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Dispersion modeling of noxious pollutants from thermal power plants

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Abstract

Air dispersion modeling software was used to estimate the air quality impacts of 3 thermal power plants located in Pakistan. The real time emission measurements were carried out for a period of 6 months. The plume concentration for carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matter were calculated with reasonable accuracy over long distances to estimate the incremental contribution of these power plants to local air quality. Although the annual average concentration increments from the limited number of power plants studied were relatively small, the long-range transport of emissions of power plants imposes potentially significant health and environmental impacts.

Key Words: Air dispersion; modeling; emissions; ADMS – 4; plume; CO; NO_x; SO_2; particulate matters

Introduction

Around the world, many studies related to emission measurements from thermal power plants have confirmed the severity of the impacts of the measured air pollutants, particularly with respect to global warming and health impacts (Gillani et al., 1998; Ryerson et al., 1998; Garg et al., 2001; Jorge et al., 2002). The toxic gaseous and particulate pollutants emitted from thermal power plants are dispersed over large areas in the surroundings of these plants (Hart et al., 1995; Kouprianov, 2002). Severe health and environmental impacts of the emissions of thermal power plants are well recognized (Kouprianov et al., 2002; Dopatka et al., 2003).

Many studies have been conducted in different parts of the world that have linked atmospheric dispersion modeling with epidemiological assessment to evaluate source-specific health impacts or environmental externalities (ORNL, 1994; EC, 1995; Rowe et al., 1995). While some tried to reconcile the differences between these studies (Krupnick and Burtraw, 1996; Levy et al., 1999), substantial differences remained that were attributed in large part to atmospheric modeling assumptions.

Pakistan has a total installed power generation capacity of 19,252 MW, of which the main sources are thermal and hydropower; only a small portion uses nuclear power. The fossil fuel power generation accounts for 64% of the total power generation capacity of the country (NEPRA, 2004). In Pakistan, environmental regulations

were introduced in 1997, when the Pakistan Environmental Protection Act was approved by parliament, and National Environmental Quality Standards (NEQS) were implemented in 1999. Due to the absence of emission inventories and proper environmental impact assessment practices for the installation of power plants, the impacts of the emissions of thermal power plants are not well known in these areas. Most of the thermal power plants were installed before 1999, and even most of the plants installed after 2000 were installed without dispersion modeling.

In the absence of emission inventories and an air quality database, it is very difficult to predict the deterioration rate of air quality. In this study, we conducted dispersion modeling from the thermal power plants located in the Raiwind area, which is one of the main industrial areas with thermal power plants located in close vicinity. It is probably the first such study in Pakistan for determining the dispersions of gases and particulate pollutants from thermal power plants. The study would be instrumental in determining the pollutant increments to ambient air quality in this area and provoking further research in this and other localities.

In the present study, we used Air Dispersion Modeling Software (ADMS – 4), which is primarily used for environmental impact assessment of point sources and local air quality management. The ADMS – 4 dispersion modeling system was applied to predict the concentration of these pollutants over longer distances. The aim of this study was to evaluate the current status of the air pollution from power plants in the Raiwind area and to gain information on the necessity of further control.

Methodology

Study approach

The 3 studied thermal power plants were located in the Raiwind Industrial Area, which is hardly 10 km from Lahore. Lahore is located at 31°34'N, 74°20'E, with an urban extension of 1,000 km^2. According to the 2001 census report of the Ministry of Population and Statistics, the population of Lahore was about 7.5 million and is expected to increase to up to 10 million by the end of 2010. It is considered one of the 30 largest cities of the world. The main receptor of the emissions of these power plants is the population of Lahore. In addition, the settlements and suburban areas in the vicinity of these power plants are also affected by the plants' emissions of toxic pollutants.

In order to find the dispersion of pollutants from thermal power generation sources and its impact on air quality, air dispersion modeling was carried out on emission data from 3 thermal power plants in the Raiwind area. The 6-month emissions measurements were taken from selected thermal power plants to draw emission profiles. The 6-month average emission rates were used for dispersion modeling to predict the impacts of the thermal power plants' emissions on local air quality in terms of concentration increments of pollutants. The pollutant data processed for air dispersion modeling were values for carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matters. The meteorological data were collected from the Pakistan Meteorological Department, which has installed the weather stations at the Lahore airport.

Model

The dispersion model used in the study was ADMS – 4, which is a Gaussian-type model. ADMS calculates the spread of a plume from turbulence profiles modeling the boundary layer, and convective profiles are skewed away from the Gaussian model to recognize the difference between updrafts and downdrafts. Within the ADMS dispersion model is a meteorological model, the met preprocessor, which can accept a range of inputs including

surface wind speed and direction, temperature, cloud cover, surface heat flux, specific humidity, albedo, and precipitation.

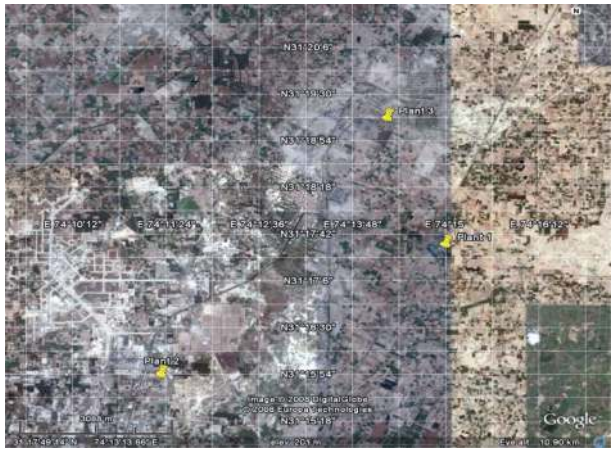

Figure 1. Satellite imagery of 3 thermal power plants in the Raiwind area.

Surface characters are also input, such as surface roughness and albedo. Boundary layer height (BLH) is calculated within the met pre-processor. During the present study, ADMS was run using hourly surface station data from the nearest airport (Lahore). ADMS calculates the sensible heat flux, friction velocity, Monin-Obukhov length scale, and convective velocity scale, among other parameters (Nieuwstadt, 1981). The sensible heat flux is estimated within ADMS from empirical data using time, position, and the other input surface meteorological data.

