MODELS FOR ASSESSING AIR POLLUTION IN CITIES

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ABSTRACT

For air quality modeling, the Gaussian plume model has been extensively used to analytically solve the steady and unsteady transport equation including the effects of particle deposition and settling. Along with the standard analytical solution of the Gaussian plume model for modeling air pollution dispersion in the atmosphere this work explores the adaptation of a Lagrangian Branched Atmospheric Trajectory approach for computing ground level concentrations of PM10 (suspended Particulate Matter of aerodynamic diameter of less than 10 micro meter), PM2.5 emitted from different air pollution sources in and around the city of Ahmedabad, India. With a transport time step of 6 hrs, the model includes necessary meteorological data which couple with multi-pollutant emission grid. The results obtained from the model are found to be very close to the measured PM10 data (2009-2011) from Gujarat Pollution Control Board.

Keywords: Air pollution dispersion, Gaussian Plume Model, Branched Atmospheric Trajectory Model, Suspended Particulate Matter.

1. Introduction:

The impact of air pollution is quite alarming with the overall detrimental effects of environmental pollution around the globe. Common citizens of several metro cities in India are heavily suffering from urban air pollution resulting in irritation to the eyes, nose and throat, chronic respiratory diseases, lung cancer, heart disease, and even damage to the brain, nerves, liver, or kidneys of. In India, the state of Gujarat has achieved the leading position among all the other states in establishing industries and infrastructures. Still, it seems that somehow Gujarat has overlooked its environment cost in its calculation of industrial development. This rapid growth of industries in Gujarat has raised the concerns about the possible impact of air-pollutant emissions and their effects on local air quality. There are several populous cities in Gujarat and among them Ahmedabad is the largest city and former capital of the Indian state of Gujarat. It is home to a population of ~5.57 million spread over an area of 464 km². Consequently the urban air pollution at Ahmedabad directly affects the largest residential community. The morbidity rate is reported to be very high in Ahmedabad due to air pollution as in Guttikunda and Jawahar (2012).

Moreover, the chemical and petrochemical industries have grown rapidly within its municipal limits of Naroda, Odhav, Vatwa, and Behrampur. The usual particulate matter (PM10) concentration remains always as 80-140 μg/m³ which is almost two times higher than the national annual prescribed limit of 60 μg/m³ and the limit of 40 μg/m³ prescribed by WHO as well (2013).

2. Atmospheric Dispersion Modeling Methodologies

The pollutants emitting out of a smoke stack propagates through the air along the direction of wind. Here five point sources representing smoke stack emission have been considered at
various locations in Ahmedabad city as shown in Fig. 1, and each source has a different rate of emission. While propagating the concentration profile of pollutant maintains a certain pattern depending on various meteorological parameters.

![Fig. 1 Full gridded computational region of Ahmedabad city.](image)

### 2.1 Gaussian Plume Dispersion Model

The analytical approach is applied to obtain a direct mathematical solution by using some well known functions which provides a closed form expression thereby making it easier to solve the problem within the reasonable assumptions made to transform the problem. As there is a clear similarity between the Gaussian distribution and the concentration profile of pollutants in air, the Gaussian distribution function defined as

\[
P(x) = \frac{1}{\sigma^x \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \forall \ x \in (-\infty, +\infty)
\]

serves as an approximate analytical solution to the transport equation for pollutant concentration in space and time as

\[
\frac{\partial C}{\partial t} + \nabla \cdot (Cu) = \nabla \cdot (K \nabla C) + S
\]

Here \( C(\vec{x}, t) \) is defined as the mass-concentration of a single pollutant, (kg m\(^{-3}\)) and \( S(\vec{x}, t) \) is a source or sink term for the pollutant, (kg m\(^{-3}\)). Wind velocity is \( \vec{u} \) and eddy diffusivity is \( K(\vec{x}) \). The units of wind velocity and eddy diffusivity are (m s\(^{-1}\)) and (m\(^2\) s\(^{-1}\)) respectively. To solve the transport equation, one must provide necessary and sufficient initial and boundary conditions. These conditions are stated below.

**Initial conditions:**

\[
\left. u(\vec{x},t) \right|_{t=0} = (u, 0, 0) \quad \text{for some constant } u \geq 0
\]
Boundary conditions:

\[
C(0, y, z) = 0, C(\infty, y, z) = 0,
\]
\[
C(x, \pm\infty, z) = 0, C(x, y, \infty) = 0
\]  

(4)

Implementation of these conditions results in the steady-state analytical solution as outlined in Stockie (2011) for the spatial and temporal variation of pollutant concentration in a given domain of interest as

\[
C(x, y, z) = \frac{Q}{u} \times \frac{1}{\pi \sigma_y \sigma_z} e^{\left( -\frac{y^2}{2\sigma^2_y} \right)} e^{\left( -\frac{z^2}{2\sigma^2_z} \right)}
\]  

