Performance Evaluation of Some Regulatory Air Quality Models with Comprehensive Emission Inventory over Megacity Delhi

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Air Quality Modelling

- In air pollution problems, the air quality models are used to predict concentrations of one or more species in space and time as related to the dependent variables.

- Air Quality Models provide the ability to asses the current and future air quality in order to enable well versed policy decisions.

- Thus, air quality models play an important role in providing information for better and more efficient air quality management planning.

Air Quality Models

Physical Models

Simulation of nature on smaller scales in laboratory

Statistical Models

Calculate ambient air concentration from statistical analysis of past air monitoring data even in the absence of emission data. They are good for short term forecasting

Deterministic Models

Calculate ambient air concentration using a solution of various equations representing the relevant physical processes

Air Quality Modelling

- **AQM is performed using Deterministic models over Delhi**
- **Deterministic Models used are US and UK regulatory Models viz. AERMOD (07026) and ADMS-Urban respectively**
- **Model evaluation and inter-comparison is also performed**
- **It is important to perform model evaluation from perspectives of both model users and developers; former to build confidence of it's application in a new climatic condition other than it was developed for and later increased case studies help the model developers/users to judge and improve model performance**

Background

- **The capital city of Delhi is located at latitude 28° 38' 17'' N and longitude 77° 15' 51'' E with an altitude of 215 m above sea level.**

- **Delhi has been designated as an air pollution control area by Ministry of Environment and Forests (MoEF, 1998) in recognition of the severity of air pollution due to vehicular, industrial and domestic sources.**

- **Particulate matter, SO_2 and NO_2 are some of the key constituents of the pollutants in ambient air in Delhi.**

Background

- **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. Based on this premise, the models were used to estimate particulate matter concentrations (PM concentrations exceed above the AQ standards often in a year) in winter months in Delhi.**

- **Ambient particulate matter concentrations have been estimated over seven sites in Delhi by two models viz. AERMOD (07026) and ADMS-Urban for two years 2000 and 2004.**

