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Performance Evaluation of AERMOD and ADMS-Urban for Total Suspended Particulate Matter Concentrations in Megacity Delhi

Manju Mohan[1*], Shweta Bhati[1], Archana Sreenivas[2], Pallavi Marrapu[3]

[1] *Centre for Atmospheric Sciences, Indian Institute of Technology, Hauz Khas, New Delhi-110016, India*
[2] *Tata Consultancy Services, Mumbai, India*
[3] *Center for Global and Regional Environmental Research, The University of Iowa, 424 IATL, Iowa City*

ABSTRACT

Regulatory models are useful tools for air quality management. However, application of models without proper evaluation may lead to erroneous conclusions and thus systematic model evaluation studies are essential prior to model application. Often, models are evaluated for a specific source and climatic condition and then find application to another source and climatic condition without this realization. In this context, two well known regulatory models namely; AERMOD (07026) and ADMS-Urban (2.2) are applied throughout the world in various countries without rigorous evaluation procedures. An attempt is made here to undertake performance evaluation of these models for a tropical city such as Delhi in India which is a well known megacity of the world. The models have been applied to estimate ambient particulate matter concentrations for the years 2000 and 2004 over seven sites in Delhi and model evaluation and inter-comparison is performed. Concentrations have been estimated for winter season in both years as the low temperature and low speed wind conditions in this season make it most significant from air pollution point of view. It has been found that though both the models have a tendency towards under-prediction, estimated values by both models agree with the observed concentrations within factor of two. However ADMS-Urban results show better trend correlation with observed values while bias between observed and estimated values is lower for AERMOD Results. The models include all the urban sources (ie. elevated point sources, vehicular traffic, domestic and other sources) in the city. The model validation is discussed in the light of emission inventory, requisite meteorological inputs and statistical performance measures. Performance evaluation of the above models is examined based on boundary layer parameterisations used in these models. Intercomparison of the model performances is envisaged to be useful for application to air quality management and further development of these models.

***Keywords*:** Air Quality Modeling; Boundary Layer Height, Model Evaluation; Particulate Matter; Regulatory Models.

INTRODUCTION

The capital city of Delhi, India has been undergoing catalytic reforms in urban demographics and infrastructure. The rapid growth in population in recent decades accompanied with the city's economic progress has resulted in deterioration of environmental resources which is manifested in the city's status as one of the most polluted cities in the world. Particularly, the air quality of the city is worst affected due to various air pollution sources. In year 1998, the Ministry of Environment and Forests, Government of India designated Delhi as an air pollution control area in recognition of the severity of air pollution due to vehicular, industrial and domestic sources (MoEF, 1998). More than a decade later, after implementation of various control measures, exceedences of prescribed concentrations of some pollutants, specially suspended particulate matter (SPM), are still frequently reported in the city. Annual average ambient levels of respirable suspended particulate matter (PM_{10}) have consistently been observed much above the prescribed standard of 60 μg/m^3 for past many years. In year 2000, the annual average of PM_{10} concentration in the city was 168 μg/m^3 which improved in year 2004 to 149 μg/m^3 but again deteriorated to 165 μg/m^3 in year 2009 (CAI, 2010; CPCB, 2009). Air Quality Index values in Delhi range from unhealthy to hazardous levels in winter season and particulate matter is the chief contributor towards it (Mohan *et al.*, 2007b). The poor air quality of the city in terms of particulate matter is attributed mainly to emissions from exhaust of motor vehicles, coal based thermal power plants and commercial and domestic use of solid and liquid fuels. Adverse impact of elevated levels of particulate matter in air on human health is evident in many earlier studies (Russel *et al.*, 2009; Sawyer *et al.*, 2010) which show a strong

* Corresponding author. Tel: 91-11-26591313;
Fax: 91-11-26
E-mail address: mmohan6@hotmail.com

relationship of respiratory and cardiovascular morbidity as well as mortality with finer particles such as PM_{10} (Jonathan *et al*., 2008; Samoli *et al*., 2008) and $PM_{2.5}$ (Chen *et al*., 2005; Cavallari *et al*., 2008). Mohan *et al*. (2011) applied AERMOD for the exposure assessment for the year 2004 based on air quality predictions of total suspended particulate matter and found a significant decrease in mortality with reduction scenarios in particulate matter emissions.

Prediction of pollutant concentrations with the aid of regulatory air quality models is an essential part for air quality management strategies. However, validation of the regulatory model is important before implementation in a different geographical and climatic zone for which the model is originally developed. Thus, prior to application, a model must be evaluated for local site conditions as performance of model varies for different source scenarios and climatic conditions. The present study evaluates the performance of USEPA model AERMOD (07026) and ADMS-Urban (version 2.2) for modeling concentrations of total suspended particulate matter (TSPM) in Delhi. These two models are most commonly known Gaussian dispersion models for regulatory implementation. AERMOD was developed at the United States Environmental Protection Agency. The model is used for regulatory purposes in the United States and is a highly recommended model in many countries. In India, AERMOD has recently been added to the list of recommended models for regulatory applications (CPCB, 2008). However, the most often used model is still ISCST3 which may be due to unavailability or inaccessibility of requisite extensive input data for AERMOD or other more sophisticated models for various regions of the country. ADMS-Urban, which was developed by Cambridge Environmental Research Consultants, United Kingdom, is also widely used for regulatory purposes in the United Kingdom and other countries across the world. Though both these models are used widely, there are very few case studies of validation as well as inter-comparison of these models in tropical/sub-tropical latitudes. Most of the model inter-comparison studies have been performed for European/American countries located largely in mid-latitudes where neutral conditions and high winds are more prevalent (Hall *et al*., 2000; Hanna *et al*., 2001; Sidle *et al*., 2004; Carruthers, 2010). While the current study of an Indian city (viz., Delhi) has tropical climatic conditions characterized by intense convective mixing during daytime, intense ground based inversions during nighttime, low boundary layer heights and calm winds. Hence model performance in different climatic conditions help in better applications and understanding of the model as well as further scoping studies for the development of model physics.

The models have been applied for the winter months (November, December, January and February) of two years: 2000 and 2004. On a mandate by Supreme Court of India, public transport vehicles in New Delhi were required to switch their fuel to compressed natural gas (CNG), in an attempt to reduce their air pollution impacts. This switch was initiated in 2001 and was completed by 2003 (Reynolds and Kandlikar, 2008). The years 2000 and 2004, thus correspond to pre and post phase respectively of implementation of CNG thereby representing two different air quality scenarios in Delhi. The estimated concentrations by both models have been compared with the observed values and evaluation of the performance is based on various statistical parameters.

