PREDICTION OF AIR POLLUTION CONCENTRATION IN MANALI REGION USING GAUSSIAN PLUME MODEL

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Abstract. *The principal causes of air pollution are known to be industries, domestic fuel use, and transport. There are about six major industrial complexes situated in the Chennai metropolitan area namely Manali, Guindy, Maraimalar Nagar, Ambattur, Perungudi, and Thirumilisai. Of these, major air pollution industries are concentrated in Manali area. In this study, all industrial point source emissions namely 46 stacks/chimneys situated within Manali, Chennai are identified. The hourly concentration of SO_2, NO_x and SPM prevailing in the study area, are predicted using a Gaussian plume model and the model predictions are compared with the observed values. The results indicate that the model predictions are comparable with the observed values in the study area.*

Keywords: Gaussian plume model, Observed concentration, Mixing height, Seasonal variations

1. INTRODUCTION

Considerable resources are often devoted to the measurements of air pollutant concentrations in the ambient atmosphere but measurements on their own provide little information on the origin of the pollutants, on the dispersal process in the atmosphere and on the impact of new sources or on the benefit of controls. Complicated processes occurring in nature can be described using mathematical models. When a pollution source emits a chemical into the atmosphere at an initial concentration, the chemical does not remain at that initial concentration. Atmospheric processes act to disperse the emissions downwind into less concentrated form. Simply stated, air dispersion models are computer tools that use equations to describe the dispersion process. By knowing the initial chemical release characteristics, one can predict air concentrations at selected downwind receptor locations. Pasquill (1983) has shown that a wide variety of techniques for determination of pollutant concentrations are available, ranging from the most simple box model to numerical solutions of the basic equations of fluid flow.Dispersion model types can be broadly divided into steady-state Gaussian-plume models and 'advanced' models. Plume models have been in common use for decades, while advanced models are beginning to be used more widely for regulatory applications. Turner (1964) presented a working model for the diffusion of gases from multiple sources in an urban area.

A fundamental difference between steady state and advanced models is in their meteorological data requirements. Venkatraman (1981) showed that the stochastic nature of concentration fields could impose severe limitations on the ability of models to predict short-term concentrations. Donald (1977) presented an analytical model for air pollutant transport and deposition from a point source. Anfossi et al. (1978) developed a new model based on virtual stack concept for computing plume rise from multiple sources. Roy et al. (1980) compared the prediction of NOx arising from nitric acid works using a Gaussian plume dispersion model with measurements of pollutant concentration at ground level and aloft. Rama Krishna et al. (2004) and Manju et al. (2002) studied the assimilative capacity of industrial zones in Vishakapatinam bowl area and Manali area. Goyal et al. (2004) studied the seasonal variation of SPM from Badarpur thermal station using a Gaussian plume model.

Tripathy et al. (2002) estimated the sulphur dioxide concentration in and around an industrial complex using a Gaussian diffusion model. The effect of change in meteorological parameters on SO_2 concentration was studied by Gupta et al. (2002) by varying the wind speed and stability class using the ISCST-3 model. Sivacoumar et al. (2001) estimated the impact of NO_x emissions resulting from various air pollution sources like industries, vehicles and domestic sources using the Industrial Source Complex short-term model. Marziano et al. (1979) studied the SO_2 distribution in Venice by means of an air quality simulation model. Jeffrey et al. (1977) evaluated the Gaussian plume model at the Dickerson power plant by comparison with measurements of dispersion and ground-level concentration of sulphur dioxide.

The ambient air quality is monitored regularly to check the pollutant levels by the regulatory agencies such as Central pollution Control Board, State pollution Control boards etc. Regular monitoring of pollutants both temporarily and spatially is not always feasible and it is cumbersome and costly. The present study focuses on the prediction of air pollution concentration for the Manali region, in Chennai using a Gaussian plume model. The main aim of this study is to compare the predicted three months average concentrations of SO_2, NOx and SPM with the observed concentrations.