The sensible heat flux, friction velocity, Monin-Obukhov length scale, convective velocity scale, and BLH are then used to determine the growth rate of the boundary layer. Surface parameters (albedo, surface moisture, roughness length) are also used. The model follows the schemes of Tennekes and Driedonks (Tennekes, 1973; Tennekes and Driedonks, 1981), taking the constant values detailed by Driedonks (1982). ADMS has been validated against a wide range of data sets from different parts of the world (Hanna et al., 1999; Carruthers et al., 2001). The validation has confirmed that over flat terrain, in both urban and rural settings, the predictions of the model are in reasonable agreement with the observations. The present research was limited to the dispersion modeling and its impact on air quality and does not include the validation of the model, because the historical data, background data, and monitoring stations are still not available in the country to validate the predicted conditions with the actual conditions. As the ADMS model has already been validated by many researchers, the model's predictions are likely to be acceptable.

Emission data

In the Raiwind area, 3 independent power plants were selected for the study. The 3 plants operate on heavy furnace oil and are located in close proximity to each other; the maximum distance among them is 10 km. The satellite imagery of the studied power plants is shown in Figure 1. Due to unavailability of emissions inventories from the Environmental Protection Agencies and other relevant authorities, real-time stack emissions measurements from the 3 thermal power plants were conducted for 6 months (April-September 2005), with an interval of 1 month. The capacity, technology, and other specifications of these plants are shown in Table 1. The analysis report of the typical heavy furnace oil is shown in Table 2.

Table 1. Description of power plants.

Plant	Generation Capacity	Fuel Type	Technology	Year of Installation	No. of Stacks	Stack Height (m)	Stack Diameter (m)
Plant 1	117 MW	Heavy Furnace Oil	Diesel Engines	1998	5	22	1.0
Plant 2	131 MW	Heavy Furnace Oil	Diesel Engines	1999	8	40	0.8
Plant 3	120 MW	Heavy Furnace Oil	Diesel Engines	1997	4	25	0.9

Table 2. Analysis report of heavy furnace oil.

Sr. No.	Parameter	Unit	Concentration
1	Density (15 $^\circ$C)	kg/m^3	966
2	Viscosity (50 $^\circ$C)	mm^2/s	146
3	Water Contents	%	0.21
4	Net Calorific Value	J/g	40,168
5	Carbon	%	84.62
6	Nitrogen	%	0.9
7	Sulfur	%	2.89
8	Hydrogen	%	10.9
9	Sodium	mg/kg	6
10	Vanadium	mg/kg	48
11	Nickel	mg/kg	18
12	Iron	mg/kg	4.6

The stack emissions were measured for critical pollutants like carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, sulfur dioxide, and particulate matter. The sampling and analysis of flue gases from the stacks of power plants were conducted in accordance with methods approved by the US EPA. Following is a brief description of the US EPA methods and the equipment used for the study.

Selection of the measurement site was carried out in accordance with US EPA Method 1. Sampling ports were selected at a site located at least 8 stack or duct diameters downstream and 2 diameters upstream from any flow disturbance, such as a bend, expansion, or contraction in the stack, or from a visible flame. Where that was not possible, an alternative location was selected; at least 2 stack or duct diameters downstream and a half diameter upstream from any flow disturbance.

The measurements of carbon monoxide, carbon dioxide, and oxides of nitrogen were carried out using portable analyzers, based on US EPA CTM Method 030. A Lancom II portable flue gas analyzer (UK) was used for the measurement of carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and combined oxides of nitrogen from the stacks of the power plants. The Lancom II flue gas analyzer is equipped with electrochemical and NDIR sensors. The measurement range of the gas sensors were carbon monoxide, 0-4,000 mg/m^3; carbon dioxide, 0%-21%; nitric oxide, 0-4,000 mg/m^3; nitrogen dioxide, 0-1,000 mg/m^3; and combined oxides of nitrogen, 0-5,000 mg/m^3.

US EPA Method 6 (determination of sulfur dioxide emission from a stationary source) was used for the measurement of sulfur dioxide from the stacks. The equipment used for the sampling of sulfur dioxide was a VSS1 Sampling Train, model 2006 (VBU Ltd., India). The flue gas sample was extracted into impingers containing absorption solution (hydrogen peroxide) from the sampling point in the stack. The sulfuric acid

mist (including sulfur trioxide) and the sulfur dioxide were separated. The sulfur dioxide fraction was measured by the barium-thorin titration method. The minimum detectable limit of the method is 3.4 mg/m^3, and the upper concentration limit in a 20 L sample is about 93,300 mg/m^3.

Possible sources of interference are free ammonia, water-soluble cations, and fluorides. The cations and fluorides were removed by glass wool filters and an isopropanol bubbler, and hence did not affect the sulfur dioxide analysis. When samples were taken from a gas stream with high concentrations of fumes, a high-efficiency glass fiber filter was used in place of the glass wool plug to remove the cation interferents.

USEPA Method 5 (determination of particulate matter from a stationary source) was used for the measurement of velocity and the sampling of particulate matter at an isokinetic sampling rate. Velocity in the stack was measured using S-type pitot tubes (US EPA Method 2). The equipment used for stack velocity and particulate matter was a VSS1 Isokinetic Sampler, model 2006 (VBU Ltd., India).

US EPA Methods 1 and 2 were used to select the minimum number of sampling points and the range of velocity heads, respectively. Similarly, the moisture content was determined by using US EPA Method 4, and stack gas dry molecular weight was determined by US EPA Method 3.

From the flue gas velocity measurement, a nozzle size was selected to achieve isokinetic sampling rates. Samples of particulate matter were collected for 4 h and the sampling time at each point was kept the same. Into each of the first 2 impingers, 100mL of water was poured; the third impinger was kept empty; and 200 g of silica gel was transferred to the fourth impinger. Weighed filter paper was fixed in the filter holder. A glass cyclone was used between the probe and filter holder. The crushed ice was placed around the impingers to maintain the temperature.