BACKGROUND OF THE STUDY

The capital city of Delhi is located at latitude 28°38'17" and longitude 77°15'51" with an altitude of 215 m above sea level. The city experiences three major seasonal variations in a year. The month of March marks the onset of summer season which continues till the month of June. During the summer season, dry conditions prevail and temperatures are characteristically high. The maximum temperature peaks up to 45°C and lowest minimum temperatures in the range of 24–25°C. During the summer season, duststorms, which originate from the arid region of nearby state of Rajasthan, occasionally impact the city and ambient levels of particulate matter are suddenly raised. Such scenarios can only be captured appropriately by detailed numerical atmospheric chemical models where concentrations are estimated in a time dependent manner from seconds to minutes. However, most regulatory models are steady state model where detailed chemical modeling is absent or parameterized in a simple manner (Mohan *et al*., 2011). The months of July, august and September are dominated by humid south west monsoon and incidences of rainfall clear the atmosphere and decrease ambient concentrations of particulates. The most important season in Delhi, from air quality point of view, is the winter, which starts in November and ends with the month of February. This period is dominated by cold, dry air and ground-based inversion with low wind conditions, which occur very frequently and increase the concentrations of pollutants. In the year 2009–2010, the average PM_{10} concentration from March 2009 to October 2009 was 183 $\mu g/m^3$ against the average concentration of 265 $\mu g/m^3$ in the winter period from November 2009 to February 2010 (CPCB, 2010). Thus even though consistent exceedence of prescribed standard (i.e. 100 $\mu g/m^3$ for daily average and 60 $\mu g/m^3$ for annual average) is observed throughout the year, the situation is worst in winter season. A sudden increase in number of asthma, emphysema and chronic obstructive pulmonary disease cases is also witnessed in winter season in Delhi (Chhabra *et al*., 1999; Agarwal *et al*., 2006; WHO, 2010). Particulate matter levels in the city are emitted mainly by vehicular sources and other fuel combustion processes. Srivastava *et al.* (2008) observed that total suspended particulate matter in the city has been found to comprise mainly of vehicular pollutants (62%), followed by crustal dust (35%) in the fine size range; and crustal dust (64%) followed by vehicular pollution (29%) in the coarse size range. Perrino *et al.* (2011) noted that pollutants produced by combustion sources were major contributors of the total mass SPM in Delhi, and that the rest of it, in the absence of desert storms, was contributed from species coming from the soil, inorganic secondary compounds formed in the atmosphere and organic species.

The Central Pollution Control Board (CPCB), the nodal agency responsible for monitoring and regulating the pollution scenario, measures the particulate matter concentration at seven monitoring stations in Delhi viz. Ashok Vihar, Siri Fort, Nizamuddin, Shahzada Baug, Janak Puri, Shahadara and ITO (Fig. 1). Shahdara and Shahzada Baug are industrial areas and ITO is one of the busiest traffic intersections of Delhi. Ashok Vihar and Janakpuri represent areas of mixed residential and commercial use. Other monitoring sites are located in residential areas.

MATERIALS AND METHODS

Applied Models

AERMOD (version 07026), is a steady-state Gaussian plume air dispersion model which was developed by the U.S Environmental Protection Agency and incorporates planetary boundary layer concepts. Plume growth is determined by turbulence profiles that vary with height. AERMOD calculates the convective and mechanical mixing height. Under unstable conditions, AERMOD plume displacement is caused by random convective velocities. AERMOD is capable of estimating pollutant concentration from point, line and area sources. Sources can be individually modeled as rural or urban. The model incorporates the effects of increased surface heating from an urban area on pollutant dispersion under stable atmospheric conditions and this treatment is a function of city population. AERMOD models a system with two separate components: AERMOD (Aermic Dispersion Model) and AERMET (AERMOD Meteorological Preprocessor).The AERMET is the meteorological processor for the AERMOD. Input data for AERMET includes hourly cloud cover observations, surface meteorological observations such as wind speed and direction, temperature, dew point, humidity and sea level pressure and twice-a-day upper air soundings. Meteorological data is accepted from multiple heights and wind, temperature, and turbulence are treated as vertical profiles (EPA, 2010).

ADMS-Urban (version 2.2) developed by Cambridge Environmental Research Consultants Ltd. is a model of dispersion in atmosphere of pollutants released from industrial, domestic and road traffic sources in urban areas. The model incorporates parameterization of boundary layer based on Monin-Obukhov Length and boundary layer height. This local Gaussian type model is nested within a trajectory model for areas within 50 km × 50 km (CERC, 2006). In this model also, non-Gaussian vertical profile of concentration is created in convective conditions, which allows for the skewed nature of turbulence within the atmospheric boundary layer that can lead to high surface concentrations near the source.

Requisite hourly surface meteorological data for Delhi for the time period under consideration in this study i.e. for the months of January, February, November and December of years 2000 and 2004 was obtained from Indian Meteorological Department. The upper air data was accessed from online global Radiosonde Database of National Climatic Data Center of National Oceanic and Atmospheric Administration (NCDC, 2008).

Both AERMOD and ADMS-Urban were used to estimate 24 hour average and monthly average concentrations of TSPM, by using the meteorological data and emission inventory for the winter months of the year 2000 and 2004 for Delhi.

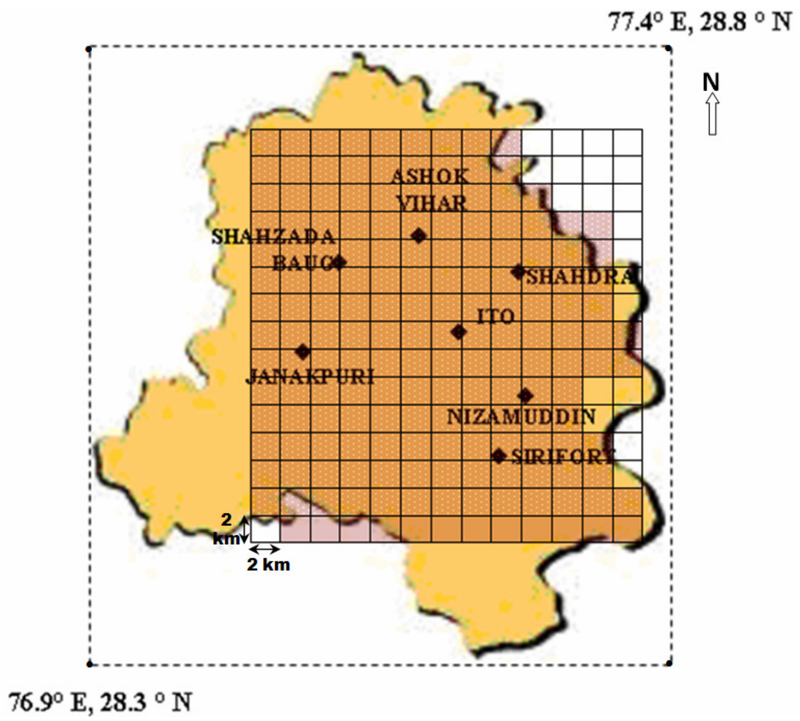

Fig. 1. Grid network (2 km^2 square grid of uniform size throughout the study area) depicting the ambient air quality monitoring stations over the study area of Delhi.