2. SYSTEM FOR THE STUDY

The area taken for study is Manali industrial complex and a 10 km wide belt surrounding the area. The study area is chosen covering all major air polluting industries, including two major thermal power stations. The study area is covered with industries, two story buildings and individual dwellings. The total population of Manali area as on 1993 census was 28,174.The most prominent wind direction pattern was observed as NW, W, N during winter season, E, S, NE during summer season followed by NW, ENE, E during monsoon season. Moderate to high wind speed was observed during the months of April and May, with prevalence of low to calm wind during the month of December to February. Moderate to heavy rain occurred during the months of October and November. The value of maximum temperature ranges from 33°C to 39°C and the value of minimum temperature ranges from 19°C to 24°C. In the case of relative humidity, the mean value ranges from 70% to 80%.

2.1 Sources of pollution

The principal sources of air pollution are known to be industry, domestic fuel use, and transport. In this study, all industrial point source emissions namely stacks/chimneys situated within Manali are identified. Both line source and area source emissions are considered negligible in the study area because of less population and low traffic density.

2.2 Pollutants considered for study

As part of the National Ambient Air Quality Monitoring programme (NAAQM), a monitoring station was established near Manali bus stand and continuous monitoring of air quality with respect to important air pollutants, namely SO_2, NO_x, and SPM is considered for the present study. The guideline for air quality management is obtained from the National standards for effluent and emissions, developed by CPCB (2000).

As per the CPCB guidelines (1998), for air quality modeling works, three seasons need to be studied. Hence, the following seasons namely, summer (April to July), Monsoon (August to November) and winter (December to March) are taken and one representative month for each seasons, i.e. summer (May), monsoon (October), and winter (February) have been identified for the study.

3. MODEL DESCRIPTION

Concentration of pollutant at a point (x, y, z) in ($\mu g/m^3$) is given by

$$C = \frac{Q}{2\pi U \sigma_y \sigma_z} \exp - \left(y^2 / 2\sigma^2_y \right) \left[\exp - \left\{ (z-H)^2 / 2\sigma^2_z \right\} + \left\{ (z+H)^2 / 2\sigma^2_z \right\} \right] \quad (1)$$

where Q is the pollutant release rate ($\mu g\ s^{-1}$), U is the horizontal wind speed at the source level ($m\ s^{-1}$), σy and σz are the vertical and horizontal crosswind dispersion coefficients respectively, which are a function of down wind distance 'x' and atmospheric stability . y is the horizontal crosswind distance from plume centerline to the receptor, z is the vertical distance from the plume centerline to the receptor (m), x is the down wind distance from the plume centerline to the receptor (m), H is the effective stack height (m) which is given as $H= h_s +\Delta h$, where Δh= plume rise (m) and hs= Physical stack height (m). The coordinate system is such that the origin (0, 0, 0) is at the source. x-axis is in the mean downwind direction, y-axis is in the horizontal crosswind direction, and z-axis is in the vertical direction. The quantities σ_y and σ_z are the standard deviations of the distribution of concentration at 'x' in the horizontal crosswind and vertical directions respectively.

In this study Gaussian dispersion concept has been used for calculation of pollution concentration from a continuous point source at steady state where the concentration distribution perpendicular to the plume axis is assumed to be Gaussian. The basic assumptions and limitations of the Gaussian plume model have been described elsewhere (CPCB, 1998). The Gaussian dispersion model has enjoyed a wide degree of popularity while predicting ground level concentration due to emission releases from stationary point sources mainly due to its simplicity. The essential elements of Gaussian dispersion model are shown in Fig.1.