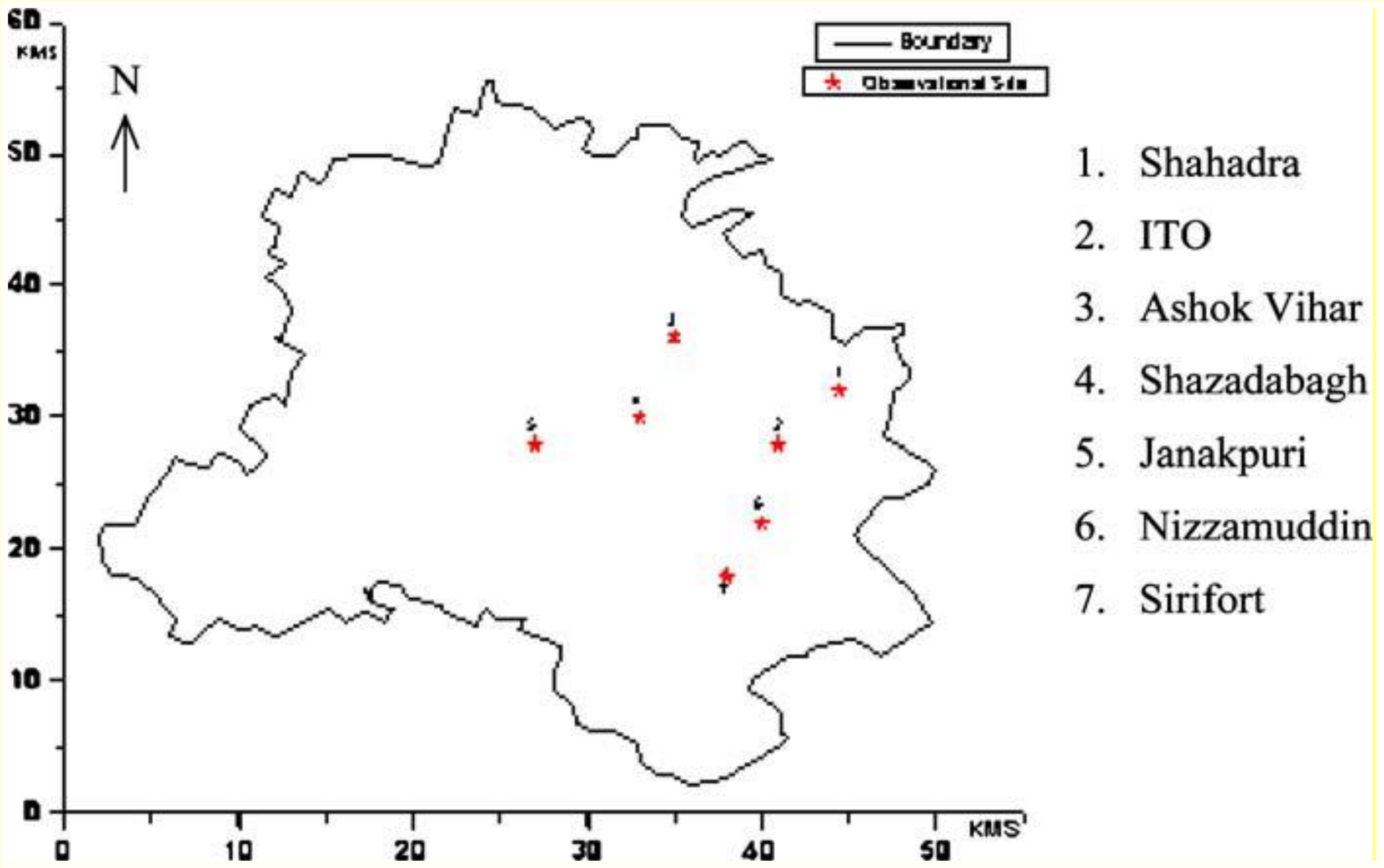
Air Quality Modelling

- **Above models were applied to estimate the particulate matter concentrations at seven monitoring stations in Delhi viz. Ashok Vihar, Siri Fort, Nizamuddin, Shahzada Baug, Janak Puri (residential areas), Shahadara (Industrial area) and ITO (Traffic Intersection).**

- **The model validation is discussed in the light of emission inventory, requisite meteorological inputs and state-of-the art performance measures at the various monitoring stations.**

- **Further the model is used to perform exposure assessment for selected case studies with some control strategies in mind**

Air Quality Monitoring Stations in Delhi



Applied Models

- **AERMOD (version 07026)**
  - **steady-state Gaussian plume air dispersion model developed by USEPA**
  - **incorporates planetary boundary layer concepts. Plume growth is determined by turbulence profiles that vary with height.**
  - **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).**
  - **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.**

Applied Models

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

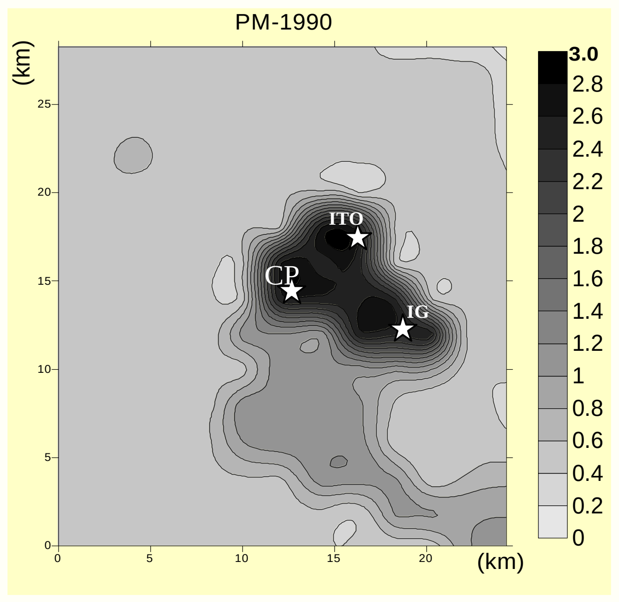
Data

- **Data for total suspended particulate matter concentrations for the years 2000 and 2004 was collected from CPCB in Delhi.**

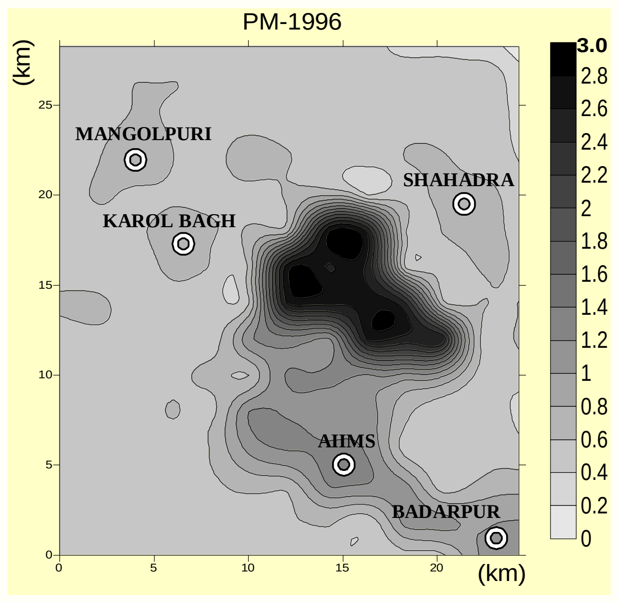
- **Hourly values of meteorological data were obtained from Indian Meteorological Department (IMD) for the time period of two years under study i.e. 2000 and 2004.**