Emission Inventory

There are three main sectors which contribute to particulate matter emissions. Exhausts from motor vehicles constitute the transport sector. Thermal power plants of the power sector in India are mostly coal based. During the study period, three coal based power plants were operational in the city. The domestic and waste sector is the third main sector wherein the particulate matter emissions arise from combustion of various solid and liquid fuels and open burning of waste. In the modeling exercises in the present study, power plants have been considered as point source emissions and emissions from transportation and other sectors have been modeled under area sources. Usually in urban areas, there are widespread vehicular sources and it is difficult to have detailed data of every road stretch at each model grid-point. In addition, other category of emission sources in the urban airshed is also considered alongside the vehicular traffic and therefore emissions from vehicular sources have been clubbed under area sources.

The construction of inventory for TSPM for years 2000 and 2004 is based on some earlier studies (Mohan and Dube, 2001; Gurjar *et al*., 2004; Mohan *et al*., 2007a; 2011).

The calculation of emission from vehicles is based on the data on emission factor for the specific vehicle type, the distance traveled by a particular vehicle type, number of vehicles and their distribution in the type of the fuel used. The emission factor of different pollutants for each vehicle type have been calculated in earlier studies conducted by organizations such as Central Pollution Control Board (CPCB, 2006a, 2006b) and Central Road Research Institute (Jalihal *et al*., 2006).

Three coal-based power plants (Badarpur, Indraprastha and Rajghat) have been considered for estimating emissions from power plants. The coal consumption in 000' tons for these power plants was obtained from Central Electricity Authority performance review report (CEA, 2006). The domestic and waste sectors include emissions from fuel consumption in households and emissions from waste burning. While cooking gas is the major domestic fuel, kerosene oil is also usually burnt in small stoves; other energy sources for domestic sector that have been considered are biomass such as fuel wood, crop waste and dung. Fuel consumption data for domestic and waste sectors is given in Delhi statistical handbook (DES, 2002, 2005) and emission factors used in Gurjar *et al*. (2004) have been used in calculations. The emissions from small scale industries have not been taken into account for this study because, according to a Supreme Court decision in 1996, polluting industries in Delhi were closed in 2000 and other non hazardous were relocated and there is absence of factual information about emissions of relocated industries. Moreover, Gurjar *et al*. (2004) estimated the contribution of small scale industries towards total particulate matter emissions to be of negligible order (< ~1%) and thus, in this study they have not been accounted for.

Methodology for the preparation of the gridded emission inventory is based on an earlier work by Mohan and Dube, (2001) and Mohan *et al*. (2007a; 2011). Emissions were estimated over a grid network of 26 × 30 km with a resolution of 2 km covering most of the urban area of Delhi. The selected area covers that part of Delhi where most of the urban activities take place and includes all major sources of air pollution, sizeable receptor population and the seven monitoring stations of CPCB. Keeping these criteria in consideration, emissions from 173 cells of the grid network were input into the model. Fig. 1 displays the grid network over the city of Delhi which was used for the study. The shaded cells are the ones for which the emissions were considered (Mohan *et al*., 2011). The unshaded areas were poorly developed and with negligible emissions. Wind Roses for the modeling duration of years 2000 and 2004 are given in Fig. 2.

Table 1 displays total emissions and contribution of different source category for winter months of 2000 and 2004. Overall, transport sector has been observed to have highest contribution to total emissions followed by domestic and waste sector and power plants. The annual growth of petrol cars and diesel cars is 8.5% and 16.6% respectively (DES, 2005). Thus, despite implementation of measures like introduction of CNG in public buses, share of transport sector is increasing in total emissions. Use of better quality coal and increase in production of electricity by gas based

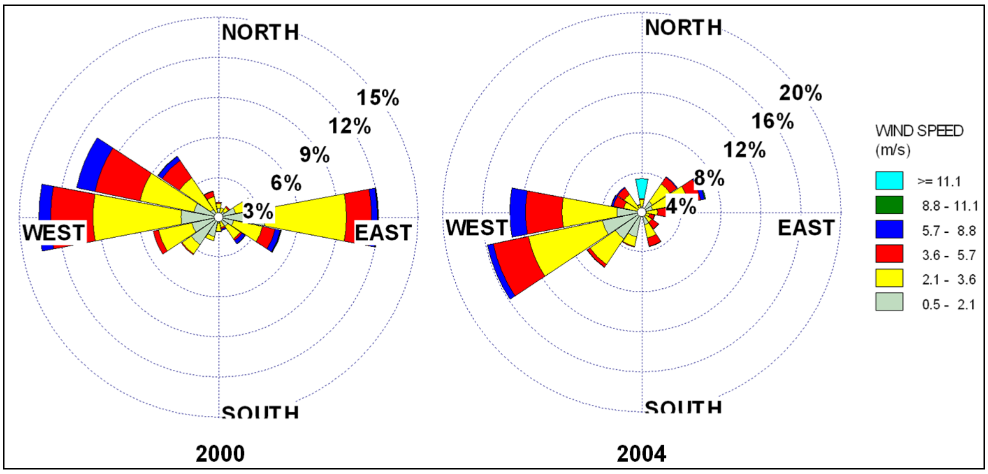

Fig. 2. Wind Roses for winter months (Jan, Feb, Nov, Dec) of year 2000 (left) and year 2004(right).

Table 1. Percentage contribution towards TSPM emissions for winter months of 2000 and 2004.