(5)

where \( \sigma_y \) and \( \sigma_z \): The standard deviations of plume dispersion in lateral (y) direction, and vertical (z) direction, in meter (m) respectively. \( Q \) is the rate of emission (kg s\(^{-1}\)). To include the effects of settling and deposition of suspended particulate matters, Equation (5) is rewritten as Ermak’s Solution as follows:

\[
C(x, y, z) = \frac{Q}{u} \times \frac{1}{\pi \sigma_y \sigma_z} \left[ \exp\left( -\frac{y^2}{2\sigma^2_y} \right) + \exp\left( -\frac{(z - H)^2}{2\sigma^2_z} \right) \right] + \exp\left( -\frac{(z + H)^2}{2\sigma^2_z} \right) -
\]
\[
\sqrt{2\pi} \frac{U_0}{K_z} \exp\left( \frac{U_0(z + H)}{K_z} + \frac{\sigma_z^2 U_0^2}{2K_z^2} \right)
\]
\[
erfc\left( \frac{\sigma_z U_0}{\sqrt{2K_z}} + \frac{z + H}{\sqrt{2\sigma_z}} \right)
\]

(6)

where \( U_{set} \) corresponds to gravitational settling speed and as a result the velocity becomes \( u = (U(t), 0, -U_{set}) \). Also \( U_0 = U_{dep} - \frac{1}{2} U_{set} \) and \( erfc(x) \) is the complementary error function which is denoted by, \( erfc(x) = \frac{1}{2} - erf(x) \). Actually, the distributions in y and z direction are measured from the centre line of plume propagation. Here the centre line is assumed to be at a height \( H \) above the ground level. So, the distance between the point of interest and centre line is \( (z-H) \).


2.2 Lagrangian Branched Atmospheric trajectory model: ATMoS

The Lagrangian Urban Region Branched Atmospheric Trajectory Model is applied through a software called ATMoS (Atmospheric Transport Modeling System) as reported by Guttikunda (2009). The Lagrangian reference frame is computationally more efficient than the simplest finite-difference scheme in Eulerian frame. Also, the Lagrangian frame is more effective for minimizing the numerical dispersion which arise from the discretizing error in the advective terms of the transport equation. In Lagrangian reference, the advective term disappears as the co-ordinate system moves at the same velocity of mean flow. Thus the Lagrangian frame almost entirely avoids the numerical dispersion as in Lauritzen et al. (2011). While following an individual particle trajectory in Lagrangian framework, all the factors that affect the propagation is accounted duly in calculations.

\[
\frac{\partial C}{\partial t} + \frac{\partial [c(u-U)]}{\partial x} = 0
\]  

(7)

The local instantaneous concentration \( c \) and the local instantaneous velocity \( u \) can be described in terms of turbulent fluctuations as:

\[
u = U + u_a + u' \quad , \quad c = C + c_a + c'
\]  

(8)

The time-averaged puff velocity is denoted by \( U \) and the pollutant concentration (averaged over a long time scale with compared to those turbulent fluctuation) based on mean cross-sectional are normal to the direction of flow is denoted by \( C \). The local values of the temporal mean value of \( u \) are referred as \( u_a \) whereas \( u' \) is the instantaneous deviation from the mean. Similarly, \( c_a \) denotes the local values of the temporal mean value of \( c \) whereas \( c' \) is the instantaneous deviation from the mean as in Moreira et al. (2010).

\[
\frac{\partial C}{\partial t} + \frac{\partial[u_a c_a + u' c']}{\partial x} = 0
\]  

(9)

The terms of \( [u_a c_a] \) and \( [u' c'] \) refer to differential convection and turbulent diffusion respectively. Clearly, the turbulence effect is negligible with respect to convective effect. So, Equation (3) can be written in the form of Equation (4).

\[
\frac{\partial C}{\partial t} + \frac{\partial [u_a c_a]}{\partial x} = 0
\]  

(10)

and applying the analogy of Fick’s Law this can be written as

\[
[u_a c_a] = D_x \frac{\partial C}{\partial x}
\]  

(11)
where, \( \vec{x} = (x, y, z) \) and \( D_x \) is the diffusion coefficient. A mixing coefficient \( DQ_k \) is introduced to capture the mixing effects at the boundary between segments \( k \) and \( k+1 \) and is defined such a way that the term \( \frac{\partial[u_s c_s]}{\partial x} \) in Equation (4) can be approximated by:

\[
\frac{\partial[u_s c_s]}{\partial x} = \frac{DQ_k(C_k - C_{k+1}) - DQ_{k-1}(C_{k-1} - C_k)}{A\Delta x}
\]  

where

\[
DQ = \int_A |u - U| \, da
\]

Here, the concentration of pollutant based on the cross-sectional average at the segment \( k \) is referred as \( C_k \). The segment volume is defined by \( A \Delta x \). Along the trajectory and its branches, the location of a particular parcel and its concentration is computed by using the following formulae:

\[
x = x_0 - \int_0^T U \, dt
\]

\[
c = c_0 - \int_0^T \frac{\partial[u_s c_s]}{\partial x} \, dt
\]