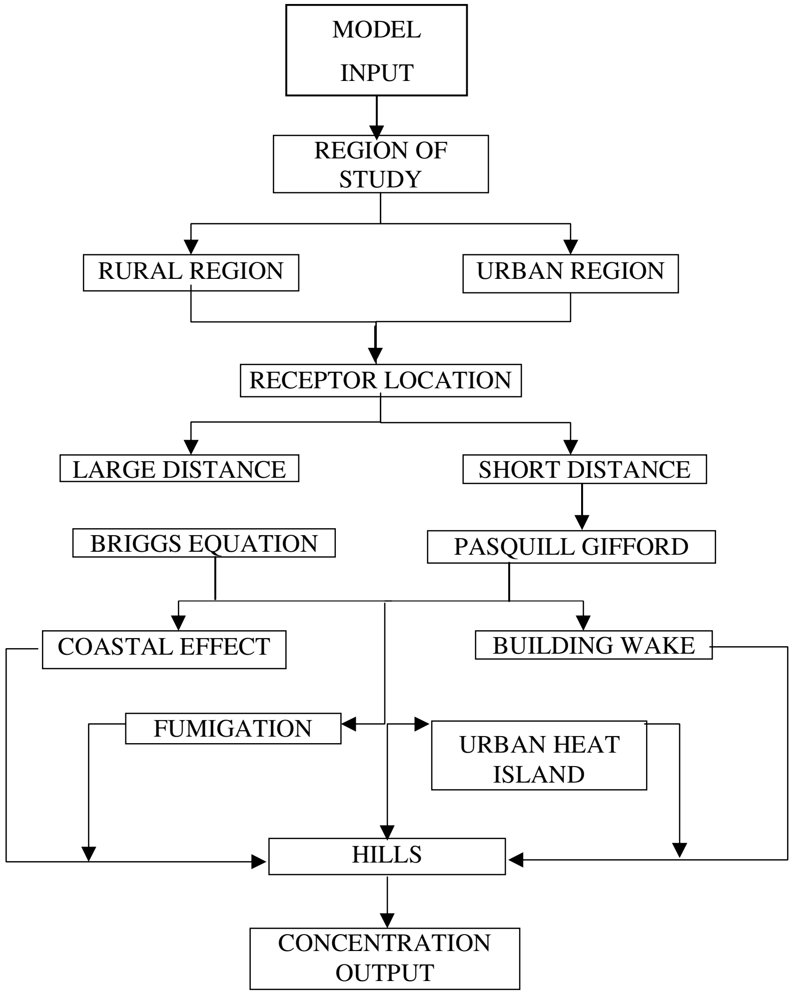


Fig.1 GENERAL FLOW DIAGRAM

Briggs (1969) and (1975) plume rise formulae for hot plumes are used for evaluating the pollutant concentrations from elevated point sources. Briggs (1973) formulas based on downwind distance x and stability's have been used to estimate the dispersion parameters σ_y and σ_z as shown in Tab.1. In the present model the following characteristics are considered. The developed model estimates the plume concentration of pollutants such as suspended particulate matter (SPM), Sulphur di-oxide (SO_2), and Nitrous oxide (NOx) from point source emissions. The parameter such as emission inventory are obtained from the industries and stored in files, which are loaded when required by the user. The meteorological data was obtained from the Indian Meteorological Department (IMD) and are also stored in files, which can be loaded when required. The Concentrations are computed for rural as well as urban regions as desired by the user . The other factors that are considered in the determination of concentrations by the dispersion of plume emitted by the various stacks are namely,

(i) Terrain characteristics
(ii) Building Wake
(iii) Urban Heat Island Effect
(iv) Coastal Sites
(v) Dispersion coefficients
(vi) Multiple point stacks

Table 1 Briggs dispersion parameters for σ_y and σ_z (100 m < x < 10000 m)

Stability Class	σ_y (m)	σ_z (m)
Rural conditions		
A	$0.22X(1+0.0001X)^{-0.5}$	0.20X
B	$0.16X(1+0.0001X)^{-0.5}$	0.12X
C	$0.11X(1+0.0001X)^{-0.5}$	$0.86X(1+0.0002X)^{-0.5}$
D	$0.08X(1+0.0001X)^{-0.5}$	$0.06X(1+0.0015X)^{-0.5}$
E	$0.06X(1+0.0001X)^{-0.5}$	$0.03X(1+0.0003X)^{-1}$
F	$0.04X(1+0.0001X)^{-0.5}$	$0.016X(1+0.0003X)^{-1}$
Urban conditions		
A – B	$0.32X(1+0.0004X)^{-0.5}$	$0.24X(1+0.001X)^{0.5}$
C	$0.22X(1+0.0004X)^{-0.5}$	0.20X
D	$0.16X(1+0.0004X)^{-0.5}$	$0.14X(1+0.0003X)^{-0.5}$
E – F	$0.11X(1+0.0004X)^{-0.5}$	$0.08X(1+0.0015X)^{-0.5}$