Source Sector	Percentage Contribution towards total Emission for year 2000 (Jan, Feb, Nov, Dec) Total Emissions: 47 Gg	Percentage Contribution towards total Emission for year 2004 (Jan, Feb, Nov, Dec) Total Emissions: 21 Gg
Power plants	15.1%	3.6%
Transportation	61.7%	65.3%
Domestic and Waste	23.2%	31.1%

power stations has resulted in decrease in percentage contribution of thermal power plants. Increase in emissions from domestic and waste sector is attributed to mainly increasing population.

Model Evaluation

Data for observed ambient air concentrations of total suspended particulate matter was collected for the years 2000 and 2004 in terms of average daily concentrations from the seven monitoring stations of CPCB in Delhi mentioned in section 2. This monitored daily average TSPM data and calculated monthly average data were compared with the models' estimated concentrations. Comparison was carried out by measuring some statistical parameters which have been used in earlier studies related to model validation (Fox, 1984; Hanna, 1988; Hanna *et al*., 1993; Mohan *et al*., 1995; ASTM, 2000). These parameters include Fractional Bias (FB), Normalized Root Mean Square Error (NMSE), Correlation Coefficient (r), Index of Agreement (d), Geometric Mean (MG), Geometric Variance (VG), Root mean square error (RMSE), Fraction of Predicted concentrations within factor of two of observed concentration (FAC_2) and Quantile - Quantile Plots. These statistical performance measures were used to evaluate the performance of both models.

RESULTS AND DISCUSSIONS

Overall Performance of Models

A comparison of monthly average observed and estimated values of total suspended particulate matter at all seven monitoring stations of Delhi for years 2000 and 2004 by both ADMS and AERMOD is depicted in Fig. 3. It can be seen that both the models have a tendency towards under-prediction of the concentrations. The observed concentrations have decreased from year 2000 to year 2004 and this decrease is captured by estimated concentrations by both models.

Scatter Plots of Predicted vs. Observed concentrations of both the models are shown in Figs. 4 and 5 along with the limits of factor of 2. Most results from both AERMOD and ADMS-Urban agreed with the measured concentration statistics to within a factor of two for daily average concentrations (Fig. 4). However, a scatter plot for monthly averages reveals that monthly average concentrations estimated from models' results correlate better with observed monthly average concentrations as compared to 24 hour daily average concentrations. Thus it can be said that there is a good degree of correlation between the observed and predicted values for both the models.

The results for performance of statistical indicators can be seen in Tables 2 and 3. Summarily, measures for bias such as FB, NMSE and RMSE are lower for AERMOD estimations while measures indicating relationship between observed and estimated values such as correlation coefficient (r) and index of agreement (d) are better for ADMS-Urban estimations.

To determine the reliability of the model, the criteria used is as set in a study by Kumar *et al.* (1993) and Chang *et al.* (2004). According to Kumar *et al.* (1993), the performance of the model can be deemed as acceptable if;

$$NMSE < 0.5 \quad \text{and} \quad -0.5 < FB < +0.5$$

The above criteria were satisfied for results for all the seven stations for concentration estimations by both models for years 2000 and 2004 inferring that performance of both models was considerably good. The fractional bias of concentrations estimated by ADMS-Urban for site of ITO is the only exception where the value is 0.508 for the year 2004.

Further, according to Chang *et al.* (2004) a ''good'' model would be expected to have about 50% of the predictions

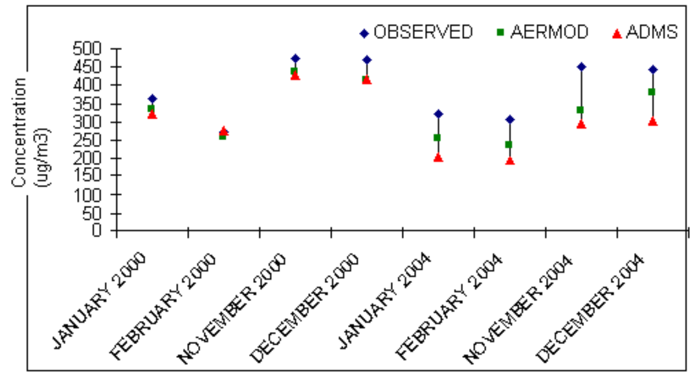

Fig. 3. Comparison of monthly average observed and estimated values of TSPM.

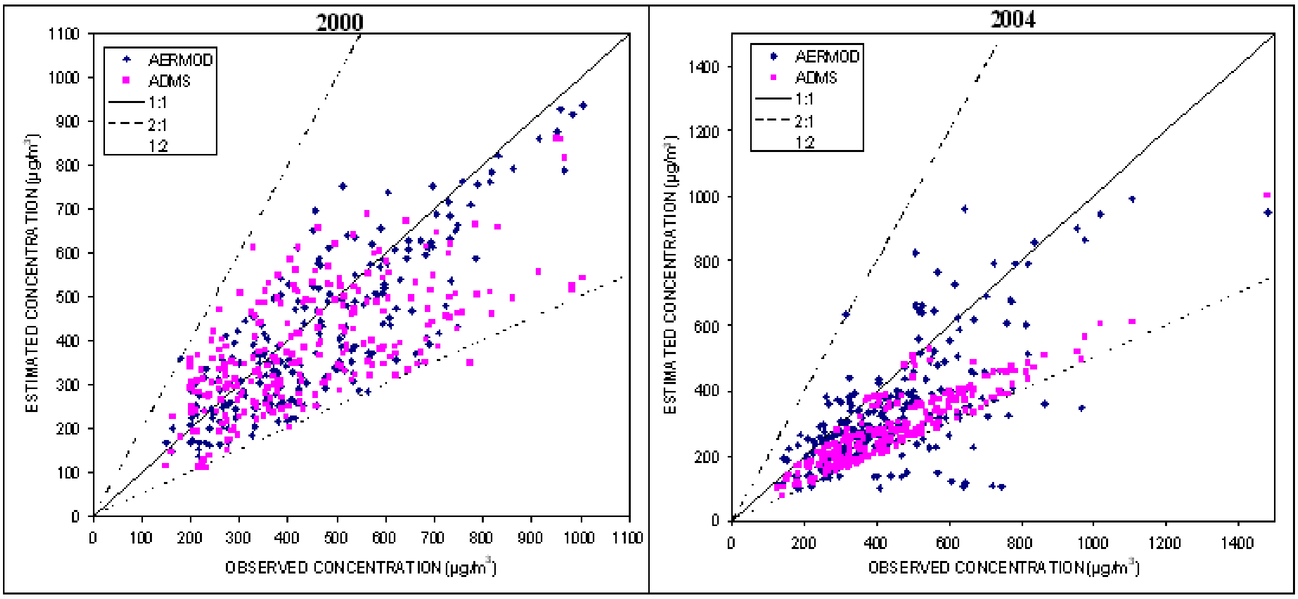

Fig. 4. Scatter plots of estimated vs. observed daily average TSPM concentrations (Left: Year 2000, Right: Year 2004).

