Research Paper

Modelling of Ambient Air Quality Over Visakhapatnam Bowl Area

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(Received on 25 November 2005; Accepted on 02 March 2006)

Visakhapatnam bowl area situated in coastal Andhra Pradesh, India hosts several major industries. These industries contribute significantly to the air pollution in this coastal city. In addition, the vehicular traffic also contributes in the deterioration of ambient air quality in the city. The ambient air quality of Visakhapatnam bowl area with respect to oxides of nitrogen due to industrial and vehicular sources has been examined using mathematical models. Gaussian Plume Model (GPM) is used for industrial sources and CALINE3 model is used for line sources. The computed 8 hourly averaged concentrations have been compared with those monitored concentrations at different receptors in two seasons, namely, summer and winter. The validation of the models has been carried out through Quantile-Quantile plots and by computing several statistical errors.

Key Words: Industrial sources, vehicular traffic, air quality model, observed concentrations, bowl area, statistical errors

Introduction

The major sources contributing to the deterioration of ambient air quality in urban areas are mainly industrial sources, vehicular traffic, power plants and domestic fuel burning. Several pollutants are released into the atmosphere as a result of these activities. The presence of these pollutants in ambient air adversely affects the health of human beings, animals and vegetation. Air quality models are used widely to assess ambient air quality of a selected region. These models have become indispensable tools to assess ambient air quality and to maintain pollution levels within permissible limits.

Several studies[1-5] have been made in the past to assess the ambient air quality of different urban areas in India with respect to different pollutants from different sources. Ever increasing vehicular traffic in urban areas is the major cause of concern to the ambient levels of pollutants in urban areas. Some of the studies were undertaken to examine the contribution of vehicular emissions in several cities using line source models[6-14]. Air quality modelling studies assume significance in assessing the ambient air quality of selected urban areas due to different sources of air pollution.

The contribution of industrial sources and vehicular emissions in Visakhapatnam bowl area has been evaluated in the present study. A Gaussian plume model for industrial sources and CALINE3 model for line sources are considered. The paper briefly describes these models and presents an evaluation of predicted concentrations with observed values at different monitoring sites in the study region.

Study area

Visakhapatnam (17°42′N; 83°20′E) is a major industrial city in the northeastern coastal Andhra Pradesh, India. It has typical topography with hills on the three sides and Bay of Bengal in the east (Fig. 1). Visakhapatnam also harbours a naturally built port and the bowl area extends over an area of 266 km^2. Visakhapatnam hosts several major industries, namely, steel, refinery, petroleum products, petrochemicals, zinc, polymers etc. The stack emissions from these industries contribute significantly to the air pollution in the bowl area. In addition, the port activities and transportation to and from due to the port is also playing a major role in the increase in the air pollution in this region. The vehicular exhaust on the

Figure 1*: Study region of Visakhapatnam bowl area. Major industries*■*; Receptors in summer* ▲*; Receptors in winter* ●.

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major roads in the city and on the National Highway also plays a pivotal role in increasing the air pollution in this area. A national highway (Kolkatta - Chennai) passes through the bowl area and there are many major roads like Malkapuram road run through the bowl area (Fig. 1).

Three pollutants namely sulphur dioxide (SO_2), oxides of nitrogen (NO_x) and suspended particulate matter are identified as major pollutants that are being emitted from the industrial stacks, mobile/line sources (vehicles) and domestic sources in this region. However, the emissions of NO_x from the industrial and line sources are considered in the present study to analyze the ambient air quality of the bowl area, as NO_x is considered to be a major emission from the vehicular sources.

Air quality models

The pollutant concentrations have been computed using the Gaussian Plume Model (GPM) due to industrial sources and using CALINE3 model due to vehicular traffic. GPM is a point source model that can be used for estimating the pollutant concentrations due to industrial stacks or elevated point sources, whereas CALINE3 is a line source model that can be used for predicting the pollutant concentrations due to mobile sources (e.g. vehicles plying on roads). Both models do not handle land or sea breeze effects. The descriptions of the models are given below.