The sample was collected at an isokinetic sampling rate (within l0% of true isokinetic conditions), and the temperature around the filter was maintained at l20 ± l4 °C. The nozzle of the sampling probe was placed at each traverse point with the tip pointing directly into the gas stream. The pump was started immediately and adjusted the flow to isokinetic conditions. The dry gas meter reading was recorded at the beginning and end of each sampling time increment. On completion of sampling, all external particulate matter near the tip of the probe nozzle was wiped off, and a cap was placed over it to prevent the loss or gain of particulate. Particulate matter and condensate from the probe nozzle, probe fitting, probe liner, and front half of the filter holder was quantitatively recovered by washing these components with acetone and placing the wash in a glass container. The filter was weighed after 24 h in a desiccator containing anhydrous calcium sulfate. The contents of second container were transferred to a 250 mL beaker, and the acetone was evaporated to dryness at an ambient temperature and pressure. The beaker was desiccated for 24 h and weighed to a constant weight. Similarly, the change in weight of the spent silica gel was calculated.

The measurement of the concentration of each pollutant was taken at the optimum load from all engine exhausts of each plant. At the time of measurement, electricity generation records and all other relevant details related to the measurement were noted from the power plant control room. The pollutant concentrations and stack data obtained from each plant over a 6-month period were statistically averaged and are presented in Tables 3-5.

All equipment used for the measurement of gaseous and particulate pollutants was calibrated either in the laboratory or at the site. The Lancom II has a program for self-calibration, and once the equipment is switched on, it automatically starts calibration. Fresh air was drawn in by the built-in pump in the instrument, which also purged out any gas or air present inside the instrument. Finally, calibration was done with respect to the

oxygen present in the atmosphere, at 20.9%. All of the experimental work was carried out by implementing the following quality control and quality assurance protocols.

Table 3. Stack emissions data of Thermal Power Plant 1.

Sr. No.	Parameter	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5
1	Average Flue Gas Temperature (°C)	357	345	361	368	360
2	Flue Gas Velocity (m/sec)	36.42	37.28	37.54	38.63	36.92
3	Volumetric Flow Rate of Flue Gas (m^3/sec)	28.59	29.26	29.47	30.32	28.98
4	Average Concentration of CO in Flue Gas (mg/m^3)	654	631	642	708	699
5	Emission Rate of CO (g/sec)	18.70	18.46	18.92	21.47	20.26
6	Average Concentration of NO_x in Flue Gas (mg/m^3)	1,795	1,758	1,768	1,822	1,879
7	Emission Rate of NO_x (g/sec)	51.32	51.44	52.10	55.24	54.45
8	Average Concentration of SO_2 in Flue Gas (mg/m^3)	1,907	1,872	1,864	1,907	1,943
9	Emission Rate of SO_2 (g/sec)	54.52	54.78	54.93	57.82	56.31
10	Average Concentration of Particulate Matter in Flue Gas (mg/m^3)	186	186	193	196	194
11	Emission Rate of Particulate Matter (g/sec)	5.32	5.44	5.69	5.94	5.62

The Lancom II was calibrated before every measurement of the stacks of the engines of the plants. Calibration of the flue gas analyzer was carried out at a location at the base of the stack, since at such locations, the possibility of mixing the flue gas (emitted from the stack at a considerable height) with the surrounding air was absolutely nil. It can therefore be assumed that the calibration of the instrument with reference to the atmospheric oxygen was acceptable.

Measurements were conducted at accessible locations of the flue gas duct. The positions of the locations were maintained at a sufficient distance from bends and obstructions in the flue ducts; thus, possible disturbances arising from irregular turbulence due to bends or obstructions were avoided, as per US EPA guidelines.

Measurements were taken repeatedly at regular time intervals to check for consistency in emission measurements (concentrations). Standard statistical methods were applied for data interpretation as per US EPA guidelines.

Meteorological data

Lahore is a historic city of Pakistan, located at 214 m above sea level. Its municipal area is 332 km^2, which, due to rapid urbanization, has extended to 1000 km^2 at the periphery of the main city. The climate of Lahore is hot and semiarid. There are 4 seasons: the hot summer season from May to July, the rainy season from July to September, the winter season from November to February, and the spring season from March to April. For dispersion modeling, 1 year of data (1 January-31 December 2005) was used as an input of meteorological conditions to run the model. The meteorological data were collected from the Pakistan Meteorological Department, which has a weather station at the Lahore airport. The rainfall in 2005 varied from 0-223.5 mm, and

Table 4. Stack emissions data of Thermal Power Plant 2.

Sr. No.	Parameter	Stack 1	Stack 2	Stack 3	Stack 4	Stack 5	Stack 6	Stack 7	Stack 8
1	Average Flue Gas Temperature (°C)	345	381	371	366	353	354	363	378
2	Flue Gas Velocity (m/sec)	31.42	29.38	30.94	31.82	30.86	32.44	31.68	30.98
3	Volumetric Flow Rate of Flue Gas (m^3/sec)	15.77	14.75	15.53	15.97	15.49	16.28	15.90	15.55
4	Average Concentration of CO in Flue Gas (mg/m^3)	597	686	699	671	614	595	698	661
5	Emission Rate of CO (g/sec)	9.41	10.12	10.86	10.72	9.51	9.69	11.10	10.28
6	Average Concentration of NO_x in Flue Gas (mg/m^3)	1,679	1,727	1,715	1,716	1,680	1,698	1,756	1,783
7	Emission Rate of NO_x (g/sec)	26.48	25.47	26.63	27.40	26.02	27.64	27.92	27.72
8	Average Concentration of SO_2 in Flue Gas (mg/m^3)	1,782	1,773	1,843	1,780	1,793	1,807	1,910	1,867
9	Emission Rate of SO_2 (g/sec)	28.10	26.15	28.62	28.43	27.77	29.42	30.37	29.03
10	Average Concentration of Particulate Matter in Flue Gas (mg/m^3)	181	194	214	200	184	184	204	179
11	Emission Rate of Particulate Matter (g/sec)	2.85	2.86	3.32	3.19	2.85	2.99	3.24	2.78

Table 5. Stack emissions data of Thermal Power Plant 3.

Sr. No.	Parameter	Stack 1	Stack 2	Stack 3	Stack 4
1	Average Flue Gas Temperature (°C)	360	360	378	372
2	Flue Gas Velocity (m/sec)	41.25	38.94	42.28	44.21
3	Volumetric Flow Rate of Flue Gas (m^3/sec)	26.24	24.76	26.89	28.12
4	Average Concentration of CO in Flue Gas (mg/m^3)	649	785	841	875
5	Emission Rate of CO (g/sec)	17.03	19.44	22.61	24.60
6	Average Concentration of NO_x in Flue Gas (mg/m^3)	2,042	2,014	1,984	2,118
7	Emission Rate of NO_x (g/sec)	53.58	49.87	53.35	59.56
8	Average Concentration of SO_2 in Flue Gas (mg/m^3)	2,452	2,667	2,854	2,594
9	Emission Rate of SO_2 (g/sec)	64.34	66.03	76.74	72.94
10	Average Concentration of Particulate Matter in Flue Gas (mg/m^3)	252	320	314	304
11	Emission Rate of Particulate Matter (g/sec)	6.61	7.92	8.44	8.55

the annual reported rainfall was 652.2 mm. The bulk of the rainfall in the Lahore region is received during the monsoon season, between July and September.

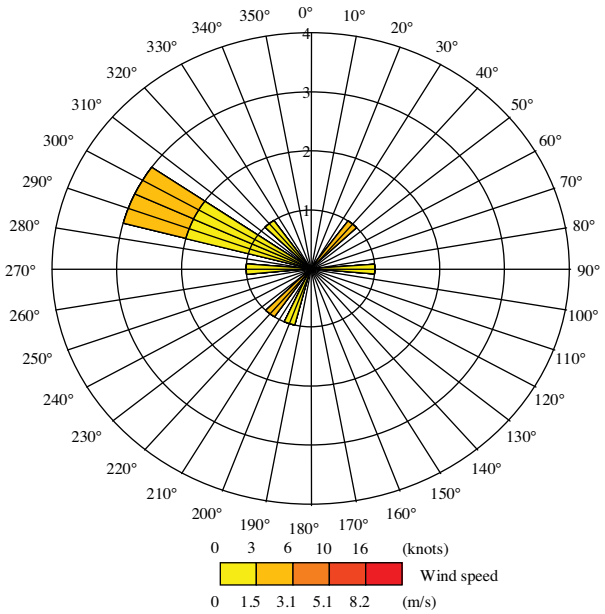

Figure 2. Wind rose for metrological data of Lahore, 2005.

In general, Lahore is subject to pronounced variations in temperature, directly and indirectly influencing the environment of the city. The mean monthly temperature in the year 2005 varied from 13.3 to 34.9 °C and the annual average temperature is 24.6 °C. The temperature is highest during summer (May-July), and lowest during winter (December-February). The relative humidity varied from 24%-68%, and humidity in the area increased from July to September and attained its peak in the range of 50%-68%, while during the rest of the year it was in the range of 24%-45%. The wind systems that affect the city generally arise from a northwestern direction. Wind speeds as well as diurnal and seasonal patterns vary considerably in the studied area. The wind speed in 2005 varied from 0.7 to 2.2 m/s. The wind rose is shown in Figure 2.

Results and Discussion

The 3 thermal power plants have different stack heights, in the range of 22-40 m. The internal diameters of the stacks are close to each other, varying from 0.8 to 1.0 m. The flue gas temperatures of the stacks were in the range of 345-381 °C; similarly, the flue gas velocities were in the range of 29.38-44.21 m/s. The 6-month average emission rates of different pollutants (carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matters) and the flue gas characteristics of individual stacks are presented in Tables 3-5.

During the study, we evaluated the impacts of 3 thermal power plants in grids of 15 × 15 km to 50 × 50 km, depending on the emission rates of the pollutants (carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matter). We developed the emission scenario of these plants by means of 6-month stack emissions monitoring to reflect the current emissions. There are no emissions inventories or air quality databases available from environmental protection agencies or relevant authorities. The 6-month averages of the pollutants were assumed to be uniform emissions across the year, a simplifying assumption due to the limited availability of data.

Additionally, due to power crises in the country, all of these plants were operating at full load throughout the year, which supports our assumption and would not be expected to substantially influence the results. Similarly, meteorological data were collected for 1 year from the airport nearest to the plant sites. To incorporate the wet and dry deposition into the ADMS model, 1-year precipitation data were also collected from the Pakistan Meteorological Department.

For flat terrain simulations, the ADMS boundary layer structure is defined in terms of the Monin-Obukhov length, BLH, and surface roughness (Carruthers et al., 1994). These parameters are used to define standard vertical profiles of mean flow and turbulence, which include profiles for neutral, stable, and unstable conditions of the mean wind and turbulent kinetic energy. In ADMS, plume spread is simulated using an analytic formulation for the concentration distribution, with the distribution being Gaussian for horizontal spread and vertical spread in neutral and stable conditions, and non-Gaussian for vertical distributions in unstable conditions.

For the simulations, the wind speed data were collected at a height of 10 m above ground level. Similarly, a ground roughness length of 0.3 m was used, which represents agricultural land. These parameters were used to calculate boundary layer profiles of velocity, turbulence kinetic energy (TKE), and turbulent dissipation using the ADMS boundary layer structure routines. The profiles were then used in the ADMS dispersion algorithms.

ADMS was run with separate model input files for each of the 3 thermal power plants. As there is no ambient air quality monitoring stations present in the country, the background air quality data was kept at default, 0. The ground level concentrations predicted by ADMS – 4 were only the contribution of these power plants. The ADMS long-term mode was used to develop the concentration files for all of the modeled pollutants. The long term mode was run for all of the plants separately, as well as collectively for the Raiwind area. The final output of the model consisted of horizontal and vertical plume spreads and maximum concentrations for each pollutant (carbon monoxide, oxides of nitrogen, sulfur dioxide, and particulate matter). The output data were contoured with the help of Surfer 6 software and are presented in Figures 3-6.

A sensitivity analysis was conducted using data from Thermal Power Plant 1 to determine the parameters that impacted the model predictions. The results showed the variations in the predicted concentrations for a base case at a point close to the source and a point farther downwind. The data analysis for locations close to the source showed that stack exit temperature, mixing height, wind speed, and stability class have the highest impact on concentration predictions. The stack exit temperature influences the plume rise and thus is important where the plume has not reached its final rise. At farther distances downwind, concentrations are mainly influenced by stability class, mixing height, and wind speed. Overall, these results confirmed that the model is sensitive to atmospheric conditions, and thus justify the selection of wind speed, mixing height, and atmospheric stability as the key parameters for modeling.

The ADMS model simulated the plumes of different pollutants for the emissions of Thermal Power Plant 1 well. The predicted peak concentrations were presented at various distances of up to 25,000 m downwind and are shown in Figures 3a-3d. The concentration of pollutants was very high within a 2,000 m radius, and the maximum carbon monoxide level predicted was 155.39 $\mu g/m^3$ at a distance of 500 m from the source. At locations closer to the source, the peak concentrations did not follow a similar decreasing trend. This is due to variations in atmospheric conditions that could not be represented by the assumptions used in the simulations. The concentration of carbon monoxide was 4 $\mu g/m^3$ at a distance of 10,000 m downwind (Figure 3a). The maximum level of oxides of nitrogen predicted was 421.69 $\mu g/m^3$ at a distance of 500 m from the source, and it remained very high within a 5,000 m radius of the source. The concentration of oxides of nitrogen at 5,000 m of distance was 12 $\mu g/m^3$; it was reduced to 6 $\mu g/m^3$ at 18,000 m downwind from the source. A ground level

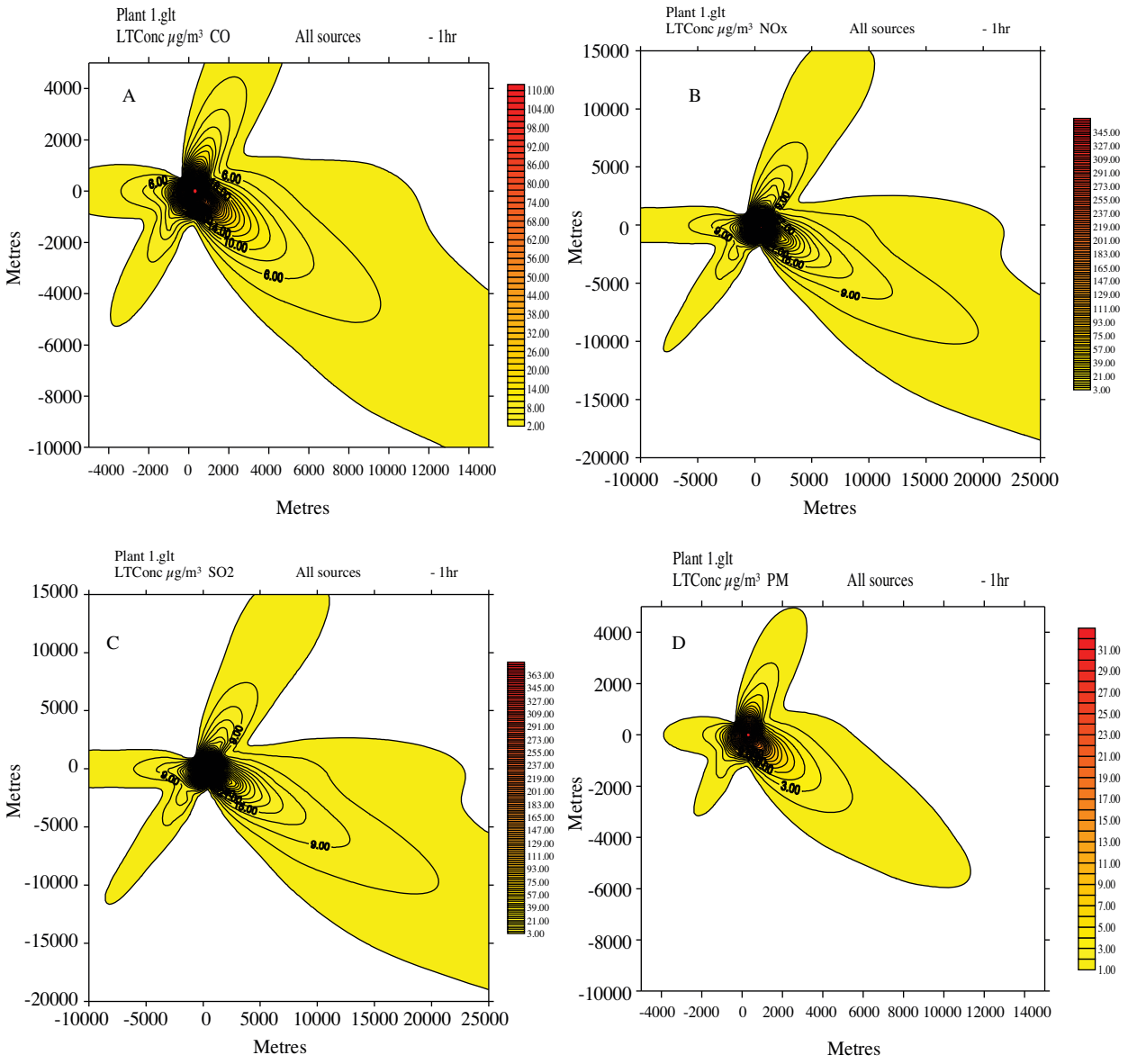

Figure 3. Plume of different pollutants, Thermal Power Plant 1 (long term).

NO_x concentration of 3 $\mu g/m^3$ was predicted at 25,000 m downwind of the source (Figure 3b). The maximum level of sulfur dioxide predicted was 442.39 $\mu g/m^3$ at a distance of 500 m downwind of the source. A high level of sulfur dioxide was predicted within a 5,000 m radius of the source, and from 25,000 m downwind its ground level concentration was 3 $\mu g/m^3$ (Figure 3c). The dispersion of particulate matter over longer distances is comparatively less than that of the gaseous pollutants. The maximum concentration of particulate matter was predicted to be 44.51 $\mu g/m^3$ at a distance of 500 m from the source, and at a distance of 10,000 m downwind, its impact was reduced to 2 $\mu g/m^3$ (Figure 3d).

The plumes of different pollutants simulated for the emissions of Thermal Power Plant 2 are presented in Figures 4a-4d. The maximum concentration of carbon monoxide predicted was 145.29 $\mu g/m^3$ at a distance

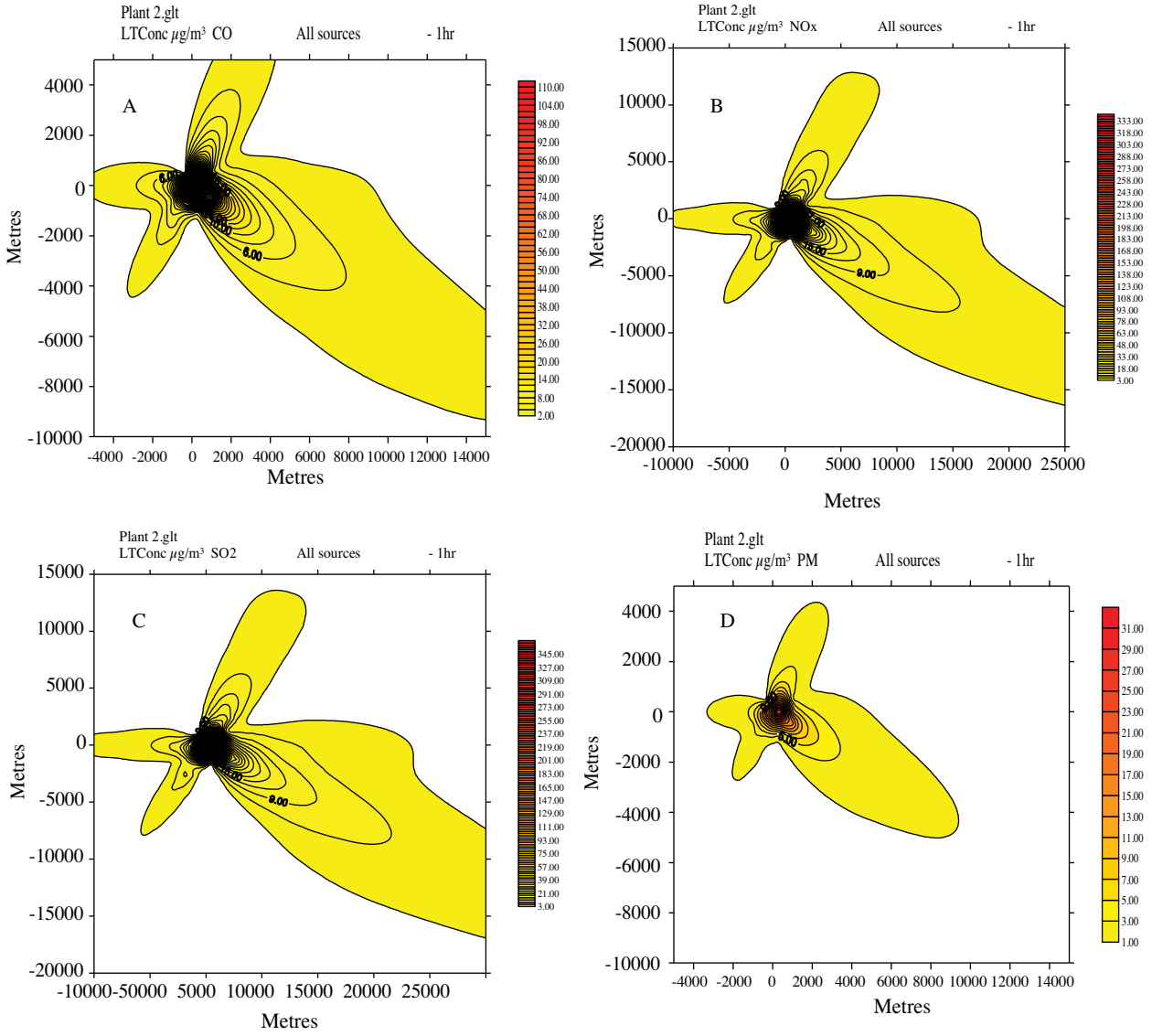

Figure 4. Plume of different pollutants, Thermal Power Plant 2 (long term).

of 500 m from the source, which was reduced to 4 μg/m^3 at a distance of 6,000 m downwind. Beyond that point and up to 15,000 m, it was 2 μg/m^3 (Figure 4a). The maximum concentration of oxides of nitrogen predicted was 384.02 μg/m^3 at a distance of 500 m from the source, and it remained very high within a 1,000 m radius of the source. The peak concentration values of NO_x at distances of 10,000 and 15,000 m were 9 and 6 μg/m^3, respectively, and beyond 15,000 m downwind, it was 3 μg/m^3 (Figure 4b). The maximum concentration predicted for the sulfur dioxide plume was 405.28 μg/m^3 at a distance of 500 m downwind of the source. At distances of 5,000 and 10,000 m, the peak concentrations of sulfur dioxide were 15 and 8 μg/m^3, respectively, while at a distance of 17,000 m downwind, it was reduced to 3 μg/m^3 (Figure 4c). The peak concentration of particulate matter was predicted to be 42.82 μg/m^3 at a distance of 500 m. The spread of the plume was not very high and the concentration was reduced to 3 μg/m^3 at distances of 2,000-2,500 m (Figure 4d).

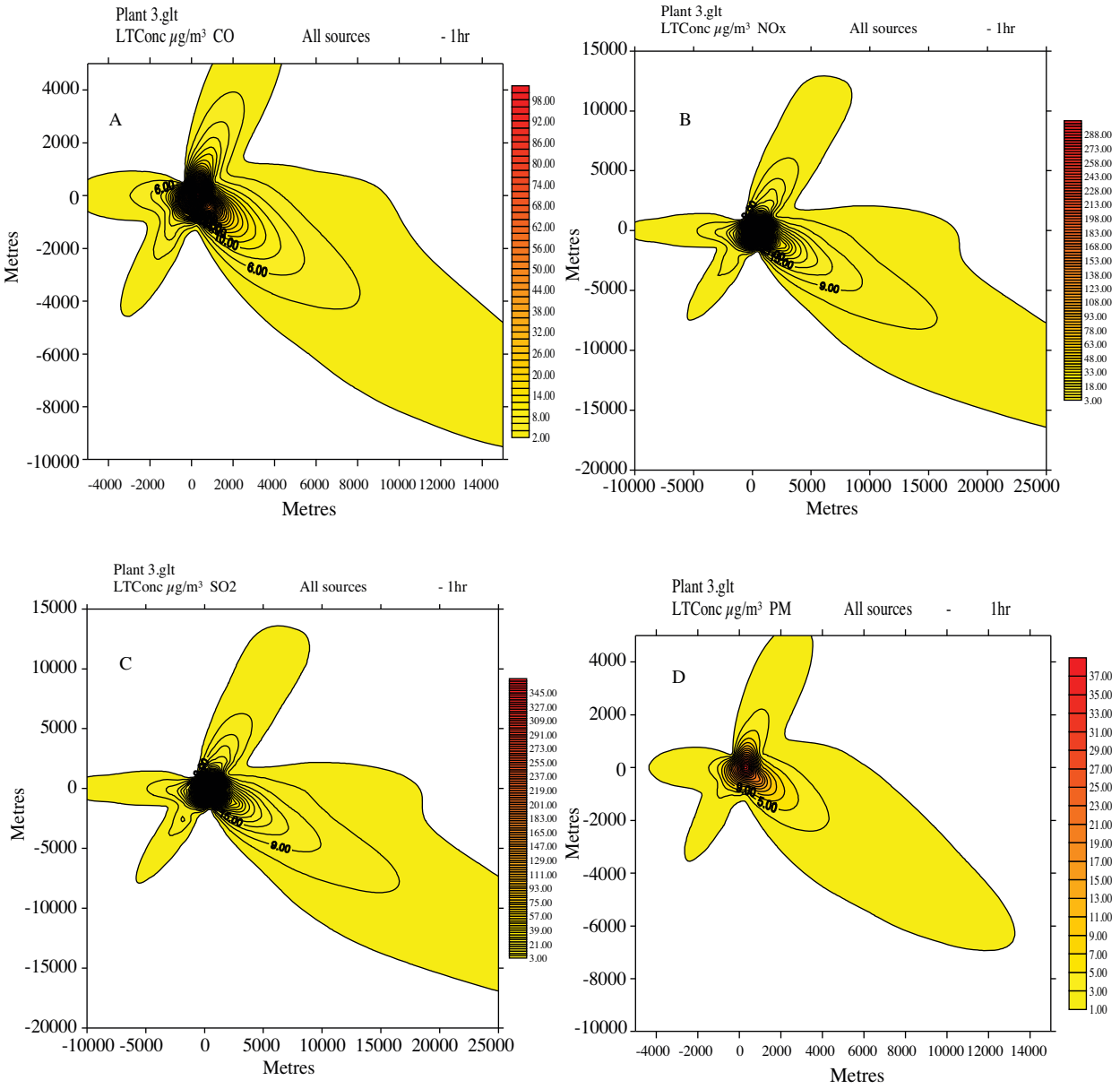

Figure 5. Plume of different pollutants, Thermal Power Plant 3 (long term).

The plumes of emissions of different pollutants from Thermal Power Plant 3 are presented in Figures 5a-5d. The peak concentrations were well predicted at various distances of up to 25,000 m downwind. The concentration of pollutants was very high in the near periphery of the stack, and the plume spread was similar to those of the other 2 plants. The maximum carbon monoxide level predicted was 134.56 μg/m^3 at a distance of 500 m from the source. At distances of 5,000 and 8,000 m, the peak concentrations of carbon monoxide were 6 and 4 μg/m^3, respectively (Figure 5a). The maximum level of oxides of nitrogen predicted was 349.38 μg/m^3 at a distance of 500 m from the source, and it remained very high within a 2,000 m radius of the source. The concentration of oxides of nitrogen at a 5,000 m distance was 15 μg/m^3; this was reduced to 9 μg/m^3 at 10,000 m downwind of the source. A ground level NO_x concentration of 3 μg/m^3 was predicted at 17,000 m downwind

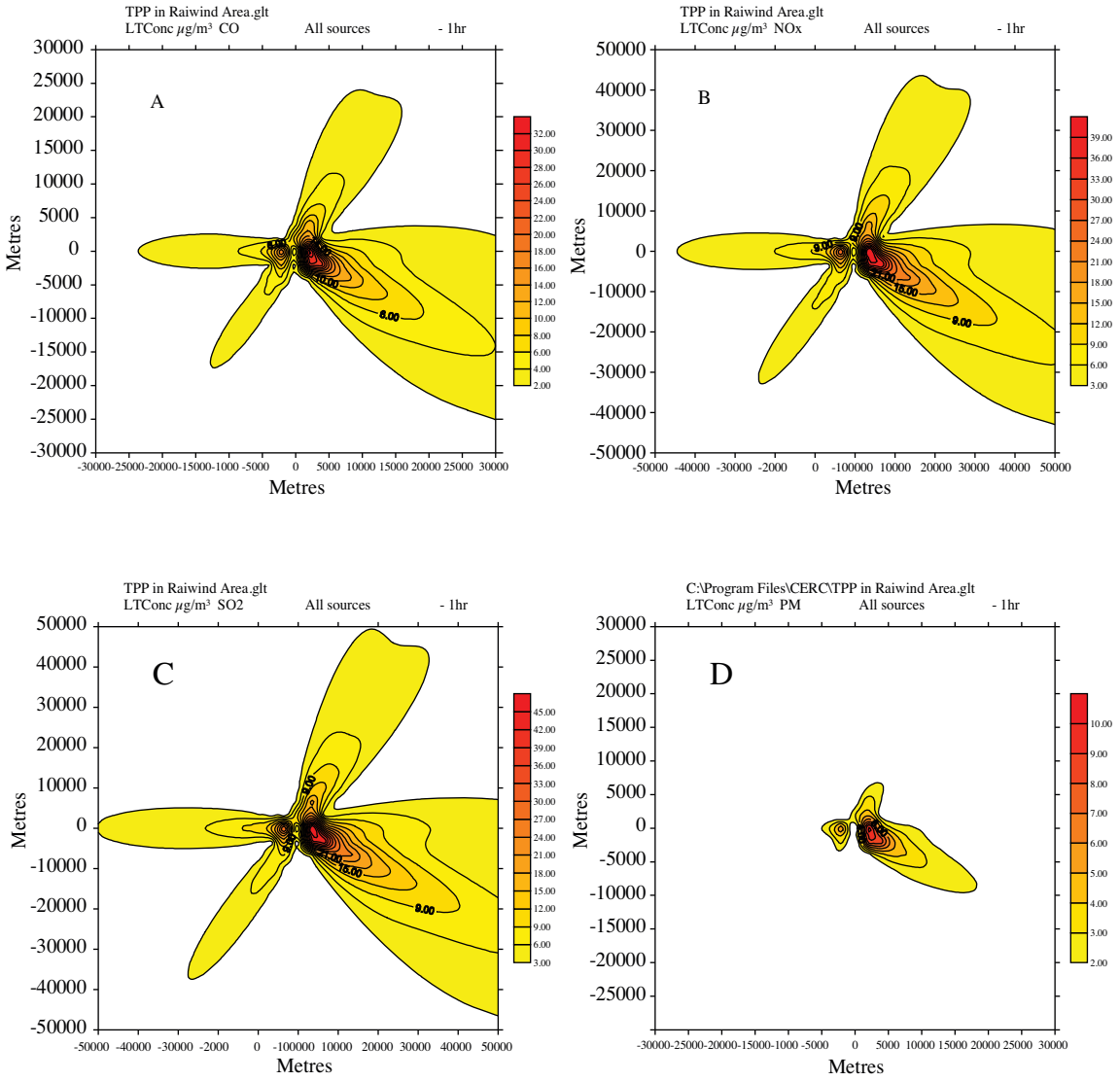

Figure 6. Plume of different pollutants of combined plants of the Raiwind area (long term).

of the source (Figure 5b). The maximum level of sulfur dioxide predicted was 450.94 μg/m^3 at a distance of 500 m from the source. A high level of sulfur dioxide was predicted within a 2,000 m of radius of the source, and at 22,000 m downwind, its concentration was 6 μg/m^3(Figure 5c). The maximum concentration of particulate matter was predicted to be 50.75 μg/m^3 at a distance of 500 m from the source, and at a distance of 4,200 m downwind, its concentration impact was reduced to 3 μg/m^3 (Figure 5d).

The model was also run with the combined input of emissions data from the 3 power plants; the plumes simulated for different pollutants are presented in Figures 6a-6d. The predicted peak concentrations were presented at various distances of up to 50,000 m downwind. The concentration of pollutants was very high within a 5,000 m radius and the maximum carbon monoxide level predicted was 34.74 μg/m^3 at a distance of 2,000 m from the source. At locations closer to the source, the peak concentrations did not follow a similar decreasing trend, which is due to variations in atmospheric conditions and the distances among the power plants. The concentrations of carbon monoxide at distances of 10,000 and 20,000 m downwind were 10 and

6 $\mu g/m^3$, respectively (Figure 6a). The maximum level of oxides of nitrogen predicted was 92.17$\mu g/m^3$ at a distance of 2,000 m from the source, and it remained very high within a 5,000 m radius of the source. The concentration of oxides of nitrogen at a 10,000 m distance was 20 $\mu g/m^3$; it was reduced to 13 $\mu g/m^3$ at 20,000 m downwind of the source. A ground level NO_x concentration of 6 $\mu g/m^3$ was predicted at 50,000 m downwind of the source (Figure 6b). The maximum level of sulfur dioxide from the 3 plants was predicted to be 103.82 $\mu g/m^3$ at a distance of 2,000 m downwind of the source. A high level of sulfur dioxide was predicted within a 10,000 m radius from the sources, and at 30,000 m downwind, its concentration was 12 $\mu g/m^3$ (Figure 6c). The maximum concentration of particulate matter was predicted to be 11.04 $\mu g/m^3$ at a distance of 2,000 m from the source, and at a distance of 10,000 m downwind, its impact was reduced to 3 $\mu g/m^3$ (Figure 6d).

Overall for the 3 power plants, approximately 60% of the total exposure of gaseous pollutants was located within 10 km of the power plants, and another 40% of the exposure occurred within 10-30 km. In contrast, for particulate pollutants, the major exposure (about 50%) occurred within 2 km from each plant site, and the remaining 50% of exposure was within 2-10 km; beyond that point, the impact was minimal. It should be noted that the absolute magnitude of these percentages would differ if the geographic scope of the analysis was changed, but the relative comparisons between different radii would not change.

Results of the dispersion modeling indicate that, using selected sets of meteorological parameters, ADMS predicted the peak concentrations within the plume relatively well. On the other hand, considering that atmospheric conditions vary diurnally, assuming an average set of meteorological parameters oversimplifies the required meteorology for accurate plume and concentration predictions. The sensitivity analysis was conducted using peak concentrations. The resulting data demonstrated that the model was most influenced by variations in wind speed, mixing height, and atmospheric stability. Further analysis considered combinations of minimum, mean, and maximum wind speed and mixing height.

For all cases, using minimum wind speed and maximum mixing height resulted in acceptable model performance. However, a consistent improvement was not observed in all combinations. Increasing the mixing height allows more volume for pollutant dilution, thus resulting in lower concentrations. In contrast, decreasing the wind speed resulted in higher concentrations. It appears that the combination of these extreme values presents an average meteorological scenario and therefore results in acceptable predictions.

In an attempt to improve the graphic representation of the plumes, emission rate and dispersion rates were varied. An increase in the emission rate resulted in a larger plume. Larger dispersion rates represent more dispersion, thus resulting in wider and shorter plumes. However, it was observed that variations in emission rate and dispersion rate did not result in consistent improvement in model performance. Therefore, a few parameters (grid size and scale) were adjusted to improve the graphic representation, and the rest of the model inputs were maintained constant for predictions of peak concentration.

An additional limitation was related to the difficulty of validating the model outputs. For the present study, since the facility of air quality monitoring stations was not available in the country for comparison of the predicted values with the observed values, ADMS had already been validated against a wide range of data sets from different parts of the world (Hanna et al., 1999; Carruthers et al., 2001). The validation confirmed that over flat terrain, in urban and rural settings, the predictions of the model are in reasonable agreement with the observations. Validation of model outputs could be done by comparison with other modeling studies of similar frameworks.

Conclusions

As mentioned earlier, the present study was the first conducted on thermal power plants in Pakistan. In spite of these limitations, we can draw some conclusions from our modeling exercise. The dispersion modeling demonstrates that the concentration impacts of emissions from a small number of power plants are relatively high on an annual average basis. However, long-range transport of pollutants implies that a large number of populations are exposed to these small concentration increments, with critical public health impacts that are potentially significant.

In addition, gaseous and particulate matter appears to contribute a large portion of the concentration and health impacts from the emissions of these power plants, which is also related to both the high current emission rates of SO_2 and NO_x and the long-range transport of secondary pollutants. Finally, our analysis demonstrates that there is a gradient in concentration impacts associated with emissions, which can have direct impact on public or environmental health, and the results of the present study can be used to help focus resources on the most important pollutants.

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