4. MODELING APPROACHES

The modeling approach consists of two parts. In the first part, the major air pollution industries are identified and stack emission inventory data (including the emission rates of SO_2, NO_x, SPM, from each stack) available with TamilNadu Pollution Control Board were collected. The processed and formatted data for all 46 stacks are given as input to the model. In the second part, the ambient air quality data for SO_2, NO_x, SPM consisting of four hourly average concentrations observed at Manali station are obtained. From the observed data 24-hour average values are calculated for each day. As per CPCB (2003a) the ambient air quality-monitoring network involves measurement of a number of air pollutants at several locations in the country so as to meet the objectives of monitoring. The pollutants chosen in the air quality-monitoring programme are the primary pollutants, which are indicators of general pollution profile of the typical urban zones. The details of pollutant-specific sampling procedures are given elsewhere (NEERI, 2000).

5. METEOROLOGICAL DATA

Meteorological data consisting of wind speed, wind direction, cloud cover, cloud height, surface temperature and mixing heights for the study period were obtained from Indian Meteorological Department (IMD) Chennai.

The mixing height is defined as the height above the surface through which relatively rigorous vertical mixing occurs. The mixing height is determined using the Holzworth (1967) technique. Lowest value of mixing height has been observed in the winter season and highest mixing has been observed in monsoon height followed by summer season. Beyrich (1997) critically examined the methods and results of mixing height determination from Sodar measurements. Nandakumar (1999) studied in detail the seasonal and diurnal pollution potential at Lucknow

CPCB (2003b) has provided the spatial distribution of Hourly mixing height over Indian region for the period 1990-92 based on the Holzworth principle. Stability classes are predicted using Pasquill-Turner method (Turner, 1969). Thus in the present study, the meteorological data of 3 hour (0200, 0500, 1100, 1400, 1700, 2000, and 2300) are used.

6. RESULT AND DISCUSSION

The concentration of SO_2, NO_X and SPM has been predicted with the Gaussian plume model at Manali for the three different seasons namely summer, winter and monsoon. The predicted and observed values are compared for seven days in each representative month of three seasons. The comparison of daily 24-hour average concentration of observed criteria pollutants with the model predictions are shown in Fig. 2 (a) to (c), Fig. 3 (a) to (c) and Fig. 4 (a) to (c). From the graphs we see a trend that the concentration is maximum during winter and lesser during summer and monsoon season.

a) During winter season the concentration of SO_2, NO_X and SPM are observed to be higher than the predicted values [Fig.2 (a), (b), (c)]. This is due to the fact that the concentrations observed are the cumulative effect of the entire industrial complex, but in our prediction we are considering the effect of Manali complex only.

b) During summer season the concentration of SO_2, NO_X and SPM are observed to be higher than the predicted due to the same reason mentioned [Fig3. (a), (b), (c)].

c) During monsoon [Fig 4. (a), (b), (c)] the predicted values are higher than the observed, because the effect of rainfall is not considered in our model. The seasonal trend of daily mean of SO_2, NO_X and SPM was almost similar during the study period. The highest value of SO_2, NO_X and SPM was observed in winter, while relatively low values were observed during summer. The favorable meteorological conditions during the monsoon and summer season's results in low concentrations