Gaussian Plume Model (GPM)

The concentration of the gaseous pollutants due to elevated point sources[15,16] is given by

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right]$$

$$\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\} \quad \text{... (1)}$$

where Q is the source strength (g s^{-1}), u is the mean wind speed (m s^{-1}), y is the cross wind distance (m), z is the vertical distance above the ground (m), σ_y, σ_z are the horizontal and vertical dispersion parameters (m) respectively. H is the effective stack height (m) which is defined as $H=h+\Delta h$, where h is the physical stack height (m) and Δh is the plume rise (m). The wind profile law[15] is used to compute the wind speed at the stack level. Plume rise due to buoyant release is parameterized using Briggs formulae[17,18] under stable, unstable and neutral atmospheric conditions. The horizontal and vertical dispersion parameters σ_y and σ_z are estimated using the Briggs formulae for urban areas[19]. The model does not treat the dry/wet deposition and chemistry is not included in the model.

CALINE3 Model

CALINE3 is a third generation line source air quality model developed by the California Department of Transportation. It is based on the Gaussian diffusion equation and employs a mixing zone concept to characterize pollutant dispersion over the roadway.

CALINE3 divides individual highway links into a series of elements from which incremental concentrations are computed and then summed to form a total concentration estimate for a particular receptor location. The receptor distance is measured along a perpendicular from the receptor to the highway centerline. The first element is formed at this point as a square with sides equal to the highway width. The lengths of subsequent elements[20] are described by:

$$EL = Wb^{N-1} \quad \text{... (2)}$$

where EL is the element length, W is the highway/roadway width, b is the element growth factor (a function of the angle between the wind direction and the direction of the roadway) and N is the element number. Each element is modeled as an equivalent finite line source (EFLS) positioned normal to the wind direction and centered at the element midpoint. The downwind concentrations from the element are modelled using the crosswind finite line source (FLS) Gaussian formulation.

$$C(x,y) = \frac{q}{\pi u \sigma_z} \int_{y_2-y}^{y_1-y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) dy \quad \text{... (3)}$$

where q is the line source strength (g $m^{-1}s^{-1}$) and y_1, y_2 are the end points of finite line source.

CALINE3 treats the region directly over the highway as a zone of uniform emissions and turbulence. This is designated as the mixing zone, and is defined as the region over the traveled way plus three meters on either side. The additional width accounts for the initial horizontal dispersion and the initial vertical dispersion is parameterized as a function of the turbulence within the mixing zone[20]. The vertical dispersion curves are formed by using the value of initial vertical dispersion from the mixing zone model and the value of σ_z at 10 kilometers[21]. The horizontal dispersion curves are parameterized using Turner's formulae[22]. CALINE3 permits the specification of up to 20 links and 20 receptors. The contributions from each link are summed to each receptor. After this has been completed for all receptors, an ambient or background value is added.

Data

The emissions data due to industrial and line sources, meteorological data and the observed air quality data[23] are described in this section.

Ambient air quality data

The ambient air quality of different pollutants is monitored at several monitoring stations (receptors) in the Visakhapatnam bowl area (Table 1). The ambient levels of NO_x are monitored at 10 receptors in summer season and at 12 receptors in winter season[4]. These observed concentrations are averaged over 8-hrs, i.e. 2 AM-10 AM; 10 AM-6 PM; 6 PM-2 AM on each day. The location (x,y,z) of the receptors are considered on the Cartesian grid of the study area.

Emissions data- Industrial sources

Nine major industries (Fig. 1) are considered in the Visakhapatnam bowl area. They are Visakhapatnam Steel Plant (20 stacks), Hindustan Petroleum Corporation Limited (23 stacks), Coromandal Fertilizers Limited (stacks), Andhra Petro Chemicals Limited (8 stacks), Rain Calcining Limited (2 stacks), Hindustan Zinc Limited (2 stacks), Alu Fluoride Limited (3 stacks), ESSAR (1 stack) and LG Polymers Limited (3 stacks). Thus a total number of 67 stacks of these industries are treated as elevated point sources in the present study. The location (x,y) of each stack on a Cartesian grid is considered in the numerical calculations. The stack characteristics such as stack height, internal diameter, stack exit velocity and exit temperature of each point source are taken in the present study along with the emission rates (source strength) of NO_x.