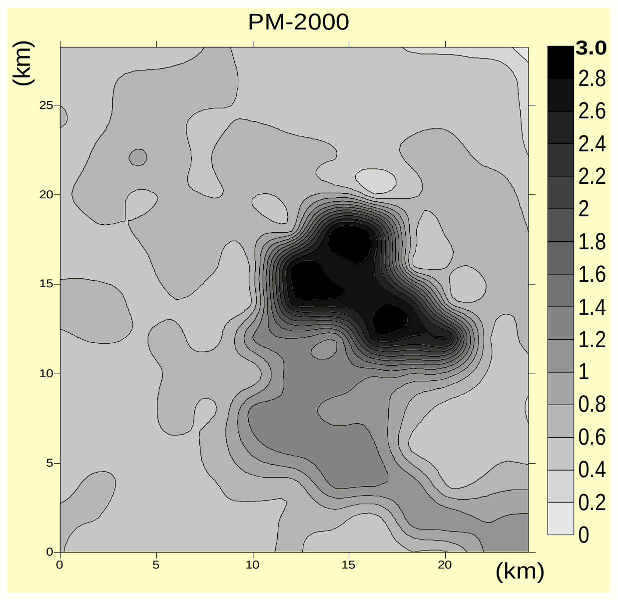
- **The upper air data was accessed from online global Radiosonde Database of National Climatic Data Center (NCDC) of National Oceanic and Atmospheric Administration (US-NOAA).**

- **The emissions for the year 2000 was based on Gurjar et al, 2004 and those required for the year 2004 have been collected from different sources such as Delhi Statistical Hand Book 2004 & 2006 and other government agencies.**



PM Emission Isopleths





Methodology

- **The preparation of gridded inventory and methodology to obtain total emission estimates was based on Mohan and Dube, 1998 and Mohan et al, 2006.**

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

- **A grid network was constructed which comprised of 173 cells (2 km X 2 km) covering 26 X 30 sq km area of Delhi, where most of the urban activities take place.**

- **This area covers all the sources, receptors, seven monitoring stations and most part of the urban Delhi and emissions were calculated for each 2 km x 2 km cell of the grid.**

Methodology

- **The models were run for two types of receptor options: (i) over the entire grid network of Delhi and (ii) for discrete specified points i.e. for the location of monitoring stations so that comparisons between estimated and observed concentration could be made. The output was generated in form of 24 hour average and monthly average total suspended particulate matter concentrations.**

- **Statistical performance measures were used to evaluate the performance of the models. The evaluation of performance of models was based on statistical measures such as Scatter Plots, Quantile-Quantile plots, Mean Square Error, Correlation coefficient, Fractional Bias, Index of agreement and Geometric Mean and Variance. (Hanna et al, 1993, Mohan et al., 1995)**

RESULTS

Overall Performance of Models

- **Comparison of monthly average observed and estimated values of SPM at all seven monitoring stations of Delhi for years 2000 and 2004 by both ADMS and AERMOD reveals that both the models have a tendency towards under-prediction of the concentrations (Fig 1).**

