    def stack(self, h, T_a, T_s, v_s, r, u_h):
        self.F = 9.8 * r**2 * v_s * (1 - float(T_a) / T_s)

      # **Limit excessive plume rise to keep the peak concentration closer**
        if self.F >= 55:
            x_f = 100 * self.F ** 0.4
        else:
            x_f = 40 * self.F ** 0.625

          self.dH = min(50, 1.4 * self.F ** (1.0 / 3) * x_f ** (2.0 /
3) / u_h)
        self.H = h + self.dH
        self.u_H = u_h * (self.H / 10.0) ** self.p
        self.T_a = float(T_a)

        print(f"Optimized H = {self.H:.2f} m")
        print(f"Optimized u_H = {self.u_H:.2f} m/s")

    def smooth_sigma_z(self, x_km, k=10):
        """ Smooth transition between σ_z equations """
        S_x = 1 / (1 + np.exp(-k * (x_km - 1)))
        s_z1 = self.c_0 * x_km ** self.d_0 + self.f_0
        s_z2 = self.c_1 * x_km ** self.d_1 + self.f_1
        return (1 - S_x) * s_z1 + S_x * s_z2

    def conc(self, x, y):
        x_km = x / 1000.0
        s_y = self.a * x_km ** 0.894
        s_z = self.smooth_sigma_z(x_km)
        return self.Q / (np.pi * self.u_H * s_y * s_z) * \
               np.exp(-1 * (self.H ** 2 / (2 * s_z ** 2))) * \
               np.exp(-1 * (y ** 2 / (2 * s_y ** 2)))
```

```
    def conc_t(self, x, y):
        x_km = x / 1000.0
        s_y = self.a * x_km ** 0.894
        s_z = self.smooth_sigma_z(x_km)

        # Modify stack height H based on ambient temperature
        self.H = self.H + 0.1 * (self.T_a - 300)  # Adjust rise height

          # Modify s_z based on temperature (higher temperature causes
more dispersion)
        s_z *= (1 + (self.T_a - 300) / 100)  # Adjust dispersion based on
temperature difference

        # Calculate concentration using the adjusted values
        return self.Q / (np.pi * s_y * s_z) * \
               np.exp(-1 * (self.H ** 2 / (2 * s_z ** 2))) * \
               np.exp(-1 * (y ** 2 / (2 * s_y ** 2)))

# Create grid (focus on 0-10 km for better resolution)
x = np.linspace(0, 20000, 1000)
y = np.linspace(-5000, 5000, 1000)
X, Y = np.meshgrid(x, y)

# Initialize and optimize parameters
model = GPM(1.0944e9, 'C')                    #for S02
model.stack(h=220, T_a=307.34, T_s=413.15, r=2, v_s=28.7, u_h=4.68)

# Compute concentration values
Z = model.conc(X, Y)

# Plot downwind concentration profile
x_range = np.linspace(0, 30000, 500)
C_values = model.conc(x_range, 0)

plt.plot(x_range / 1000, C_values, label="Optimized Concentration")
plt.xlabel("Downwind Distance (km)")
plt.ylabel("Concentration (µg/m³)")
plt.title(f"Peak Concentration at {model.H:.2f} m Stack Height")
plt.legend()
plt.grid()
plt.savefig("optimized_gaussian_plume.png")
plt.show()

# Check concentration at key distances
print("Concentration at 5 km:", model.conc(5000, 0))
```

```
print("Concentration at 10 km:", model.conc(10000, 0))
print("Concentration at 15 km:", model.conc(15000, 0))
print("Concentration at 20 km:", model.conc(20000, 0))
print("Concentration at 25 km:", model.conc(25000, 0))
print("Concentration at 30 km:", model.conc(30000, 0))

# Plot a contour map
fig1 = plt.figure()
plt.contourf(X, Y, Z, levels=200, cmap="plasma")
colorbar = plt.colorbar()
colorbar.set_label("SO$_{2}$ ($\mu g / m^3$)")
contours = plt.contour(X, Y, Z,
                           levels=[1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30,
40, 50],
                       colors="red", linewidths=0.5, linestyles="dotted")
plt.xlabel("$x$ (m)")
plt.ylabel("$y$ (m)")
plt.title("Concentrations of SO$_{2}$")
plt.clabel(contours, inline=True, colors="black", fmt="%d", fontsize=8)
filename = f"H_stubble_{model.H:.2f}.png"
plt.savefig(filename)
plt.clf()
print(f"Filename: {filename}")

# Create the 3D plot
fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')

# Plot the surface
ax.plot_surface(X, Y, Z, cmap="viridis", edgecolor="none")

# Labels and title
ax.set_xlabel('Downwind Distance (m)')
ax.set_ylabel('Crosswind Distance (m)')
ax.set_zlabel('Concentration (µg/m³)')
ax.set_title('3D Plot of Concentration vs Downwind Distance')
# Show plot
plt.show()


# Variation of downwind concentration with windspeed for a particular
ambient temperature
fig3 = plt.subplots()

model.stack(h=220, T_a=307.34, T_s=413.15, r=2, v_s=28.7, u_h=3.889)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 3.889$ m/s")
print("Concentration downwind at x = 0.5 km:", model.conc(5000, 0))
```

```
model.stack(h=220, T_a=307.34, T_s=413.15, r=2, v_s=28.7, u_h=8.527)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 8.527$ m/s")
print("Concentration downwind at x = 5 km:", model.conc(5000, 0))

model.stack(h=220, T_a=307.34, T_s=413.15, r=2, v_s=28.7, u_h=4.251)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 4.251$ m/s")
print("Concentration downwind at x = 5 km:", model.conc(5000, 0))

model.stack(h=220, T_a=307.34, T_s=413.15, r=2, v_s=28.7, u_h=2.055.0)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 10$ m/s")
print("Concentration downwind at x = 5 km:", model.conc(5000, 0))

# Set plot labels and title
plt.xlabel("x (m)")
plt.ylabel("C (μg/m³)")
plt.title("Downwind concentration, variation with u_h")
plt.legend()
plt.grid(True)
# Save and show the plot
plt.savefig("windspeed_variation.png")
plt.show()


# Variation of downwind concentration with average ambient temperature of
all the 4 seasons
fig4 = plt.subplots()

# Summer temperature
fig4 = plt.subplots()
model.stack(h=220, T_a=312.28, T_s=413.15, r=2, v_s=28.7, u_h=4.68)
plt.plot(x, model.conc_t(x, x * 0), label="$Summer = 312.28$ K")
print("Concentration downwind at x = 5 km:", model.conc_t(5000, 0))

# Monsoon temperature
model.stack(h=220, T_a=307.97, T_s=413.15, r=2, v_s=28.7, u_h=4.68)
plt.plot(x, model.conc_t(x, x * 0), label="$Monsoon = 307.97$ K")
print("Concentration downwind at x = 5 km:", model.conc_t(5000, 0))

# Autumn temperature
model.stack(h=220, T_a=304.5, T_s=413.15, r=2, v_s=28.7, u_h=4.68)
plt.plot(x, model.conc_t(x, x * 0), label="$Autumn = 304.5$ K")
print("Concentration downwind at x = 5 km:", model.conc_t(5000, 0))

# Winter temperature
model.stack(h=220, T_a=304.58, T_s=413.15, r=2, v_s=28.7, u_h=4.68)
plt.plot(x, model.conc_t(x, x * 0), label="$Winter = 304.58$ K")
```

```
print("Concentration downwind at x = 5 km:", model.conc_t(5000, 0))

# Set plot labels and title
plt.xlabel("Distance downwind (m)")
plt.ylabel("Concentration (µg/m³)")
plt.title("Downwind Concentration vs Ambient Temperature")
plt.legend()
plt.grid(True)
# Save and show the plot
plt.savefig("Variation_with_T_a.png")
plt.show()
```