Emissions data-Line sources

The traffic volume (number of vehicles per hour) plying on the roads at five major traffic intersections, namely Asselmetta, NAD X Road, Gajuwaka, Convent Junction and Jagadamba and at four midway intersections, namely Airport Highway, Naval Dockyard, Thatichetlapalem and Sriharipuram have been counted in the study area. The number of vehicles per hour of four different types of vehicles, namely, two wheelers, three wheelers, four wheelers (LCV and HCV) as shown in figure 2 and the emission factors of NO_x[24] as given in table 2 are used in the present study. Eleven roads at the above mentioned traffic intersections and four roads on the midway intersections have been taken. The end points of these roads are identified on the Cartesian grid.

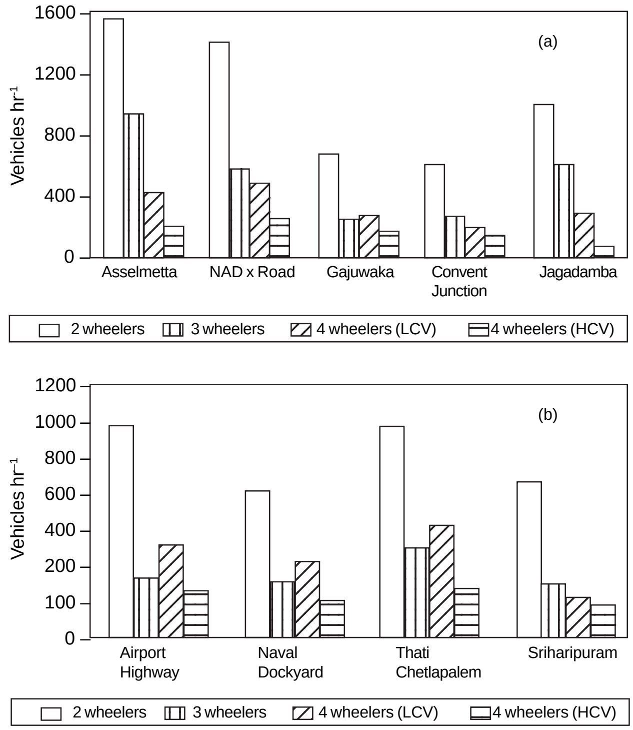


Figure 2: *Traffic volume at (a) major traffic intersections and (b) midway intersections in Visakhapatnam bowl area*

Meteorological data

The meteorological data for 20 days during the summer season of 2002 (April 26 - May 15) and for 22 days during the winter season of 2002-03 (December 28, 2002 - January 18, 2003) were taken in the present study. The meteorological data comprised the 3 hourly wind speed, wind direction, temperature, cloud cover and solar insolation which were obtained from the India Meteorological Department (IMD), Visakhapatnam.

Atmospheric stability is compiled from the wind speed, cloud cover and solar insolation following

Table 1: Ambient air quality monitoring stations in Visakhapatnam bowl area

S.No	Summer Name of receptor	Eleva-tion (m)	Period of Observation	S.No.	Winter Name of receptor	Eleva-tion (m)	Period of Observation
1.	ESSAR	10	April 26-May 5	1.	Malkapuram	12	December 30-January 8
2.	Port Office	10	May 5-May 14	2.	Mulagada	12	January 7-January 17
3.	Kancharapalem	10	May 6-May 15	3.	Venkatapuram	10	December 29-January 7
4.	Seethammadhara	70	May 6-May 15	4.	Sriharipuram	20	January 8-January 18
5.	Malkapuram	12	May 5-May 14	5.	Karasa	10	January 7-January 17
6.	Mindi	10	April 26-May 5	6.	Gajuwaka	10	January 7-January 17
7.	Naval Park	10	April 27-May 6	7.	Mindi	10	December 29-January 7
8.	Sriharipuram	20	April 26-May 6	8.	Fire Office	10	December 29-January 7
9.	Police Barracks	12	April 26-May 5	9.	Naval Park	10	January 8-January 18
10.	Fire Office	10	May 5-May 14	10.	Kakani Nagar	10	December 28-January 7
				11.	Sheela Nagar	10	December 28-January 7

Table 2: Emission factors of NO_x for different types of vehicles

Type of Vehicle	Emission factor (g km^{-1})
2 Wheelers	0.03
3 Wheelers	0.10
4 Wheelers (LCV)	3.00
4 Wheelers (HCV)	21.0

Turner's table[22] and mixing height is determined using the Holzworth technique[25]. Thus in the present study, the meteorological data of 3 hourly (0200, 0500, 0800, 1100, 1400, 1700, 2000 and 2300 hrs) wind speed, wind direction, temperature, atmospheric stability and mixing height are used.