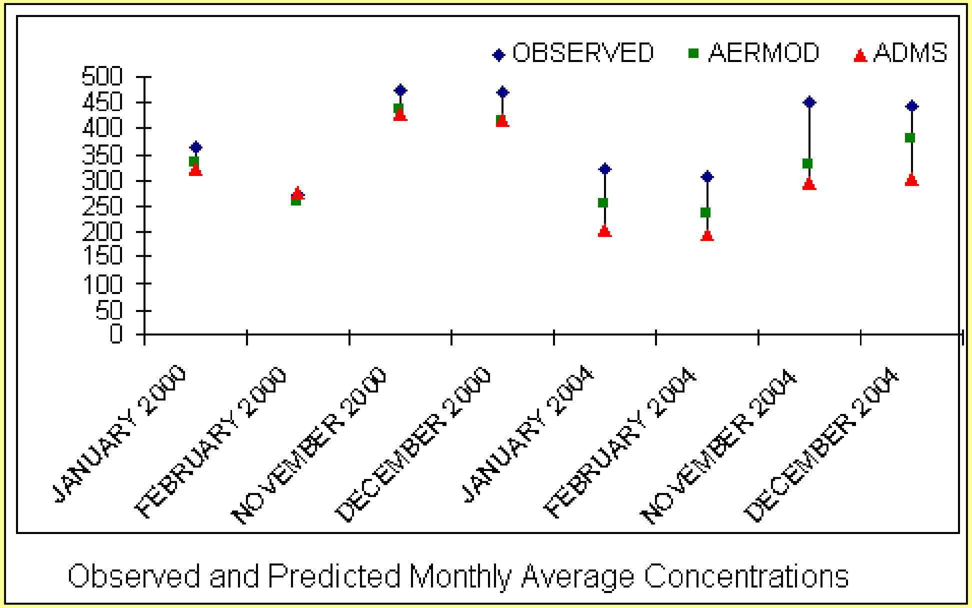
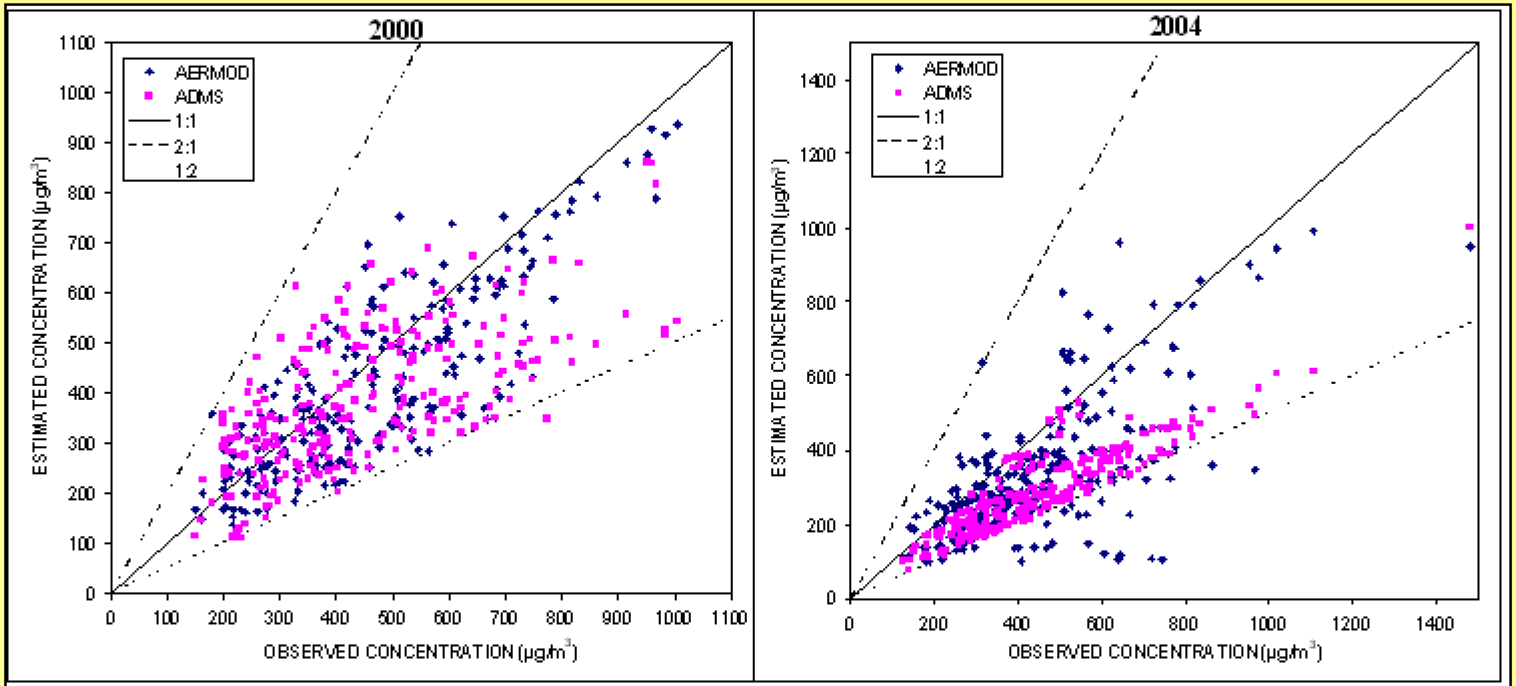