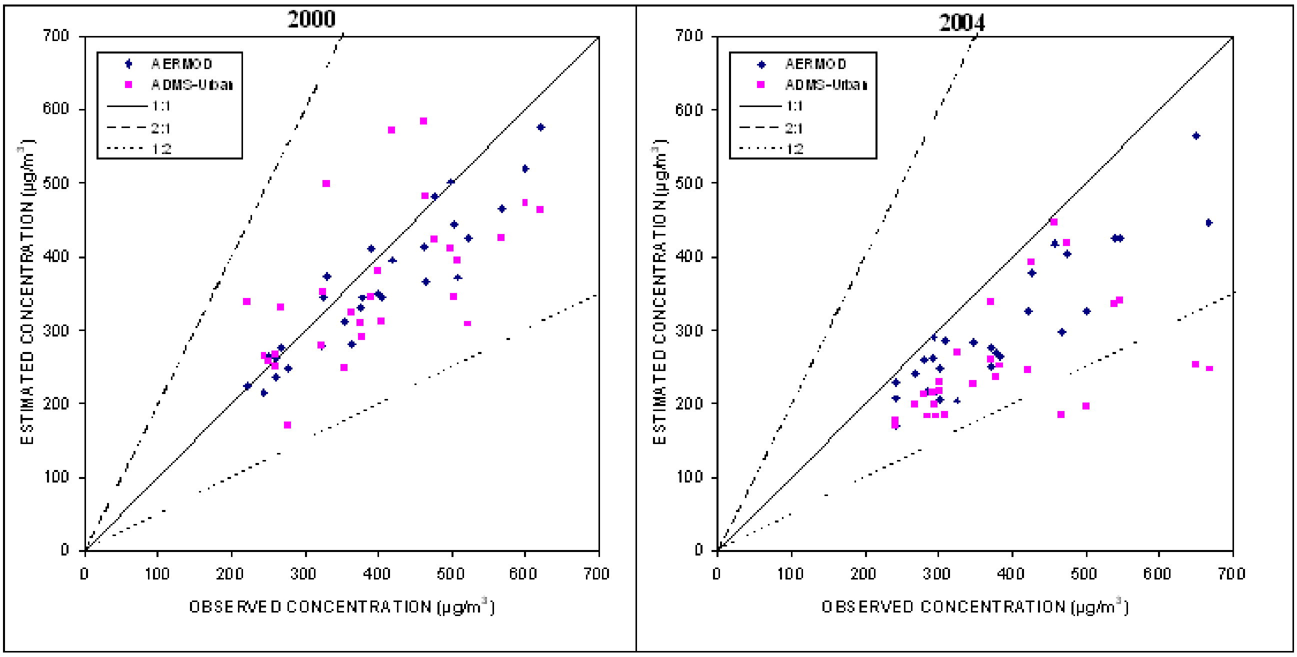

Fig. 5. Scatter plots of estimated vs. observed monthly average TSPM concentrations (Left: Year 2000, Right: Year 2004).

Table 2. Performance of statistical indicators for concentration predictions by AERMOD at different monitoring sites in Delhi.

	Ashok Vihar		ITO		Janakpuri		Nizamuddin		Shahdra		Shahzada Baug		Siri Fort	
	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004
Correlation Coefficient	0.84	0.54	0.76	0.57	0.797	0.63	0.57	0.67	0.56	0.76	0.77	0.64	0.86	0.91
Index of Agreement	0.89	0.65	0.85	0.66	0.86	0.73	0.75	0.85	0.71	0.76	0.84	0.96	0.92	0.89
Fractional Bias	0.12	0.19	0.11	0.34	0.14	0.18	0.08	0.20	0.07	0.24	0.13	0.25	0.02	0.24
NMSE	0.08	0.08	0.08	0.29	0.08	0.10	0.11	0.14	0.06	0.06	0.10	0.17	0.06	0.16
Geometric Mean Bias	1.08	1.20	1.12	1.52	1.17	1.19	1.09	1.24	1.10	1.35	1.15	1.32	1.03	1.28
Geometric Variance	1.01	1.04	1.01	1.19	1.03	1.03	1.01	1.05	1.01	1.09	1.02	1.08	1.00	1.07
RMSE	105.70	90.05	137.12	245.66	92.09	90.07	132.99	107.59	86.24	112.63	109.22	98.82	70.46	95.15

Table 3. Performance of statistical indicators for concentration predictions by ADMS-Urban at different monitoring sites in Delhi.

	Ashok Vihar		ITO		Janakpuri		Nizamuddin		Shahdra		Shahzada Baug		Siri Fort	
	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004	2000	2004
Correlation Coeffiecient	0.92	0.84	0.57	0.84	0.74	0.82	0.86	0.84	0.57	0.94	0.61	0.56	0.78	0.95
Index of Agreement	0.93	0.68	0.66	0.63	0.66	0.74	0.89	0.62	0.72	0.97	0.69	0.44	0.76	0.77
Fractional Bias	0.13	0.39	0.23	0.51	0.40	0.35	-0.12	0.43	0.12	0.12	0.24	0.45	-0.29	0.38
NMSE	0.05	0.25	0.14	0.29	0.24	0.16	0.05	0.22	0.06	0.06	0.12	0.17	0.18	0.16
Geometric Mean Bias	1.12	1.55	1.23	1.68	1.53	1.43	0.88	1.53	1.13	1.14	1.24	1.58	0.74	1.43
Geometric Variance	1.01	1.21	1.04	1.31	1.20	1.14	1.02	1.20	1.02	1.02	1.05	1.23	1.09	1.13
RMSE	84.38	118.15	192.83	248.28	149.18	104.46	89.06	135.82	74.52	50.47	145.33	115.34	140.96	128.20

within a factor of two of the observations and a relative mean bias within ± 30% or FB as within ± 0.3. Considering FAC2 values, it is evident from scatter Plots (Figs. 4 and 5), that for the present study, the condition of FAC2 > 50% is satisfied for both AERMOD and ADMS-Urban estimations for both years 2000 and 2004. Fractional Bias values are also within the range of ± 0.3 for AERMOD estimations for both years 2000 and 2004 at all sites except for ITO (0.34) in year 2004. Though ADMS-Urban satisfies the FAC2 criterion for all sites, fractional bias exceeds the limit of 0.3 for concentration estimations by ADMS-Urban for one site for year 2000 and six out of the seven sites for the year 2004. Thus it can be said, that AERMOD performs better than ADMS-Urban in relation to bias between observed and estimated concentrations.