Figure 3 illustrates the wind roses for both seasons namely, summer and winter at Visakhapatnam. The prevailing wind direction is SSW, SW and WSW and the winds are found to be stronger (Fig. 3a) in summer. The predominant wind direction in winter is E, ESE, SE followed by S, SSW. The calm conditions occur about 17% in summer (Fig. 3a) and about 56% in winter (Fig. 3b) seasons respectively.

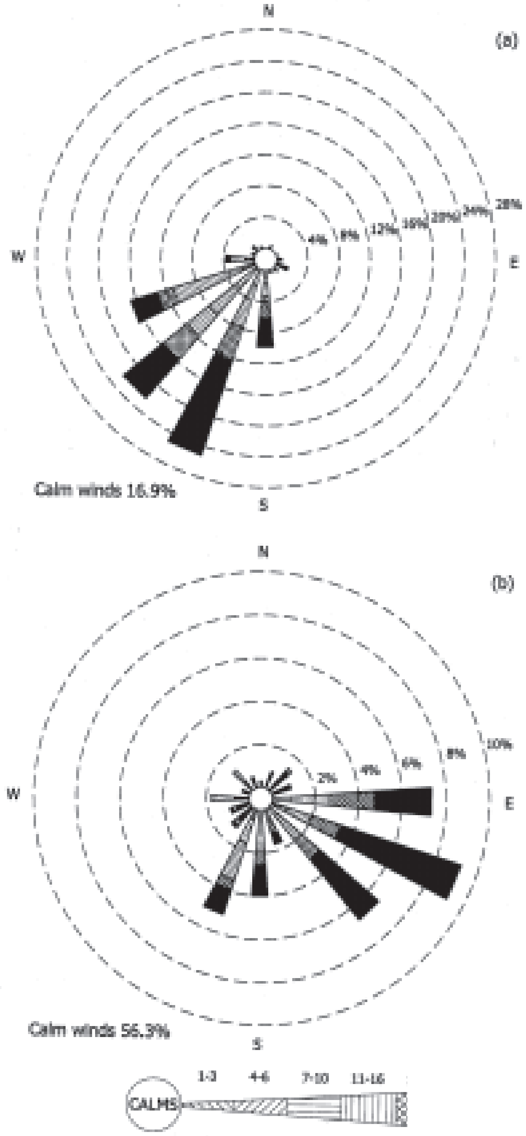


Figure 3: *Wind roses for (a) summer and (b) winter seasons at Visakhapatnam (Wind speed is in knots)*

The mean diurnal variation of wind speed and mixing height are shown in figure 4. Wind speed varies from 4.5 to 12 m s^{-1} in summer (Fig. 4a) and from 1.35 to 13.3 m s^{-1} in winter (Fig. 4b) seasons respectively. The mixing height show a typical diurnal trend as it is minimum during morning and increases rapidly towards noon with maximum value around 1400 hrs and thereby decreasing gradually towards late night (Fig. 4). The maximum value of mixing height is 832 m in summer and is 1050 m in winter. Mixing heights are observed to be higher in winter than in summer except during the late evening hours. This may be because of the possible internal boundary layer development due to the influence of sea breeze during daytime and typical topography of the study region[4]. The horizontal temperature gradients due to land and sea contrast are more in summer than in winter season in the Visakhapatnam bowl area. Low mixing height values during late night and early morning hours may be due to the occurrence of ground based inversions which reduce dispersion of pollutants[26].