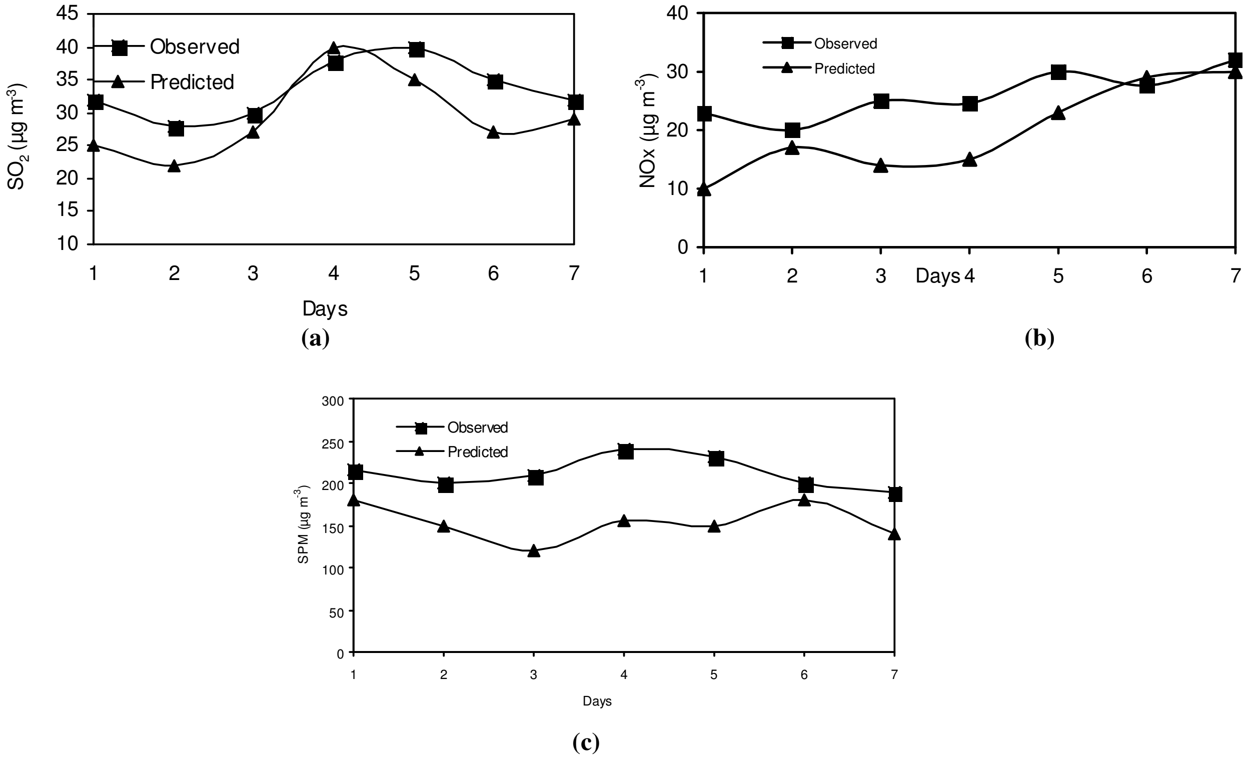


Figure 2. Predicted and observed 24-hourly average concentration of SO_2 (b) NO_x and (c) SPM during winter season

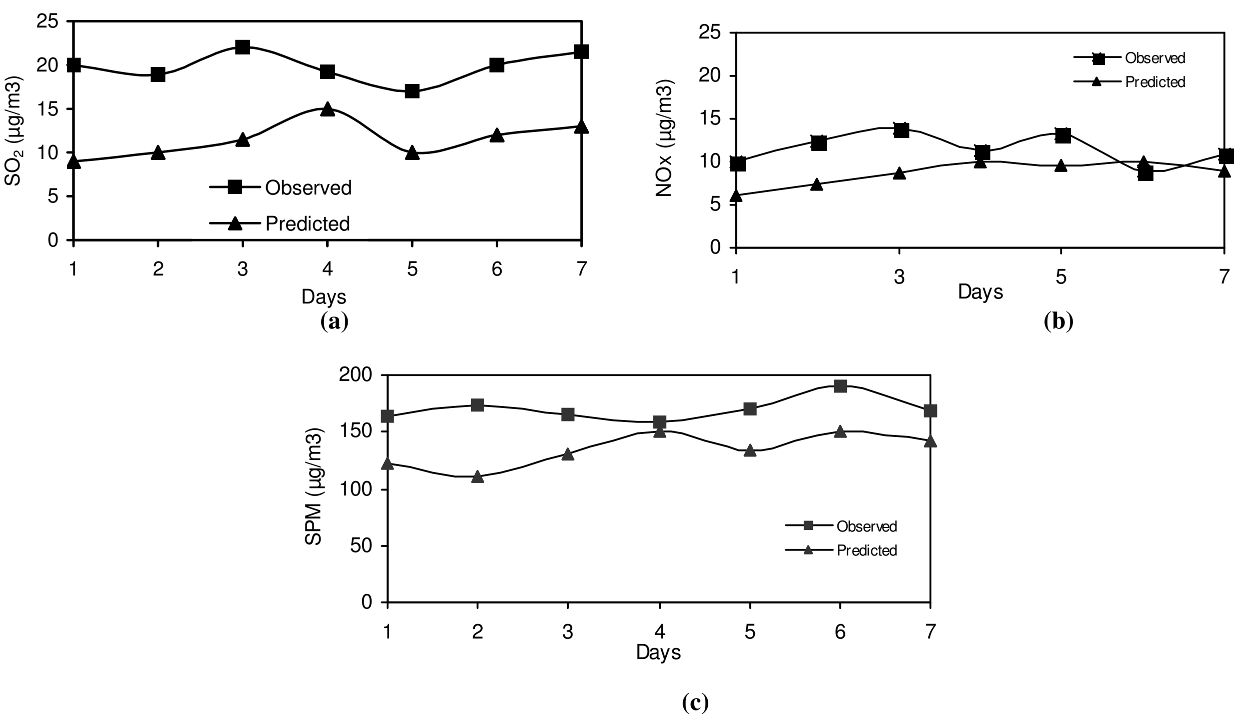
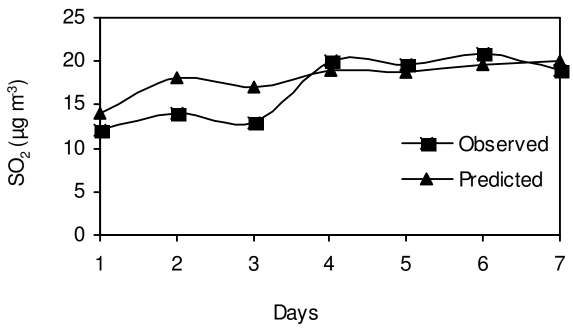
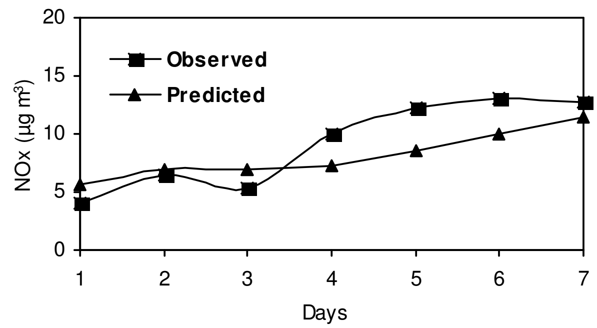
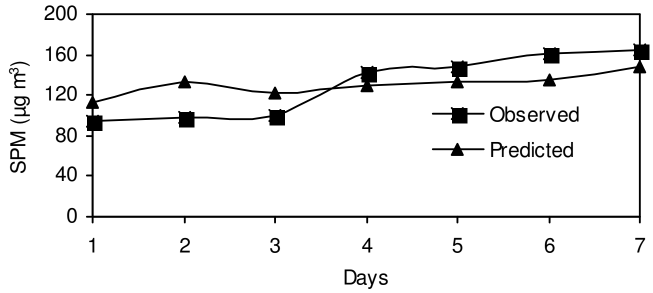


Figure 3 Predicted and observed 24-hourly average concentration of (a)SO_2 (b) NO_x and c) SPM during summer season





(a) **(b)**



(c)

Figure 4. Predicted and observed 24-hourly average concentration of (a)SO_2 (b) NO_x and (c) SPM during monsoon season

The daily variations in mixing height are also having a great influence in the model predictions [Fig 5. (a),(b),(c)]. It was found that the Maximum mixing height was observed during monsoon season followed by winter and summer. A fair estimate of the dispersion of pollutants in the atmosphere is possible based on the frequency distribution of wind direction as well as wind speed (Manju et al. 2002). During winter season the wind rose shows that predominant winds are from E, S and SE directions (Fig.6a). The average wind speed during the study period was 0.83 m/s with 72 % calm conditions. The predominant wind directions during summer were W, S and SW directions (Fig. 6b) and during monsoon season it was E, S, NE and SE (Fig.6c). Maximum wind speed recorded during the study period was around 11 m/s in monsoon and 5.7 m/s during summer season. The calm conditions prevails 26 % of time during monsoon and 39.54% during summer. The monthly prevailing wind pattern during the study period is in conformity with the climatological norms of the region.

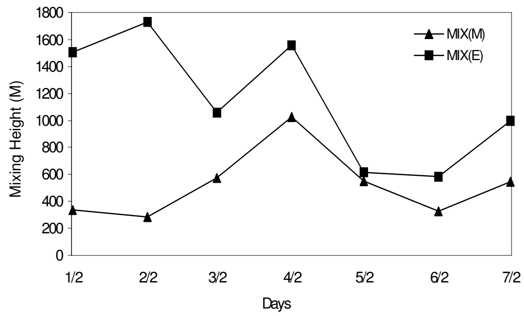
7. CONCLUSION

In this study, one of the most important sensitive areas in Chennai, namely Manali industrial complex has been considered to predict the prevailing concentrations of SO_2, NO_x and SPM for the three seasons namely winter, summer and Monsoon. On the basis of results and discussions, the following conclusions have been made:

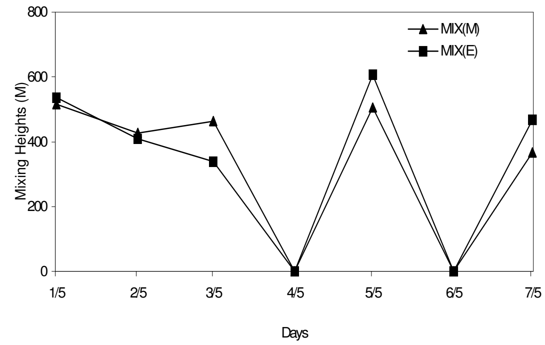
(i) The model results showed that, the percentage frequency of maximum concentration of SO_2 occurrence is high in the winter season followed by summer and monsoon.

(ii) As prescribed by TamilNadu Pollution Control Board, it was found that for the study area, NO_X is within the standards for residential and industrial area during all seasons, whereas, SPM exceeds during winter and monsoon season for the residential area standards and it is within the prescribed limits for the industrial area standards

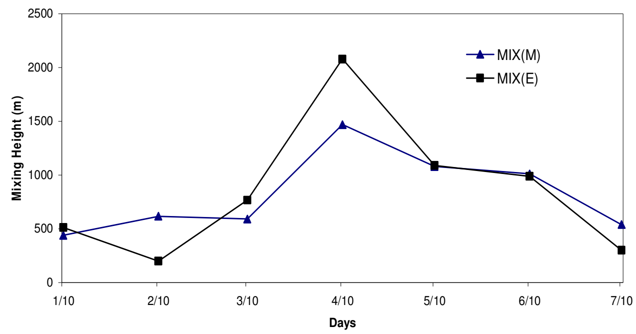
(iii) The model performance when evaluated with observed results indicated that the performance of the Gaussian plume model is well within the acceptable limits. The model may be applied to predict the concentration of criteria pollutants for other industrial regions of Chennai.



(a)



(b)



(C)

Figure 5 Variations of morning and evening mixing heights at Manali during (a) winter (b)Summer and (c) monsoon.

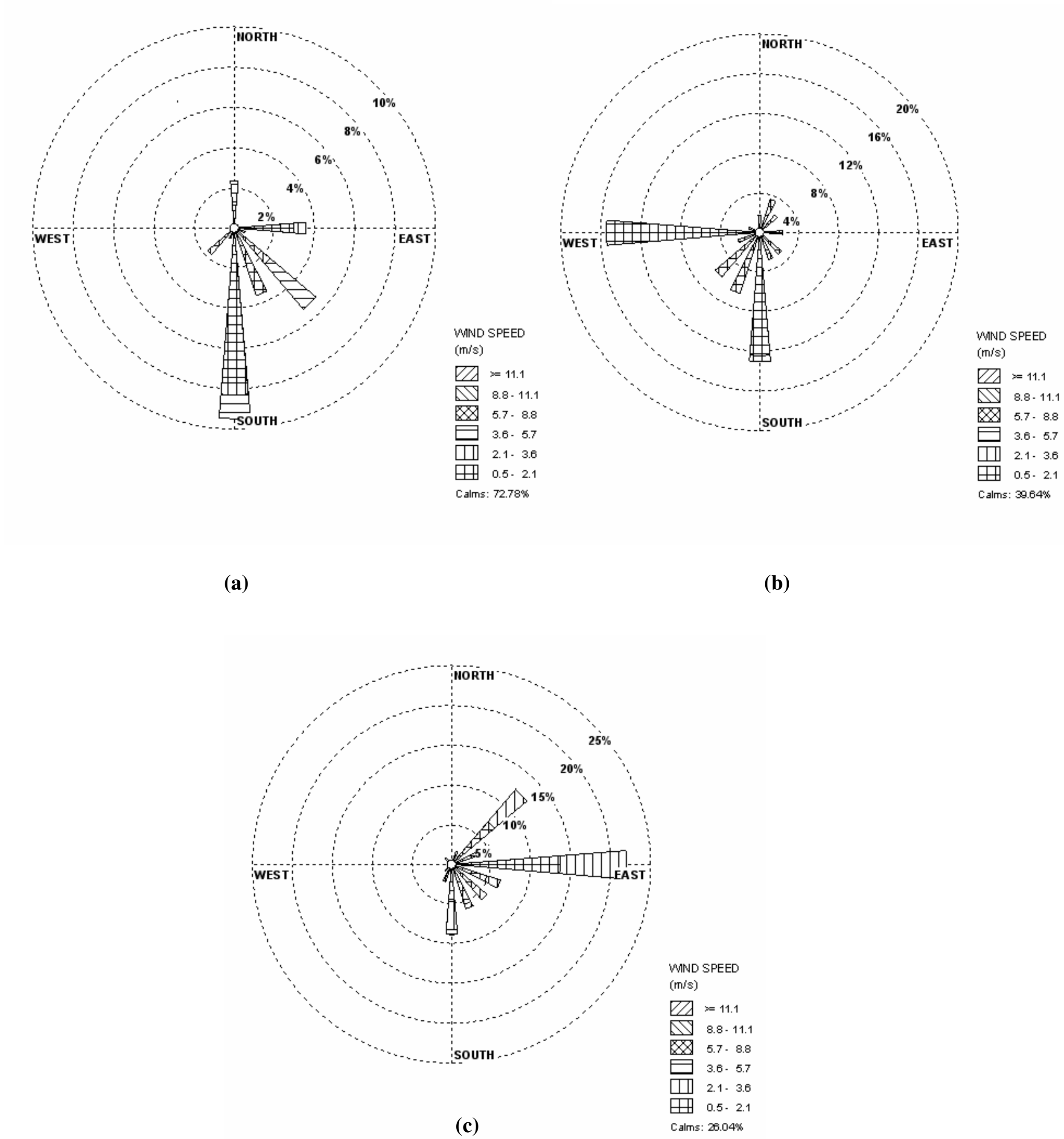


Figure 6 Wind roses for (a) Winter (b) Summer and (c) Monsoon seasons for Manali region

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