Here, \( x \) is the Eulerian or actual (stationary) distance co-ordinate along the domain. \( U \) is the mean wind velocity and \( x_0 \) is the location of puff (parcel) at time \( t=0 \). \( T \) refers to travel time. \( c_0 \) refers to concentration of the pollutant of plume at time zero and \( c \) is the concentration of pollutant after time \( t=T \). ATMos uses Heun’s method to perform the computation of definite integral in Equation (14) and (15) which must be solved for a series of plume parcel and also the locations of these parcels are continually tracked. Thus, it will provide a solution grid constructed over space and time. Tracking ceases when the computation reaches the boundary, tracking ceases or if at any point of time concentration, \( c \) drops below 0.1% of its initial value of pollutants at source. However, the computation also stops when 5 days/120 hours are over or the trajectories leave the modeling domain (whichever is earlier).

3. Results and Discussion:

3.1 Results from Gaussian Plume Dispersion Model

Analytical Gaussian Plume solution has great significance and physical insight. Basically, to obtain results with the analytical approach Equation (6) is directly used. Wind of uniform velocity of 5 m s\(^{-1}\) from West to East has been assumed to initialize the transport of the pollutants in the domain of interest in the first iteration. A time averaged wind velocity from the local meteorological data is also used to obtain the desired result. The simple analytical
Gaussian plume model incorporating the deposition and settling effects is applied to model the dispersion from the various sources located at Ahmedabad city. The manner in which the pollutant concentrations vary along the altitude (X-Y plane) in the domain of interest is shown in Fig. 2.

![Fig. 2 Ground level PM10 concentration from Analytical Gaussian Model.](image)

Figure 3 shows the contours of the pollutant concentration on X-Y planes at various altitudes above the ground. Figures 4 and 5 show the contours at selected X-Y and Y-Z planes to give an overall view of the spatial transport of the pollutant concentration in all three directions. Superimposing these contours on the map of Ahmedabad will provide insight on the range and extent of the pollution and the ground level concentration is important in developing suitable health related policies to mitigate and control pollution induced respiratory diseases.

![Fig. 3 Contour Plots of Concentration on Horizontal Cross-sections at Different Altitudes from the ground. (Continued)](image)
3.2 Results from ATMoS Simulations

To check the validity of the results obtained from ATMoS, data published in the Annual Pollution Report (2009-2010) of the Gujarat Pollution Control Board (GPCB) is used in Figure 6 which compares the measured and computed ground level concentrations of PM10 at various places in Ahmedabad in 2009-10.
Fig. 6 The bar chart representation of the results from the ATMoS model with respect to the measured data of GPCB Annual Pollution Report (2009-10) at Ahmedabad.

A graphical comparison of computed and measured ground level concentration of PM10 is shown in Fig. 7.

Fig. 7 The plot validating the ATMoS model w.r.t. GPCB Annual Pollution Report [GPCB 2010] at Ahmedabad.

Fig. 6 and 7 clearly show the consistency between the measured and computed values of pollution concentration. Still there are some discrepancies in the measured and computed concentration values at the locations of GIDC office, Naroda and Torrent Power AEC, Sabarmati, Ahmedabad. At these locations the local influence of industrial and vehicular emission, external pollution and vicinity of the river Sabarmati may cause the difference between the computed and measured data.
3.3 Comparison Study between Analytical Gaussian Plume Dispersion Model and ATMoS

While the analytical Gaussian model is a very simple to implement, in this study it is observed that this simple approach did not result in a significant match with the results from the ATMoS simulations. Within a certain radius of ~5-6km from the source, the concentration values modeled using the analytical Gaussian plume solution matches the predicted results from ATMoS. Beyond this distance, the Gaussian plume solution shows very low concentration values of pollutant and thus it fails to represent the actual scenario. While there is scope to enhance the analytical solution, it appears that the model can only compute the pollutant concentration reasonable well over a short distance of few hundred meters to ~5km from the source. The main reason is the way it handles its input parameters --meteorological and emission data for the domain. In the analytical model, only point source emission is modeled and results are obtained only on the basis of the point source emission rate. The simple analytical Gaussian model can not include the ground level pollution sources e.g. vehicular exhaust, sand storm or household emission. Thus the simple Gaussian model fails to predict the concentration values at a longer range beyond the radius of 5-6 km from the source.

4. Conclusion
The validation study with GPCB data and comparison study with analytical model of Gaussian plume clearly proves the credibility and authenticity of ATMoS. For air pollution dispersion modeling in urban areas (like Ahmedabad) ATMoS is very well suited and it proves to be simple and computationally cheap. In this study ATMoS shows excellent performance and almost accurately follows the measured data by GPCB.This study will serve as a basis for
further investigation using real meteorological data and also assessing the potential of this tool for supporting pollution control policies in the region.

References:


