Modelling the role of open air stubble and waste burning in elevated $PM_{2.5}$ concentrations in the Newtown area

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Abstract

Excessive levels of particulate matter in the atmosphere constitutes a major health hazard in Kolkata. Open air stubble burning is a major contributor to poor air quality at a localized scale. Here, we use the Gaussian plume model to quantify the resultant elevated $PM_{2.5}$ levels. We apply this model with reference to several incidents of stubble and waste burning in Newtown, Kolkata in order to judge their impact on surrounding residential areas and ecologically sensitive zones. We find that stubble burning elevates $PM_{2.5}$ levels to beyond the permissible 24 hour exposure limit of $60\,\mu g/m^3$ in a narrow region 100 m to 300 m downwind. Depending on the season, this zone includes residential areas, parks, and even hospitals. We thus conclude that this practice affects air quality on a small but concentrated scale.

1 Introduction

Particulate matter in the atmosphere is used to describe tiny particles of solids or liquids in the air, such as dust, smoke, or liquid droplets. They can enter the atmosphere directly via primary sources like incomplete combustion of fuel, or they can form within the atmosphere from other pollutants like SO_2 and NO_x. The size of such particles can vary from 5 nm to 100 µm. Fine particulate matter, or $PM_{2.5}$, describes particles with a diameter under 2.5 µm. This class of air pollutant is especially harmful for humans; short term exposure can cause irritation in the respiratory passage and shortness of breath, while long term effects include asthma, bronchitis, cardiovascular disease, and even lung cancer. The elderly, young children and babies, and those already suffering from heart or lung disease are the most vulnerable (Masters and Ela, 2014; Xing et al., 2016).

Stubble burning has become a menace in Newtown, Kolkata, with multiple instances of grass plots being set on fire (Chakraborti, 2020b, 2020c; Sengupta and Roy, 2020), reported between November and December, 2020. This becomes a source of particulate matter, along with pollutants like nitrogen oxides (NO_x) and volatile organic carbons (VOCs). The mixing of plastics and waste with the grass further releases toxins like dioxins, mercury, and halogens (Verma et al., 2016; Kim Oanh, 2017). These incidents occurred close to residential areas; others occurred in the ecologically sensitive zones surrounding Eco Park, possibly threatening the biodiversity of the area. Specific sites include the DF Block in Action Area I, and the Eco Urban Park in Action Area II (Figure 1). The former is surrounded by a belt of hospitals to the north east, and the latter has numerous parks and gardens to the south west, notably Eco Park around 3 km away. Thus, the continuation of such activities will likely put the health of many at risk. We highlight the lack of weather and air quality monitoring stations in Newtown, which obscures the severity of air pollution in the locality. While steps have been taken to combat stubble burning, including the involvement of volunteers and the use of drones (Chakraborti, 2020a), reliable air quality data is important to fully ascertain the level of damage already done and gauge the effectiveness of the response.

In this paper, we aim to quantify the elevation in $PM_{2.5}$ levels due to open air burning of stubble and waste, and identify the most severely impacted areas. We also aim to interpret the results in terms of the impact on human health and biodiversity.

2 Methods

2.1 Gaussian plume model

We use the point source Gaussian plume model as described in Masters and Ela, 2014, (Chap. 7, Sec. 11) to model the concentration and spread of pollutants at ground level. In short, the concentration of a gaseous pollutant is modelled as

$$C(x, y) = \frac{Q}{\pi u_H \sigma_y \sigma_z} e^{-H^2/2\sigma_z^2} e^{-y^2/2\sigma_y^2}.$$

What this means is that at a fixed distance x downwind, the concentration along the perpendicular varies with y like a normal distribution. The dispersion coefficients σ_y and σ_z are appropriate functions of x, where the coefficients a, b, c, d, f depend on the stability class chosen. This in turn depends on wind speed, solar insolation and cloud cover.

$$\sigma_y = ax^{0.894}, \qquad \sigma_z = cx^d + f.$$

We have chosen a stability class 'C' (slightly unstable atmosphere), based on data in Sec. 2.4. The parameter Q has been estimated based on the typical fraction of $PM_{2.5}$ emitted per mass of burnt stubble, as detailed in Sec. 2.3. The effective height upto which the plume of pollutants rises has been estimated using

$$H = 1.6\frac{F^{1/3}x_f^{2/3}}{u_h}, \qquad F = gr^2 v_s \left(1 - \frac{T_a}{T_s}\right).$$

We model a burning pile of stubble at ground level as a source of airborne pollutant with radius $1\,\mathrm{m}$ and with gas escaping at a rate of $0.5\,\mathrm{m\,s^{-1}}$. The gas exit velocity is a visual estimate, based on how fast smoke rises from a burning site. The ambient and stack gas temperatures have been estimated as $300\,\mathrm{K}$ and $600\,\mathrm{K}$, where $600\,\mathrm{K} \approx 320\,°\mathrm{C}$ is a typical temperature for a grass/shrub fire (Bailey and Anderson, 1980). Note that the buoyancy flux parameter F turns out to be very small, on the order of $2.5\,\mathrm{m^4/s^3}$, so the distance downwind to the point of final plume rise is given by

$$x_f = 50F^{0.625}.$$

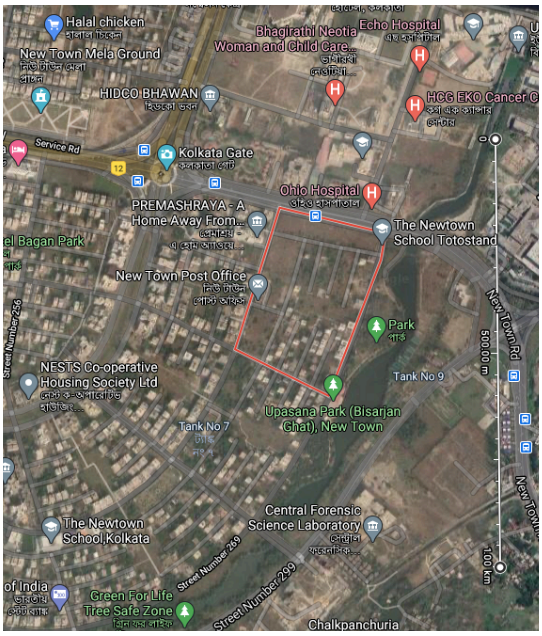
This is calculated as around $87\,\mathrm{m}$. The effective stack height turns out to be on the order of $15\,\mathrm{m}$. The complete set of assumed and calculated parameters has been tabulated in Table. 1.

The Gaussian plume model makes the following assumptions.

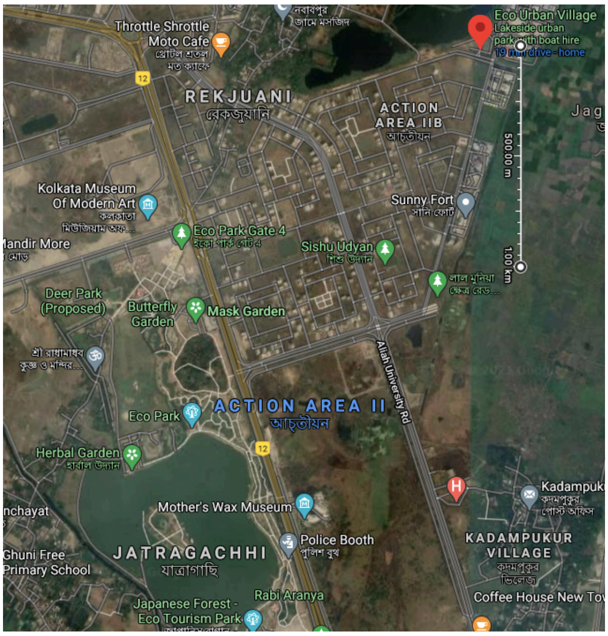
1. The burning rate, and hence the emission rate of pollutants from the stubble is constant over time. We consider timescales on the order of a few hours.
2. Steady state flow is attained relatively quickly, with the ground level concentrations being very close to the steady state concentration for the duration of burning.
3. The windspeed remains constant over time, and with elevation.
4. The pollutant under consideration ($PM_{2.5}$) is conservative.
5. The terrain is flat and open.

2.2 Locations

We run our model over a downwind distance of the order of 1.5 km. The presence of residential areas with obstructions such as tall buildings means that the terrain cannot be considered open and flat beyond such distances where the model breaks down. Given the lack of a permanent site of burning, the model results can be rotated and superimposed onto a map of Newtown at any flat, open and grassy plot in order to predict the consequences of burning there. In this paper, we choose the two reported sites in the DF Block and the Eco Urban Park area (Figure 1), and also extrapolate the effects of burning in similar locations.



(a) The DF Block area. Note the presence of a cluster of hospitals to the north and parks to the south, with the Newtown School to the south west.



(b) The Eco Urban area. Note the presence of parks and gardens to the south.

Figure 1: Locations of reported stubble and waste burning in Newtown, with a 1 km scale for distance measurements. Images from Google Maps.

2.3 Pollutants generated by burning

The amount of fine particulate matter released per tonne of stubble burnt can be estimated as 3 kg (Abdurrahman, Chaki, and Saini, 2020), which is equivalent to 3 g per kilogram burnt. Open burning of municipal waste and plastics emits $PM_{2.5}$ at a rate of 6 g per kilogram burnt (Kim Oanh, 2017). Thus, a 50-50 mixture by mass of grass stubble and waste ought to emit 4.5 g of $PM_{2.5}$ per kilogram on average, neglecting any inhibitory effects due to mixing. If burnt at a rate of $100\,\mathrm{g\,s^{-1}}$, the rate of $PM_{2.5}$ emitted becomes $0.45\,\mathrm{g\,s^{-1}}$, which gives $Q \approx 4.5 \times 10^5\,\mathrm{\mu g\,s^{-1}}$. Of course, the steady state concentration of any pollutant given by the model scales linearly with Q, hence we put aside the question of obtaining a more precise composition or burning rate owing to lack of more precise data[1]. Any corrections in this regard will merely scale the pollutant concentrations without changing the shape and form of the distribution.

[1]Note that a pile of grass of radius 1 m and height 1 m has a volume of around $3\,\mathrm{m}^3$, thus weighing about 300 kg. At the assumed rate of $100\,\mathrm{g\,s^{-1}}$, this would burn up within an hour. Mixing with waste, which has a higher density, would of course make the pile burn for longer. This gives a rough lower limit on the duration of burning.

Table 1: Parameters, their interpretation, and their value assumed/calculated. Standard parameters which depend on the stability class (p, a, b, c, d, f) have been sourced from Masters and Ela (2014, Chap. 7, Sec. 11, Tables 6, 7, 8).

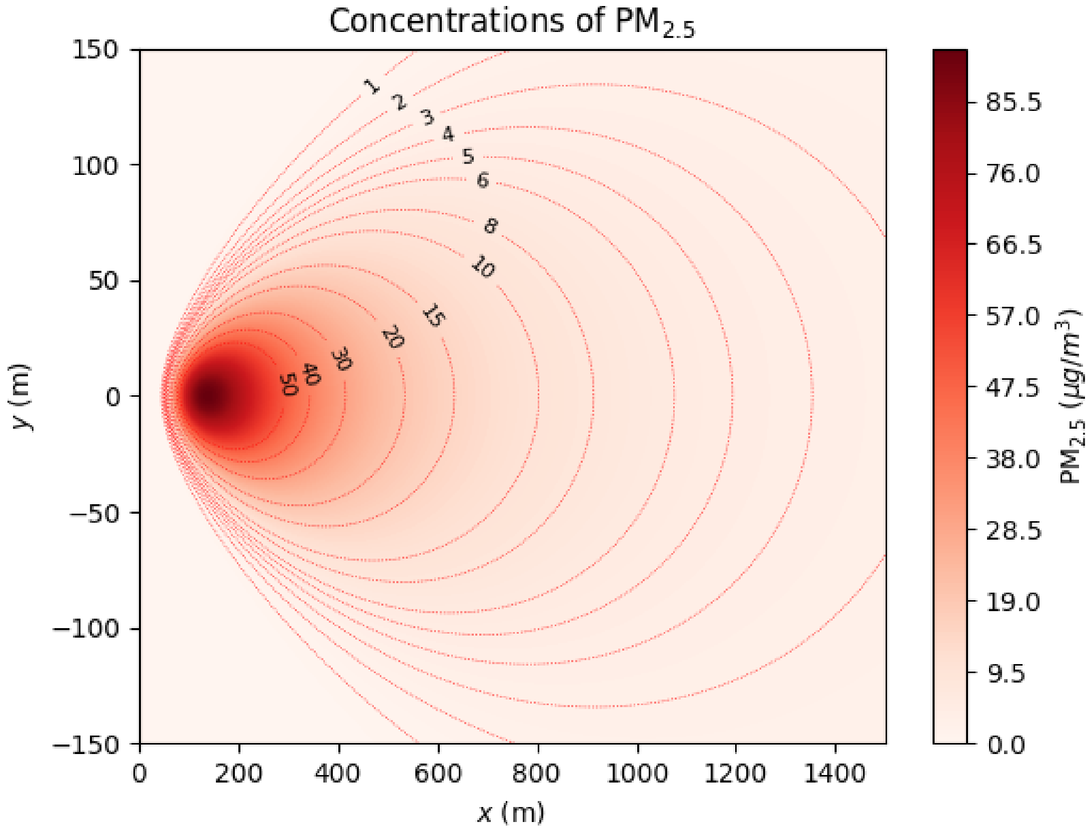
Parameter	Interpretation	Value	Unit
Q	Rate of emission of $PM_{2.5}$	4.5×10^5	$\mu g\, s^{-1}$
h	Stack height for release of pollutant	0	m
H	Effective stack height, including plume rise	14.17	m
u_h	Wind speed at ground level (10 m)	3	$m\, s^{-1}$
u_H	Wind speed at elevation H	3.22	$m\, s^{-1}$
σ_y	Horizontal dispersion coefficient	–	m
σ_z	Vertical dispersion coefficient	–	m
r	Radius of the stack	1	m
v_s	Exit velocity of pollutant from stack	0.5	$m\, s^{-1}$
g	Acceleration due to gravity	9.8	m/s^2
T_a	Ambient temperature	300	K
T_s	Stack temperature	600	K
x_f	Distance downwind to point of plume rise	87.54	m
F	Flux buoyancy parameter	2.45	m^4/s^3

2.4 Wind and insolation data

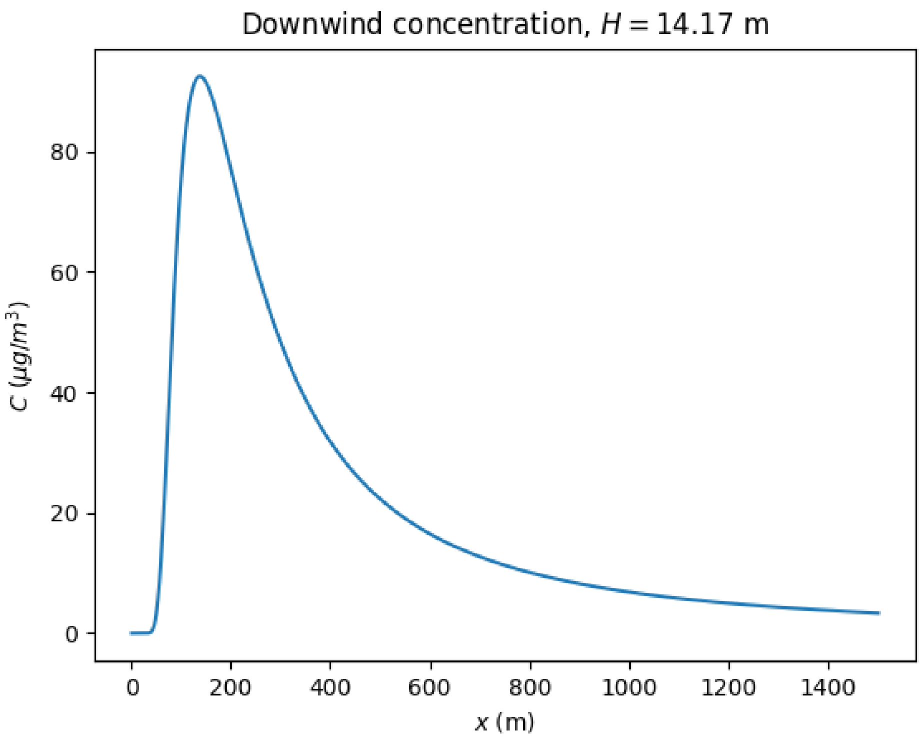
Wind and insolation data has been obtained from IndianClimate.com (2021) and Weather Spark (2021). We note that solar insolation during the winter months of November and December is slight during the day; the solar elevation averages at 40% (Suncalc.org, 2021), but cloud cover is around 25%. The surface wind speed data over this period has been averaged to $3\, m\, s^{-1}$. This means that we can fix our stability class as 'C', which indicates slightly unstable atmospheric conditions. The directional wind data is used to rotate the outputted concentration map as necessary. The wind direction varies from North-North-Easterly to North-North-Westerly during this time, which means that the positive x-axis in our model will be oriented between 150° to 210° from North.

2.5 Air quality data

Data on air quality has been obtained from the nearby Bidhannagar station (Central Pollution Control Board, 2021). Note that $PM_{2.5}$ levels are extremely high, sometimes exceeding $150\, \mu g/m^3$, which makes this the major air pollutant in Kolkata and its neighbouring areas. $PM_{2.5}$ levels consistently hover above $100\, \mu g/m^3$ in winter. This is far above the acceptable 24 hour exposure level of around $60\, \mu g/m^3$ for residential and ecologically sensitive zones (Central Pollution Control Board, 2009).



(a) Modelled $PM_{2.5}$ 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.



(b) $PM_{2.5}$ concentrations directly downwind ($y = 0$).

Figure 2: Concentrations of $PM_{2.5}$, with stubble burning at the origin and wind blowing at $3\,\mathrm{m\,s^{-1}}$ along the positive x-axis.

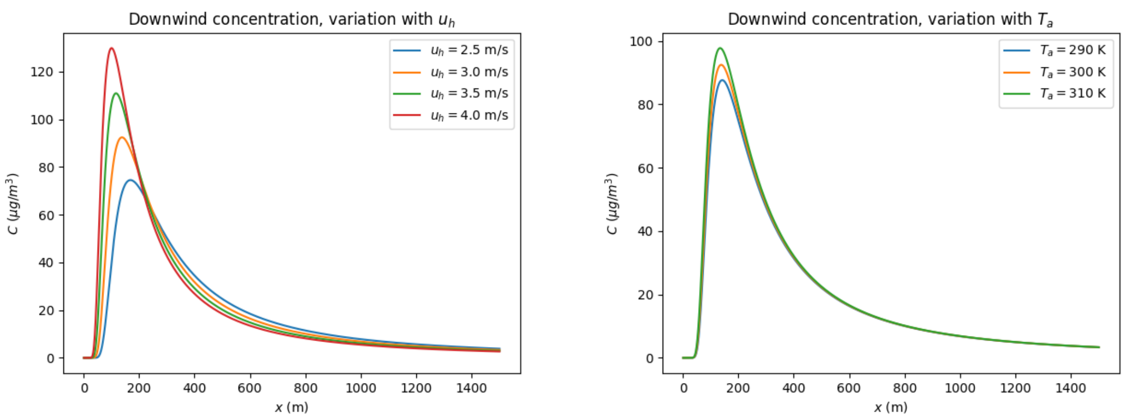
3 Results

3.1 Distribution of PM$_{2.5}$

The distribution of PM$_{2.5}$ concentrations due to a single burning site has been illustrated in Figure. 2, where the origin corresponds to location of burning and the positive x axis in in the direction of the blowing wind. Figure. 2a justifies the scale over which we have run our model, with the majority of the 3 µg/m^3 contour being visible. Figure. 2b shows that the pollutant concentration peaks around 200 m downwind, with values as high as 90 µg/m^3. From then on, the concentration drops off sharply – 6.8 µg/m^3 at 1 km and 3.3 µg/m^3 at 1.5 km. Furthermore, the spread of pollutants is highly directional. Figure. 2a shows that the contours are confined to a narrow region around 300 m broad (perpendicular to the direction of the wind) – compare this with the length of 1500 m (along the direction of the wind).

3.2 Sensitivity of downwind concentration

We examine how the down wind concentration changes when we vary the windspeed between 2.5 m s^{-1} to 4.5 m s^{-1}, and also when we vary the ambient temperature between 290 K to 310 K. The results have been presented in Figure. 3. In the first case, Figure. 3a, the peak concentration becomes higher and closer to the origin with decreasing windspeed – we infer that stronger winds are able to carry and distribute the pollutant more effectively. However, concentrations beyond 500 m are effectively the same (20 µg/m^3 to 25 µg/m^3 at 500 m), which means that there is not much variation over long distances. Similarly, there is almost no variation with ambient temperature, with the curves in Figure. 3b coinciding everywhere except at the peaks – higher ambient temperatures give higher peaks.



(a) Variation with ground windspeed.

(b) Variation with ambient temperature.

Figure 3: Variation of downwind concentration with windspeed and ambient temperature. In each case, all other parameters are fixed as per Table. 1.

4 Discussion and Conclusions

We have shown that a single pile of burning stubble can raise PM$_{2.5}$ levels beyond the permissible limit of 60 µg/m^3, but only in a narrow region between 100 m to 300 m downwind. This is indeed a health concern for residential areas within 500 m downwind. In our sites of interest, we see that there are indeed multiple housing complexes and parks which have been potentially affected, both in the DF Block and in the Eco Urban area, as is evident from Figure. 1. It is also important to note that if such incidents continue into the summer months beyond April, the direction of wind becomes Southerly (Weather Spark, 2021). As a result, we infer from Figure. 1a that the cluster of hospitals around DF Block, including the Ohio Hospital, Bhagirathi Neotia Women and Child Care Centre and HCG EKO Cancer Centre, will be affected, with $PM_{2.5}$ levels in the $20\,\mu g/m^3$ to $60\,\mu g/m^3$ range.

Beyond the above discussed zones, or in other directions, the contribution to $PM_{2.5}$ levels becomes negligible. Because of this limited range, stubble burning is unlikely to be a major factor behind the high ambient $PM_{2.5}$ levels in Kolkata which seem to persist over much larger areas.

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Online resources

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A Code listing

The code used for all calculations and generating figures is listed below.

```
#!/usr/bin/env python3

import numpy as np
import matplotlib.pyplot as plt

# Set up constants which vary with choice of stability class
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  }


# Implementation of the Gaussian plume model
class GPM:
    # Set primary parameters (pollutant emission rate and stability class)
    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]

    # Calculate and set parameters relating to the stack
    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)
        # print(self.F)
        if self.F >= 55:
            x_f = 120 * self.F ** 0.4
        else:
            x_f = 50 * self.F ** 0.625
        # print(x_f)
        self.dH = 1.6 * 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
        print(f"H = {self.H:.2f}")
        print(f"u_H = {self.u_H:.2f}")

    # Calculate the concentration at a given point
    def conc(self, x, y):
        x_km = x / 1000.0
        s_y = self.a * x_km ** 0.894
```

```python
        s_z = np.where(x_km < 1, \
            self.c_0 * x_km ** self.d_0 + self.f_0, \
            self.c_1 * x_km ** self.d_1 + self.f_1)
        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)))

# Set up grid (x from 0 to 1.5 km, y from -150 to +150 m)
x = np.linspace(0, 1500, 1000)
y = np.linspace(-150, 150, 1000)
X, Y = np.meshgrid(x, y)

# Initialize model with parameters
model = GPM(4.5e5, 'C')
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=3)

# Run calculations over the grid
Z = model.conc(X, Y)
H = model.H

# Plot a contour map
plt.contourf(X, Y, Z, levels=200, cmap="Reds")
colorbar = plt.colorbar()
colorbar.set_label("PM$_{2.5}$ ($\mu g / m^3$)")
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 PM$_{2.5}$")
# Click on the contours to set the locations of the labels manually
plt.clabel(contours, inline=True, colors="black", fmt="%d", fontsize=8, manual=True)
filename = f"H_stubble_{H:.2f}.png"
# plt.show()
plt.savefig(filename)
plt.clf()
print(f"Filename : ", filename)

# Plot the downwind concentration
plt.plot(x, model.conc(x, x * 0))
plt.xlabel("$x$ (m)")
plt.ylabel("$C$ $(\mu g/m^3)$")
plt.title(f"Downwind concentration, $H = {H:.2f}$ m")
filename = f"H_stubble_{H:.2f}_downwind.png"
plt.savefig(filename)
plt.clf()

print("Concentration downwind at x = 1km   : ", model.conc(1000, 0))
print("Concentration downwind at x = 1.5km : ", model.conc(1500, 0))
print("Concentration downwind at x = 2km   : ", model.conc(2000, 0))

# Variation of downwind concentration with windspeed
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=2.5)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 2.5$ m/s")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=3)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 3.0$ m/s")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=3.5)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 3.5$ m/s")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=4)
plt.plot(x, model.conc(x, x * 0), label="$u_h = 4.0$ m/s")
```

```
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
plt.xlabel("$x$ (m)")
plt.ylabel("$C$ $(\mu g/m^3)$")
plt.title(f"Downwind concentration, variation with $u_h$")
plt.legend()
filename = f"Variation_with_u_h.png"
plt.savefig(filename)
print(f"Filename : ", filename)
plt.clf()

# Variation of downwind concentration with ambient temperature
model.stack(h=0, T_a=290, T_s=600, r=1, v_s=0.5, u_h=3)
plt.plot(x, model.conc(x, x * 0), label="$T_a = 290$ K")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
model.stack(h=0, T_a=300, T_s=600, r=1, v_s=0.5, u_h=3)
plt.plot(x, model.conc(x, x * 0), label="$T_a = 300$ K")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
model.stack(h=0, T_a=310, T_s=600, r=1, v_s=0.5, u_h=3)
plt.plot(x, model.conc(x, x * 0), label="$T_a = 310$ K")
print("Concentration downwind at x = 0.5km   : ", model.conc(500, 0))
plt.xlabel("$x$ (m)")
plt.ylabel("$C$ $(\mu g/m^3)$")
plt.title(f"Downwind concentration, variation with $T_a$")
plt.legend()
filename = f"Variation_with_T_a.png"
plt.savefig(filename)
print(f"Filename : ", filename)
plt.clf()
```