Figure 1

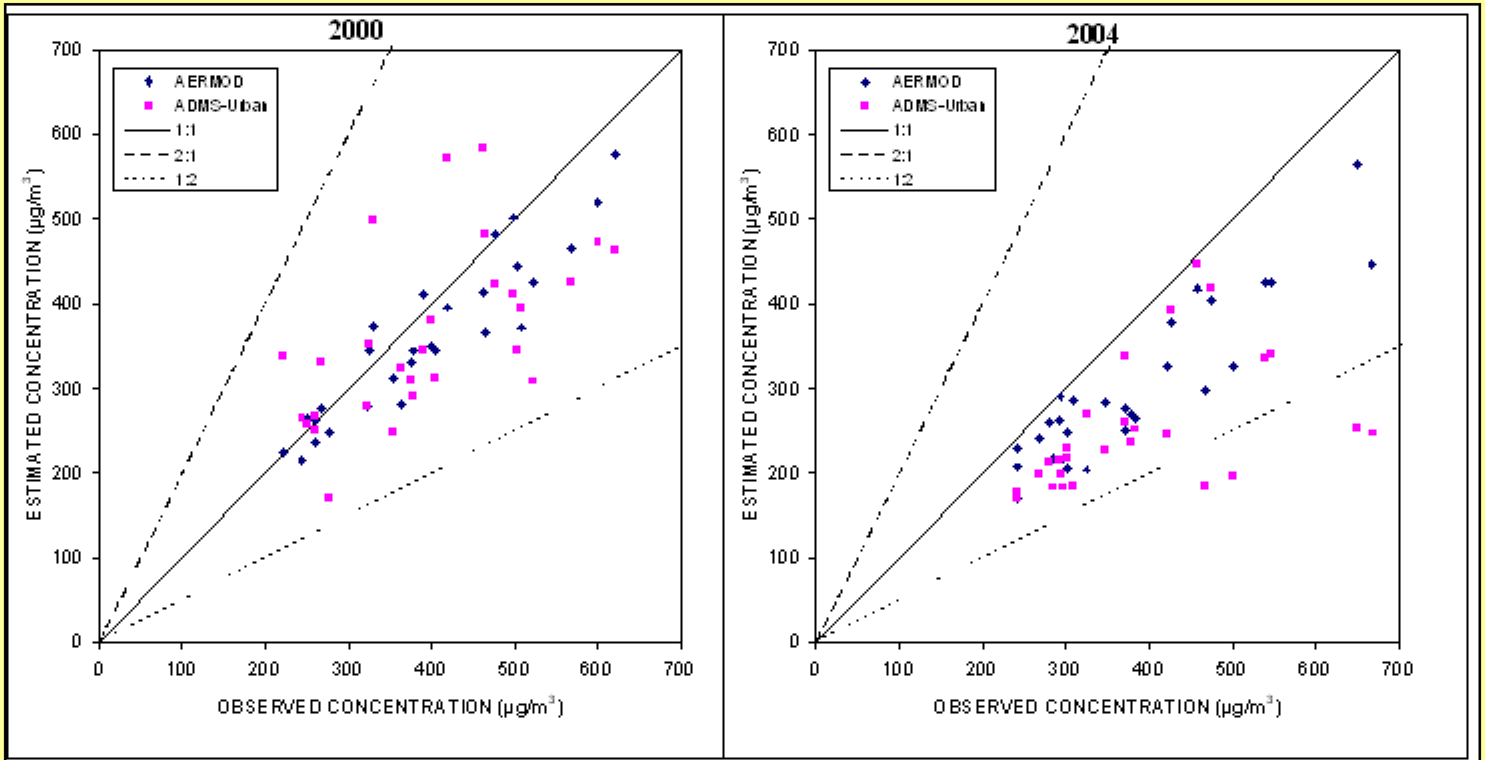
- Most results from both AERMOD and ADMS-Urban agreed with the measured concentration statistics to within a factor of two for daily average concentrations (*Fig 2*)



Scatter Plot of Observed and Estimated Particulate Matter Concentrations (Daily Averages) (Left: Year 2000, Right: Year 2004 for Year 2000)

Figure 2

- **Though, there is a good degree of correlation between the observed and predicted values for both the models, monthly average concentrations estimated from models' results correlate better with observed monthly average concentrations as compared to 24 hour daily average concentrations (*Fig 3*).**



Scatter Plot of Observed and Estimated Particulate Matter Concentrations (Monthly Averages) (Left: Year 2000, Right: Year 2004 for Year 2000)

Figure 3

- **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 (i) NMSE < 0.5 and (ii) -0.5 < FB < +0.5.**

- **These criteria were satisfied for results for all the seven stations for concentration estimations by both models for years 2000 and 2004 (except for ITO for year 2004) inferring that performance of both models was considerably good.**

- According to Chang et al (2004) a ‘‘good’’ model would be expected to have relative mean bias or FB as within ± 0.3. This condition is satisfied for AERMOD estimations for both years 2000 and 2004 at all sites except for ITO (0.34) in year 2004. For ADMS-Urban estimations , fractional bias exceeds the limit of 0.3 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.

Table 1: 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	0.79	0.63	0.57	0.67	0.56	0.76	0.77	0.64	0.86	0.91
Index of Agreement	0.89	0.64	0.85	0.66	0.85	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	0.19	0.07	0.24	0.13	0.25	0.02	0.24
NMSE	0.08	0.07	0.08	0.29	0.08	0.09	0.11	0.14	0.06	0.06	0.09	0.17	0.06	0.15
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	1.02	1.28
Geometric Variance	1.01	1.03	1.01	1.19	1.02	1.03	1.01	1.05	1.01	1.09	1.02	1.08	1.00	1.06

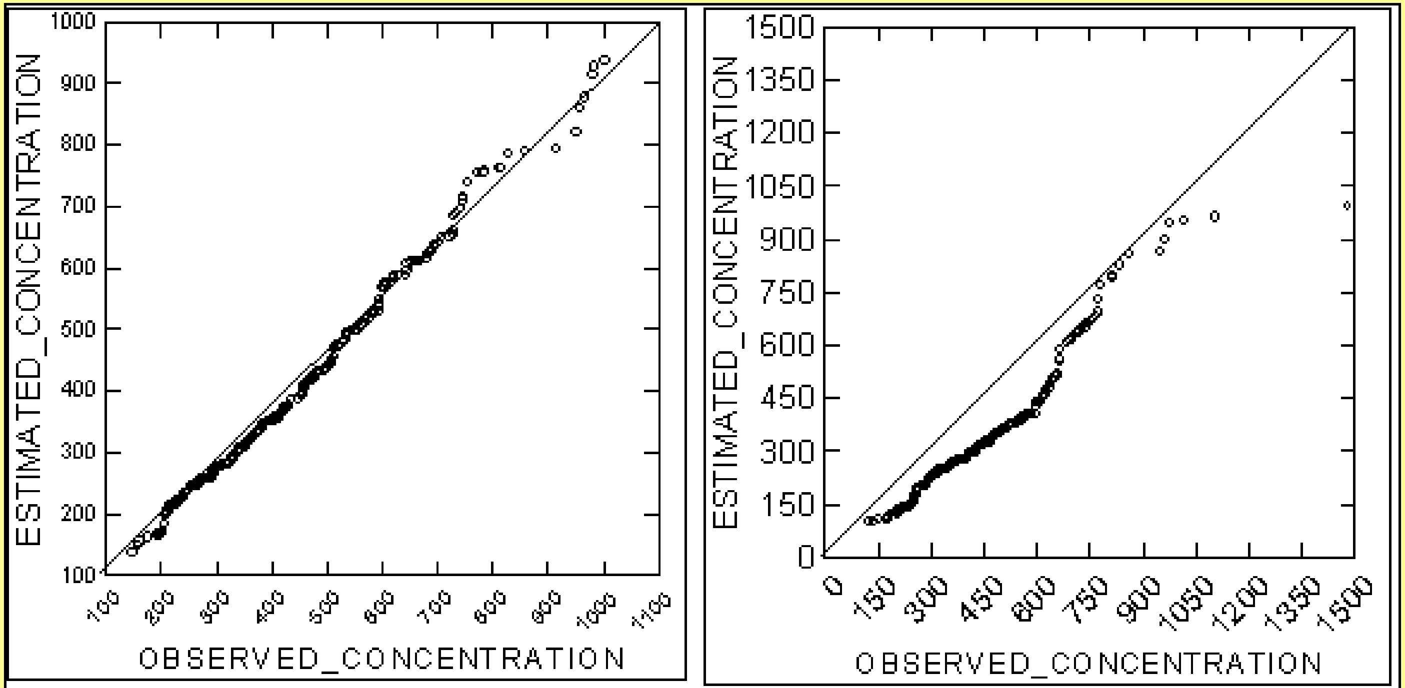
Table 2: Performance of statistical indicators for concentration predictions by ADMS-Urban at different monitoring sites in Delhi.

	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	0.923	0.844	0.574	0.837	0.743	0.823	0.857	0.835	0.566	0.938	0.614	0.564	0.779	0.951
Index of Agreement	0.929	0.679	0.657	0.626	0.660	0.737	0.894	0.616	0.717	0.973	0.689	0.437	0.760	0.767
Fractional Bias	0.131	0.390	0.232	0.508	0.399	0.345	-0.122	0.431	0.124	0.117	0.238	0.454	-0.292	0.378
NMSE	0.05	0.245	0.14	0.289	0.24	0.163	0.05	0.217	0.06	0.056	0.12	0.168	0.18	0.156
Geometric Mean Bias	1.120	1.553	1.231	1.680	1.533	1.428	0.881	1.533	1.134	1.138	1.242	1.579	0.741	1.426
Geometric Variance	1.013	1.214	1.044	1.309	1.201	1.135	1.016	1.200	1.016	1.017	1.048	1.232	1.094	1.134

- **Satisfactorily high values for Correlation Coefficient and Index of agreement indicate that the predicted values follow the trend of the observed values for both models.**

- **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.**

- **Quantile-Quantile (Q-Q) plots explain the model behavior in terms of similarity in distribution and consequently underprediction or overprediction. If the observed and predicted concentrations 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**



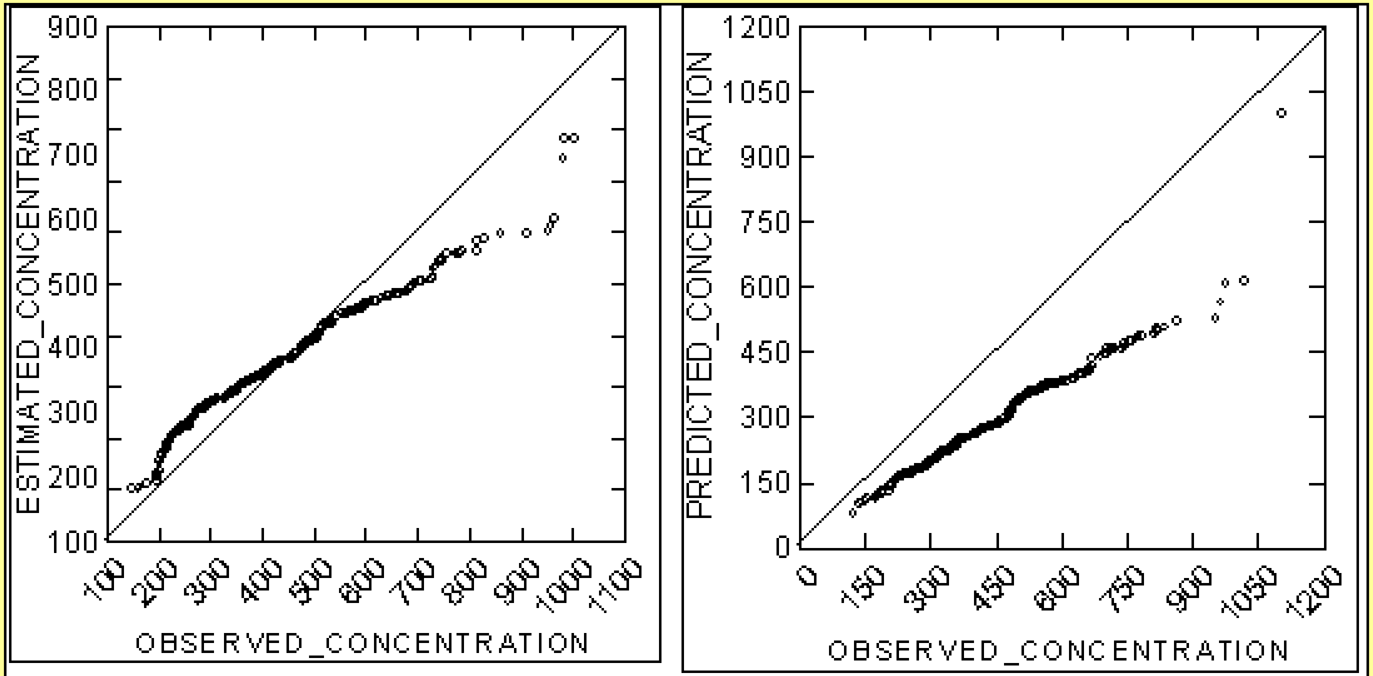
Q-Q Plots of Modeled and Observed (by AERMOD) PM Concentration for years 2000 (Left) and 2004 (Right) (All concentration units are in µg/m³)

Figure 4

AERMOD performs extremely well for year 2000 as most of the quantile points lie along the 1:1 reference line. However there is a consistent tendency towards underprediction for estimations in year 2004 (*Fig 4*).

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 with greater magnitude.

Figure 5



Q-Q Plots of Modeled (by ADMS-Urban) and Observed PM Concentration for years 2000 (Left) and 2004 (Right) (All concentration units are in μg/m^3)

Comparison of the Performance of Both Models

- **Trend correlation between observed and modeled values is better for ADMS-Urban predictions as compared to AERMOD owing to higher correlation coefficients .**

- **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.**

Comparison of the Performance of Both Models

- **ADMS-Urban has a slightly greater tendency towards under-prediction in comparison to AERMOD**
- **However, 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.**
- **In general predictions by both models are better for the year 2000 in comparison to 2004.**

Discussions

- **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 contributing to ambient particulate pollution.**

- **Moreover, 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. Thus quantitative estimation of emissions from these sectors is based on many assumptions. The monitored ambient data, however, would measure concentration due to all sources and thus observed concentrations are usually higher than those estimated by models.**

Discussions

- 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 through out the year. But this is not possible in the real scenario, hence at times, when the emissions decrease, the monitored values might tend to be lower than the model values.

- 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.

Conclusions

- **Both the models have a tendency towards under-prediction of concentrations. Irregularities and assumptions in emission input can be a possible cause.**
- **Greater differences in these models for high concentrations are likely due to differences in the treatment of atmospheric stability conditions as highly stable conditions are associated with higher concentrations. Further work is required to understand the differences**
- **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 due to lack of appropriate good quality meteorological data. The surface layer parameterizations based on similarity theory that requires only the surface data those are often available and of good quality has worked equally well in ADMS-Urban.**

Conclusions

- **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.**

- **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.**

- **Monthly average estimations of both the years taken together, reveals that AERMOD estimates are marginally better than ADMS-Urban.**

Exposure Assessment

- **Health effects of particulate matter pollution range from minor symptoms like irritation of the airways, coughing to severe ones such as development of chronic bronchitis, irregular heartbeat, nonfatal heart attacks and premature deaths.**

- **Since death is the most clearly defined health end point, mortality cases are more extensively analysed in exposure assessment studies. Exposure assessment in the study area of Delhi has been conducted from the view point of change in mortality associated with change in particulate matter concentration.**
- **Dose- response equation developed by Ostro (1994) has been used to estimate change in mortality cases in different scenarios. The equation has an advantage in this study in terms of being applicable for ambient PM_{10} concentration rather than personal PM_{10} exposure values.**

$$T_{mortality} = \sum_{i=1}^{173} C_r \text{ x } \Delta (PM_{10})_i \text{ x } P_i \text{ x } C_{mortality} \qquad \text{(i)}$$

- **$T_{mortality}$ is total change in mortality over the entire study area derived by summation of grid cell specific mortality change associated with cell *i* of the grid network where population P_i is exposed to a decrease (or increase) of $\Delta\ (PM_{10})_i$ in ambient concentration level. The cell specific $\Delta\ PM_{10}$ is estimated by AERMOD.**

- **C_r is Concentration- response coefficient and $C_{Mortality}$ is the crude mortality rate. The value of C_r was calculated from equation (i) by substituting all other parameters (i.e. every year change in number of deaths, PM_{10} concentration, population and mortality rate due to respiratory diseases) for Delhi for a time period of ten years (1991-2000). The concentration- response coefficient was calculated for each of the ten years using the above equation and the obtained average value was used in the assessment. The crude mortality rate for Delhi has been taken as projected in census reports.**

- **Two hypothetical scenarios have been take up for assessment studies**

Case 1: Change of production of power from coal based sources to Natural Gas:

- **Replacement of fuel from coal to natural gas leads to significant reduction in particulate matter. Assuming that total electric energy in Delhi is generated using Natural Gas only as fuel, the decrease in Particulate Matter emissions was estimated based on emission factors derived in earlier studies and Change in mortality was then estimated using equation (i). .**

- **Equation (i) yielded a change of 482 deaths per year in this scenario. Thus a decrease of 482 deaths per year can be expected if there is a complete shift from coal based power production to gas based power production.**

Case 2: 20 % decrease in emissions from Transportation Sector.

- **Increased use of public transport like CNG (Compressed Natural Gas) buses and Metro Rails will result in a decrease from emissions from sources like motor cycles and petrol and diesel based cars. Since estimation of actual change in emissions due to such a shift in use of public transport was outside the scope of this study, a conservative decrease of 20 % in emissions from transport sector has been taken up as a case.**

- **The decrease in the number of mortality cases was estimated at 2527 using equation (i). In other words if an efficient and less polluting public transport system leads to a decrease of 20 % in ambient particulate matter levels, we can expect a reduction of about 2527 deaths per year in the city.**

- **It is clear from the results of Case 1 and 2 that it is emissions from the transport sector in Delhi which need consideration for reduction in terms of particulate matter pollution from the viewpoint of public health. A small decrease in vehicular emissions leads to five times greater reduction in mortality count as compared to a major shift from coal to natural gas sources in power production sector.**

- **There is always an uncertainty associated with such dose response relationships. The ratio of PM_{10} /TSP keeps on varying and its estimation is also based on many assumptions. We can rely on model results only if we are confirmed about accuracy of our emission input. Mortality is a complex phenomenon which cannot be attributed to a handful of parameters. However, in the present study, we have made an attempt to integrate air quality modeling with health risk analysis to assess their application for formulation of air quality management strategies and this first attempt has given a reasonable estimate of scenarios.**

CONCLUSIONS

- Regulatory models namely AERMOD and ADMS-URBAN are validated for a tropical city such as Delhi
- Model validation shows a satisfactory performance of the two models
- It is revealed that sophisticated models where input data requirements are more do not always lead to a better model performance in case there is inadequate data for such studies
- AERMOD is applied for exposure assessment study for some specific case studies for Delhi
- The two case studies chosen for pollution reduction shows that a small decrease in vehicular emissions causes significant reduction in mortality.

Thanks