RMSE values, which account for difference between modeled and observed values, are high. However, low values of NMSE indicate that the overall deviations are less. Satisfactorily high values for Correlation Coefficient and Index of agreement indicate that the predicted values follow the trend of the observed values.

Greater prevalence of positive Fractional Bias values for both the models indicates that both the models have a tendency towards under-prediction as compared to observed values. Over prediction or under prediction of the model is explained further in Quantile-Quantile (Q-Q) plots. In Q-Q plots, the sorted predicted concentrations are plotted against the sorted observed values (i.e. independent of time and position) to determine whether the observed and predicted concentrations datasets come from populations with a common distribution. If the two sets come from a population with the same distribution, the points should fall approximately along the 1:1 reference line. The greater the departure from this reference line, the greater the evidence for the conclusion that the two data sets have come from populations with different distributions (Venkatram *et al.*, 2001; Luhar *et al.*, 2006). Figs. 6 and 7 show a Q-Q plot for 24 hour average particulate matter observed and estimated concentrations. The plots reveal the general tendency of both models towards underprediction at the higher end of the observed concentration distributions. AERMOD performs extremely well for year 2000 as most of the quantile points lie along the 1:1 reference line (Fig. 6, Left). However there is a consistent tendency towards underprediction for estimations in year 2004. ADMS-Urban overpredicts concentrations at lower end of the observed concentration distribution and underpredicts towards higher end in year 2000. However its performance in year 2004 is similar to that of AERMOD showing consistent underprediction.

Dispersion models can substantially under-predict impacts because the theoretical and physical assumptions on which they are based don't match a particular environmental or meteorological situation. Moreover, the meteorological (weather) inputs provided may be too few or too limited to allow the model to function properly (AReCO, 2002). Often emission inventory that comprises of large number of variety of sources find it difficult to suitably account for all of these sources that may affect the model bias. The total suspended particulate matter concentration in Delhi gets affected at times by long range transport of dust by dust-storms due to its close proximity to desert land in the nearby state of Rajasthan. Such random and irregular phenomenon is not being accounted for in the emission inventory presently. As stated in section 3.2, polluting industries in Delhi were relocated in accordance with Supreme Court ruling. However, certain small factories are still expected to be operational within city boundary limits. Another important reason is that, the activities under sectors such as transport and waste, which lead to particulate matter emissions, are under the purview of regulatory authorities and hence a close estimate of total emissions from these sectors can be obtained. However, activities under domestic sector (such as domestic fuel usage), cannot be surveyed in entirety as a large section of low income group people live in unauthorized slums and colonies in Delhi which are not under legal purview. Though emissions from these sections are significant, but their quantitative estimation is based on many assumptions (Kandlikar and Ramachandran, 2000; Gurjar *et al.*, 2004). The monitored ambient data, however, would measure concentration due to all sources and thus observed concentrations are usually higher than those estimated by models.

In certain cases, the model results exceeded the monitored values; this could be due to some disturbances in the local activities. The emission data which serves as an input to the models has been derived from suitable averaging of the annual emission data. Hence, the emissions data for each grid is taken to be constant throughout the year. But this is not possible in the real scenario, thus at times, when the emissions decrease, the monitored values might tend to be lower than the model values.

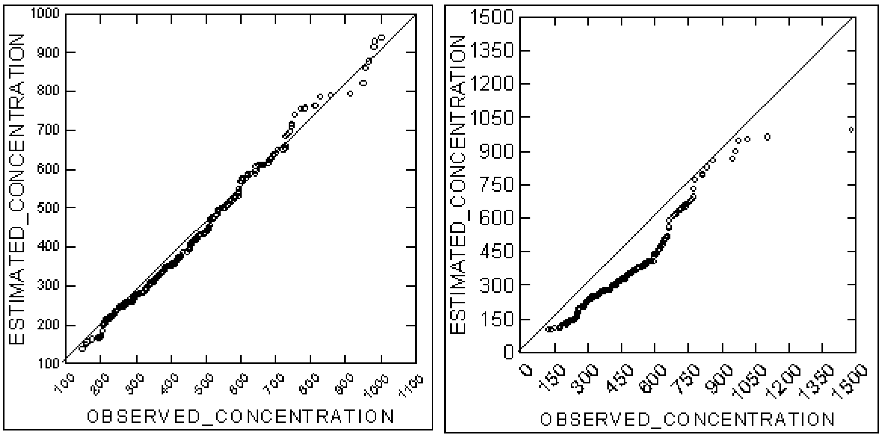

Fig. 6. Q–Q plots of estimated (by AERMOD) and observed daily average TSPM concentrations for years 2000 (left) and 2004 (right). All concentration units are in µg/m^3.

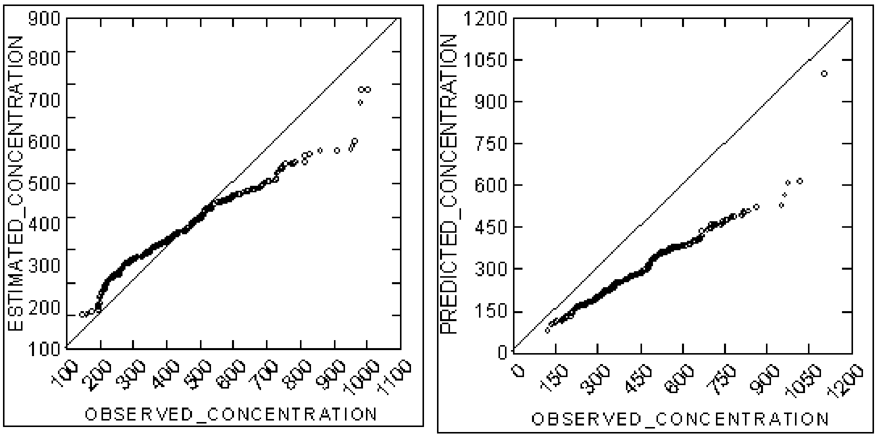

Fig. 7. Q–Q plots of estimated (by ADMS-Urban) and observed daily average TSPM concentrations for years 2000 (left) and 2004 (right). All concentration units are in µg/m^3.