Computational methodology

The concentrations NO_x were computed using two mathematical dispersion models namely GPM for industrial sources and CALINE3 for line sources. The input data for each model are presented in Table 3. The 3 hourly concentrations of NO_x were computed using

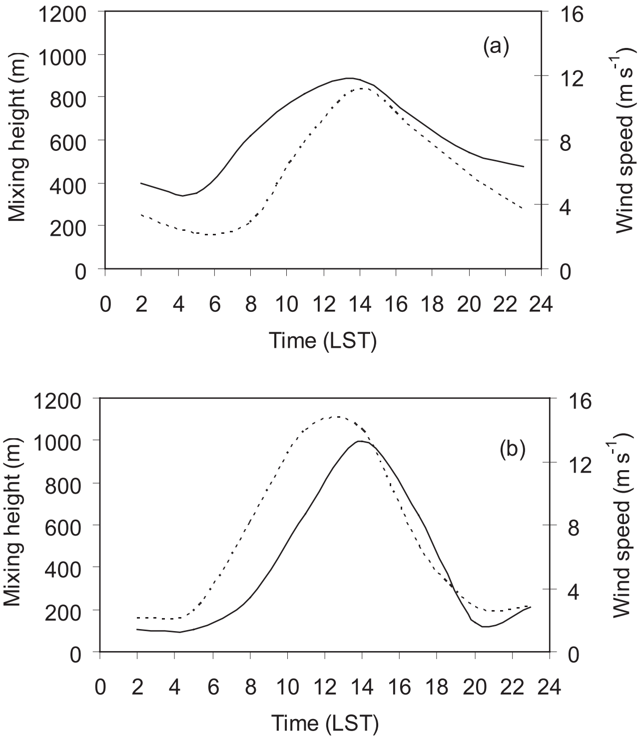


Figure 4: *Mean diurnal variation of wind speed (________) and mixing height (- - - - - - - - - -) in (a) summer and (b) winter seasons in Visakhapatnam bowl area*

Table 3: Input data for GPM and CALINE3

GPM for elevated point sources	CALINE3 for line sources
(a) Source data	(a) Source data
Stack height	Location of each link/road (X,Y,Z)
Stack internal diameter	Source height
Stack gas exit velocity	Source width
Stack gas exit temperature	Traffic volume
Location of stack (X,Y,Z)	Pollutant emission factor
(b) Receptor data	(b) Receptor data
Location of receptors (X,Y,Z)	Location of receptors (X,Y,Z)
(c) Meteorological data	(c) Meteorological data
Wind speed	Wind speed
Wind direction	Wind direction
Temperature	Mixing height
Mixing height	Atmospheric stability
Atmospheric stability	
	(d) Others
	Ambient concentration of pollutant
	Surface roughness
	Averaging time

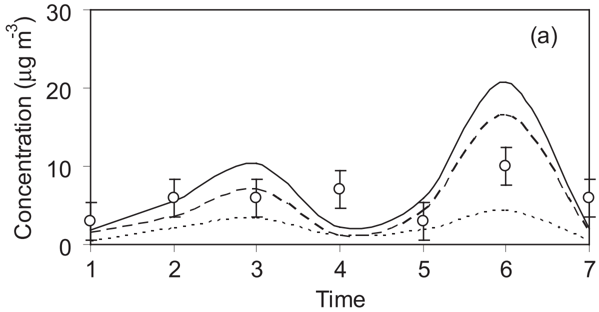
both the models in both summer as well as winter seasons. The 8 hourly averages of computed concentrations were obtained from the 3 hourly values for summer and winter seasons at each receptor as described in[4]. The 8 hourly averages of predicted concentrations obtained from both the models GPM and CALINE3 were compared with those 8 hourly observed concentrations in both seasons.

Different statistical errors namely Normalized Mean Square Error (NMSE), Fraction of Two (FA2), Fractional Bias (FB) and Index of Agreement (IOA)[4,16] were computed using the 8 hourly averaged computed and observed NO_x concentrations in both seasons.

Results and discussion

The models computed NO_x concentrations, due to industrial and line sources are compared with the observed concentrations at different receptors. Both models were used to compute 3 hourly pollutant concentrations using 3 hourly meteorological data at different receptors in summer and winter seasons. The 8 hourly averaged values were calculated from the 3 hourly computed values at all receptors. Thus the 8 hourly averaged computed values are compared with the 8 hourly observed concentrations at these receptors. Validation of the models' predictions has also been carried out through Q-Q plots and computing several statistical errors such as NMSE, FA2, FB and IOA.

Figure 5 illustrates the comparison of the cumulative NO_x concentrations due to industrial and line sources with the observed values at Fire Office and Sriharipuram during summer. The concentrations predicted by the GPM due to industrial sources and CALINE3 model due to line sources are also superimposed to examine the influence of industrial and vehicular sources individually. It is observed that the predicted cumulative concentrations are close to the observed values at Fire Office (Fig. 5a). Contribution of industrial sources is more that that of line sources or vehicular emissions at this receptor. Fire Office is located reasonably far from the major traffic intersections that are considered in the present study. Contribution of line sources is found to be very low compared to industrial sources at Sriharipuram also (Fig. 5b). The negligible contribution from vehicular emissions at Sriharipuram may be due to the predominant wind direction during summer which is SSW to SW (Fig. 3). Sriharipuram is located in the upwind direction to the major road (Malkapuram road).



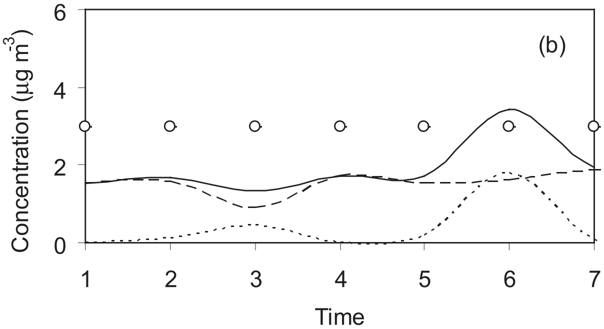


Figure 5: *Comparison of predicted and observed NO_x concentrations in summer season at (a) Fire Office and (b) Sriharipuram in Visakhapatnam bowl area. GPM ------; CALINE3 - - - - -; Cumulative concentrations ——— Observed O. Errors bars are standard deviations of the observed values*

The predicted cumulative concentrations are less than the observed values as all the industrial sources also exist in the upwind direction to this receptor (Fig. 1).

Figure 6 shows the comparison of computed NO_x concentrations with the observed values at Gajuwaka and Karasa in winter. It is seen that the cumulative concentrations are close to the observed values at both the receptors during winter. The contribution from industrial sources is more than the vehicular emissions at Gajuwaka (Fig. 6a) and the contribution from line sources is much higher than those from industrial sources at Karasa (Fig. 6b). Gajuwaka is situated reasonably close to major industrial sources and is also close to a national highway. It is also a major traffic junction in the study area (Fig. 1). Karasa is also close to a national highway. The four wheelers, both LCV and HCV, have contributed more to the vehicular emissions at Gajuwaka (Fig. 2).

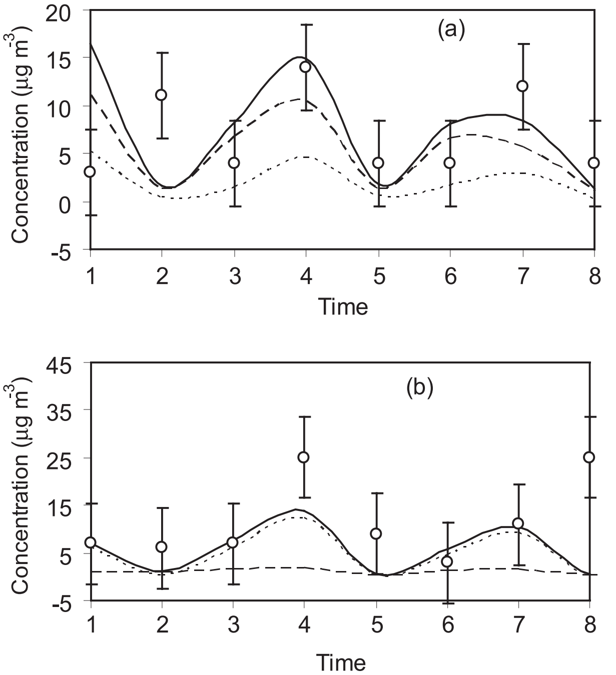


Figure 6: *Comparison of predicted and observed NO_x concentrations in winter season at (a) Gajuwaka and (b) Karasa in Visakhapatnam bowl area. GPM ------; CALINE3 - - - - - -; Cumulative concentrations ———— Observed O. Errors bars are standard deviations of the observed values*

From the above, it may be concluded that by considering the line source emissions through CALINE3 along with industrial emissions through GPM, the ambient air quality predictions are in reasonably good agreement with the observed air quality levels in Visakhapatnam bowl area. The influence of vehicular traffic is appealing at those receptors that are close to the major roads in the present study.