Comparison of the Performance of Both Models

Comparison of the performance of AERMOD and ADMS-Urban has been based on results of mainly four statistical measures:

- Correlation Coefficient: to compare the trend of modeled values to that of measured concentrations.
- NMSE and Fractional Bias: to compare the deviations between observed and predicted values.
- Index of Agreement: to assess the extent to which magnitudes of mean observed values are related to the predicted deviations about them.

Comparison of model predictions based on statistical measures reveals that modeled values by ADMS-Urban have higher correlations with observed concentrations. Hence correlation between observed and modeled values is better for ADMS-Urban predictions as compared to AERMOD. However, Fractional Bias values are mostly lower in AERMOD modeled concentrations as compared to ADMS-Urban. This indicates that concentrations predicted by AERMOD are closer to observed concentrations than those estimated by ADMS-Urban. Both the models perform similarly as far as results of index of agreement and NMSE are concerned. It is therefore concluded that performance of both models is comparable based on statistical performance measures.

Table 4 lists the values of above mentioned statistical parameters for monthly averages of both 2000 and 2004 taken together. It can be seen that AERMOD performs marginally better than ADMS-Urban for monthly averages for all considered statistical measures. Thus while ADMS performs better for 24 hour average concentrations, AERMOD is better for monthly averages. However, it must be noted that in both scenarios, i.e. 24 hour average as well as monthly average, difference between performances of both models is not significant enough to conclude one model as better than the other.

Table 4. Overall performance of statistical indicators for monthly averages of all years and all monitoring sites combined.

	AERMOD	ADMS-Urban
Correlation Coefficient	0.790	0.688
Index of Agreement	0.768	0.643
Fractional Bias	0.164	0.240
NMSE	0.045	0.155

Both models usually underpredict the concentrations. However, ADMS-Urban has a slightly greater tendency towards under-prediction in comparison to AERMOD. This fact can be observed from Q-Q plots in Figs. 6 and 7 in which concentrations by ADMS-Urban show greater deviation from 45-degree reference line towards under-prediction. The following model evaluation studies have been performed on these models and reported of underpredictions as in the present study.

Hanna *et al*. (2001) compared the results of ADMS and AERMOD to five sets of field measurements, which represent a cross-section of scenarios common in modelling studies. Though, in general both models performed well for all scenarios, the ADMS performance was slightly better than the AERMOD performance. On average in the study by Hanna *et al*. (2001), ADMS underpredicted by about 20% and AERMOD underpredicted by about 40%, and both had a scatter of about a factor of two. Approximately 53% and 46% of the ADMS and AERMOD predictions, respectively, are within a factor of two of observations in their study. Overall, both ADMS and AERMOD tended to underpredict the mean and maximum concentrations. This result is in consonance with the findings of our present study for megacity Delhi. Carruthers *et al*. (2000) compared the results of ADMS to measurements from urban and industrial locations in London, Ireland and Wales. The PM_{10} concentrations were significantly underpredicted. The authors suggested that this could be due to emission sources or strengths being poorly defined, exclusion of periodic releases from the modeling, regional variations in the background concentrations or the use of incorrect emission factors. Kesarkar *et al*. (2006) compared the estimated values of PM_{10} to that of observed values over the city of Pune, India using AERMOD coupled with Weather Research and Forecasting Model where underestimation of the concentrations were reported.

Spatial Variation of TSPM

Figs. 8(a)–(d) display concentration contours of TSPM for years 2000 and 2004 as estimated by both AERMOD and ADMS. The region around ITO (marked by star symbol), which is both a traffic intersection and in vicinity of a thermal power plant is a major hotspot in all the isopleths. Some other hotspots which are common in all isopleths are regions around Mangolpuri and CP. Other hotspots are Uttam Nagar and Silampur. ADMS-Urban contours have more distinct concentration hotspots in comparison to AERMOD estimated concentration isopleths. It can be noted that emissions in the city dominate over wind direction. It can be noted that emissions dominate more over wind direction in year 2004 in comparison to year 2000, as concentration distribution does not follow wind rose pattern for year 2004. Also, since vehicular sources are spread throughout the city, the effect of wind direction is not significant in the directions of the contours.

Influence of Boundary Layer Height on Model Results

The difference between estimated concentrations by both models arises due to processing of the meteorological data which result in different estimations of the depth of boundary layer. Since winter months are characterized by low boundary layer conditions, the estimated concentrations are very sensitive to any change in this parameter. Fig. 9 displays boundary layer height (BLH) estimations by AERMET and meteorological processor of ADMS-Urban for both years 2000 and 2004. About 64 % of estimated values of boundary layer height fall within the *ADMS/AERMET* ratio of 0.5 and 2. About 14% of BLH estimations by AERMET are more than twice of those estimated by ADMS-Urban. On the other hand, about 22% of BLH estimations by ADMS-Urban are more than twice those of AERMET. Thus overall, BLH estimations by ADMS-Urban are comparatively higher than those by AERMET. This could be the reason for slightly higher concentration estimations by AERMOD in comparison to ADMS-Urban and consequently lower bias. Brooke *et al.* (2007) compared boundary layer heights estimation by AERMET (04300) and ADMS 3.3 for Yorkshire, UK and found that AERMET estimation of BLH were higher than that of ADMS-Urban. The models could perform differently in different climatic zones. The ADMS-Urban meteorological module provides good estimates of boundary layer depth when the site is in mid-latitudes (CERC, 2006). However, there is no comparison of these two models for Indian conditions (tropical/sub-tropical) from meteorological processing viewpoint exist as undertaken in this study which could help in model implementation. Meteorological processing in AERMOD modeling system includes upper air soundings whereas this feature is absent in ADMS-Urban. However, deeper understanding of the meteorological preprocessors of both models is required for determining specific reasons of difference in estimated concentrations. Comparable performance of both AERMOD and ADMS-Urban reveals that use of sophisticated parameterizations to describe boundary layer physics in AERMOD do not always help in improving the model performance perhaps due to lack of appropriate good quality upper air meteorological data. The surface layer parameterizations in ADMS-Urban based on similarity theory requiring only the surface data has also performed equally well.