The Q-Q plots have been plotted and different statistical errors were estimated for evaluating the models performance. Figure 7 depicts the Q-Q plot for ranked model predictions against ranked observations. The points would lie on the one-to-one line if the distribution of the model predictions and observations is identical[27]. The predicted values represent the cumulative concentrations obtained from GPM due to industrial sources and from CALINE3 model due to vehicular/ line sources. The Q-Q plot shows underprediction as well as overprediction, however about 30% of the points lie close to the one-to-one line.

It is found that the numerical values of the estimated errors computed using the predicted cumulative concentrations and observed values are close to the respective ideal values of NMSE, FA2, FB and IOA as given in Table 4. The values of FB and IOA suggest the underprediction of the concentrations. From these errors (Table 4), the performance of both models is reasonably good as majority of their predictions are within a factor of two[28].

Table 4: Statistical errors

Error	Ideal value	GPM + CALINE3
NMSE	Least Value	0.54
FA2	1	1.00
FB	0	-0.009
IOA	1	0.80

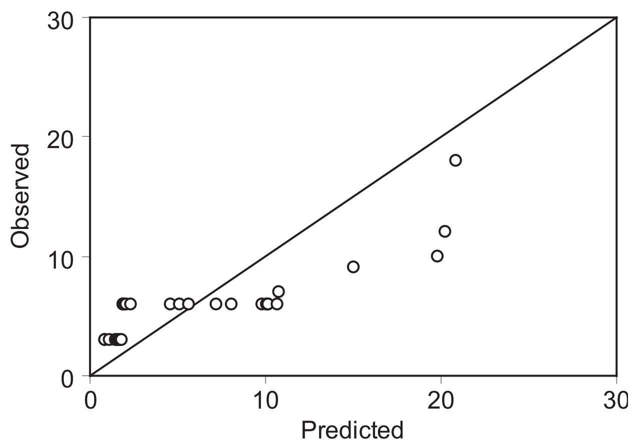


Figure 7: *Q-Q plot of cumulative NO_x concentrations*

Gaussian models are widely used as regulatory models for assessing the ambient air quality of various regions. These models were proven to perform better under moderate to strong wind conditions; under moderately stable/unstable conditions for short range (< 50 km) and for short term prediction of pollutant concentrations[16]. The influence of vehicular traffic at major traffic intersections may be studied by considering the idling, cruising, and acceleration or deceleration emissions from vehicles at the traffic signals in Visakhapatnam bowl area through other available models and when data required by those models is available.

Conclusions

Visakhapatnam bowl area situated in coastal Andhra Pradesh, India hosts several major industries. These industries contribute significantly to the air pollution in this coastal city. In addition the vehicular traffic which is known as mobile or line sources also contributes to the deterioration of ambient air quality of the city. The ambient air quality of Visakhapatnam bowl area with respect to oxides of nitrogen due to industrial and line sources has been examined using two different mathematical models. Gaussian Plume Model (GPM) is used for industrial sources and CALINE3 model is used for line sources. The meteorological data of two seasons namely summer and winter during 2002-03 has been used for predicting the concentrations at different receptors where ambient levels of NO_x were monitored. The computed 8 hourly averaged concentrations have been compared with those monitored concentrations at different receptors in both the seasons. The validation of the models has been carried out through Quantile-

Quantile (Q-Q) plots and by computing several statistical errors. It is found that the cumulative concentrations obtained from GPM due to industrial sources and from CALINE3 due to line sources are in good agreement with the observed values at Fire Office in summer and at Gajuwaka and Karasa in winter seasons respectively except for few hours at Gajuwaka and Karasa. However the cumulative concentrations show underprediction at Sriharipuram in summer. The predicted concentrations follow the observed concentration pattern. The Q-Q plots show both underprediction and overprediction of concentrations. The numerical values of NMSE, FA2, FB and IOA suggest better performance of the models selected. The ambient levels of NO_x are found to be within the National Ambient Air Quality Standards in Visakhapatnam bowl area.

Acknowledgements

The authors would like to thank the Andhra Pradesh Pollution Control Board, Hyderabad for the financial support to carry out ambient air quality monitoring. The authors wish to thank the anonymous reviewers for their valuable comments and suggestions.

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