CONCLUSIONS

- Performance evaluation of two commonly used regulatory air quality models across the world namely AERMOD (07026) and ADMS-Urban (2.2) has been performed using statistical measures for a sub-tropical region of Delhi in India.
- Estimated daily and monthly averaged concentration values by both models agreed with the observed concentrations within a factor of two. Agreement of monthly average estimated particulate matter concentrations with observed monthly average concentrations is better as compared to 24 hour average concentrations.
- Both the models have a tendency towards under-prediction of concentrations. Irregularities and assumptions in emission input can be a possible cause.

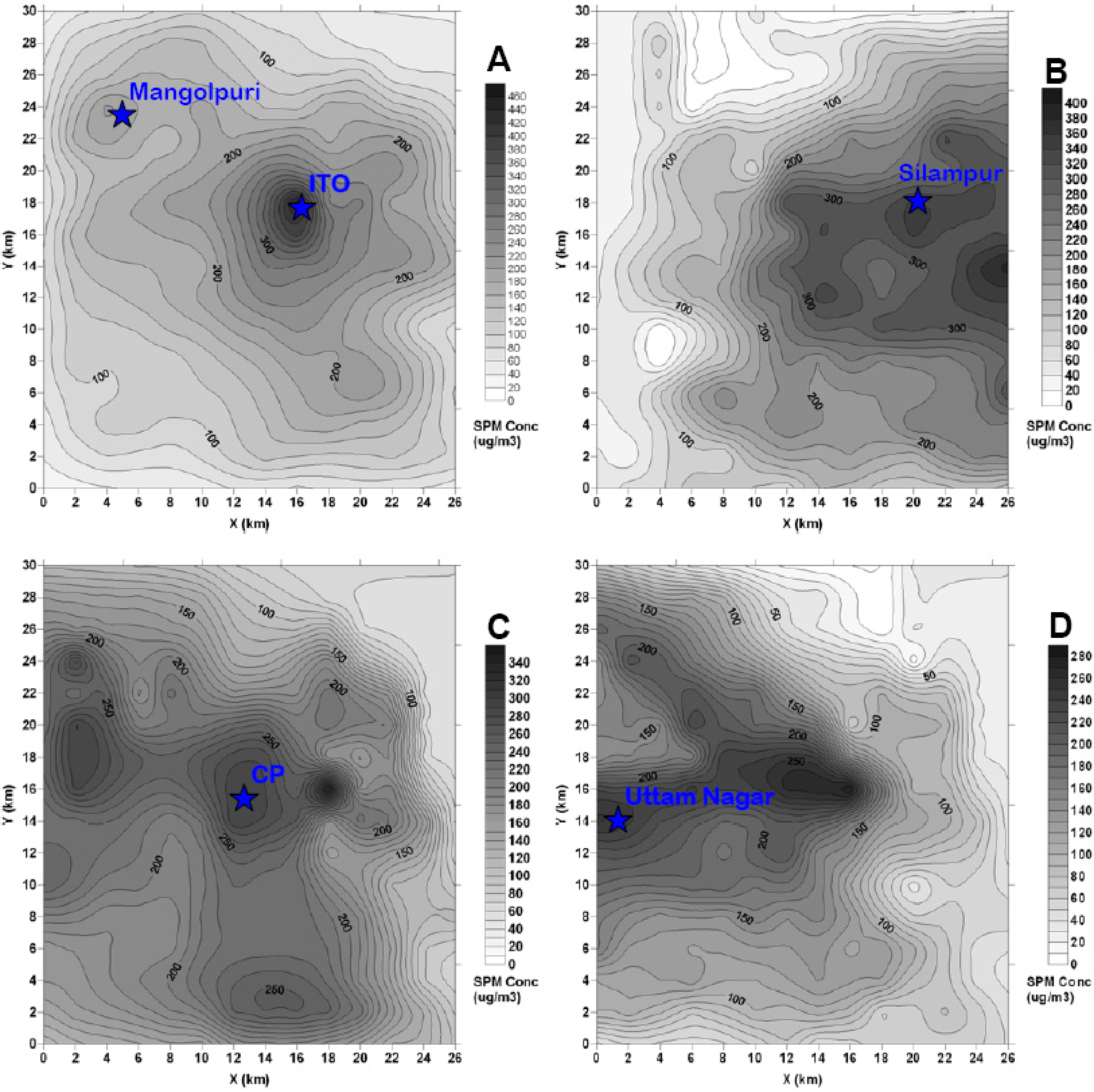

Fig. 8. Concentration isopleths for TSPM as estimated by (A) AERMOD, year 2000 (B) ADMS-Urban, year 2000; (C) AERMOD, year 2004; (D) ADMS-Urban, year 2004.

ADMS-Urban shows greater tendency towards under-prediction as compared to AERMOD. However, AERMOD requires more input meteorological data as compared to ADMS-Urban.

- Monthly average estimations of both the years taken together, reveals that AERMOD estimates are marginally better than ADMS-Urban.
- Overall, both the models have comparable performance and the differences between estimated concentrations are mainly due to processing of the meteorological data. Specifically the influence of boundary layer estimations on the model results were observed that could explain most of the differences amongst the two models. Additional case studies for model performance evaluation always enhance the credibility of the models for both model users and developers. It is helpful from the standpoint of the modeling community targeting their application in tropical urban areas as well as to provide insight for further improvement of these models.

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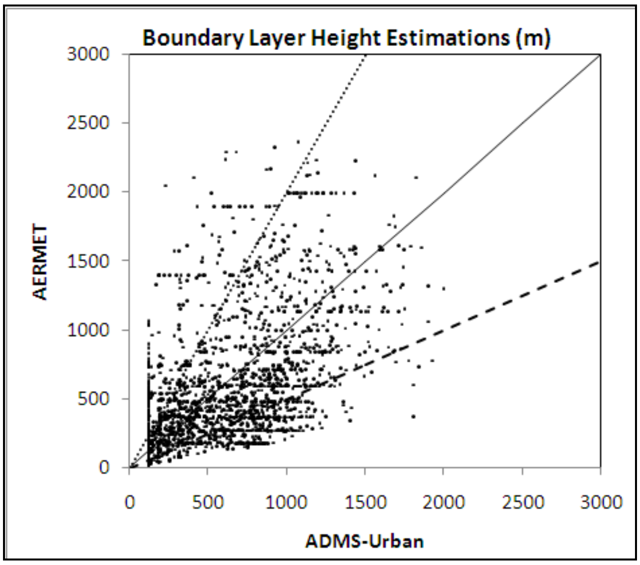

Fig. 9. Boundary layer height estimations (meters) by AERMET and meteorological processor of ADMS-Urban for years 2000 and 2004.

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