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SUMMARY

The Norwegian Institute for Air Research (NILU) is in collaboration with the Central Pollution Control Board (CPCB) in Delhi performing an air quality programme for the Norwegian Agency for Development Co-operation (NORAD). The project is described in the Agreement between India and Norway in: "Training programme on/Modelling and Surveillance of Dispersion and Movement of Pollutants".

The first phase of the project was to adapt the KILDER modelling system into CPCB's computer, carry out training and present the first model estimates based on the limited data available on emission and meteorology. This report contains the first model estimates of air quality in Delhi.

The model calculations were carried out for four source categories; industrial point sources, small industry, traffic and domestic coal consumption. The major source of sulphur dioxide was the industrial sources (82%). For nitrogen oxides, traffic emitted about 2/3 and point sources 1/3 of the total emissions. For suspended particulate matters, point sources emitted about 37% and small industry about 38% of the total emissions.

The model calculations were carried out for the winter season, and compared with average values at six stations for the period 1987-1989. For sulphur dioxide the model calculations agreed well with the observed values. The highest concentrations were found southeast of the chemical industry and around the small industries.

For nitrogen oxides, maximum winter averaged concentrations up to 100 $\mu g/m^3$ as NO_2 were estimated southeast of Connaught Place. The observed NO_2-concentrations at the six stations varied between 20 and 30 $\mu g/m^3$. The conversion of nitrogen monoxide to nitrogen dioxide is dependent on several factors such as the ozone concentrations available and the photochemical activity in the atmosphere.

The model calculations gave concentrations of particles much less than measured in Delhi. Even after adding a "natural background" dust level of 300 $\mu g/m^3$, the estimated values were still somewhat lower than observed, especially in the high polluted areas.

Stability or turbulence data for Delhi were not available during this phase. The model estimates were therefore based on observed wind measurements and estimated stability. Hourly data of wind and atmospheric stability should be collected for at least one year to obtain a better description of the meteorological conditions in the area.

The traffic emission fields in the first estimates were based upon countings at 15-20 places in Delhi. Several additional countings will be carried out to improve the resolution of the traffic pattern in the city. The traffic countings and the road description will be entered into datafiles to be prepared further by the KILDER supporting programmes.

Detailed consumption data of fossil fuels such as coal, oil, kerosene etc. for domestic use has to be collected. Based upon living standard and population distribution, these data will be distributed within the grid area.

Consumption data and process data for the industry must be improved to better understand the variation and composition of industrial emissions.

Improved emission factors for different types of burning of fossil fuels must be obtained, especially for the particle emissions from domestic use of coal. The traffic emission factors used in these first estimates were based upon the US EPA 1970 standard. The relative old vehicle park in the city and no control of the emissions from the vehicles, indicates that the emission factors will deviate considerably from the factors used, especially for particles.

The quality of the model results strongly depends on the number of well defined industrial point sources. Based on consumption and process data, each major industry with a stack above 20 m should be considered as an industrial point source.

MODEL CALCULATIONS OF LONG TERM AVERAGE CONCENTRATIONS OF SO_2, NO_x AND SPM IN DELHI

1 INTRODUCTION

The Norwegian Institute for Air Research (NILU) is in collaboration with the Central Pollution Control Board (CPCB) in Delhi performing an air quality programme for the Norwegian Agency for Development Co-operation (NORAD). The project is described in the Agreement between India and Norway in: "Training programme on/Modelling and Surveillance of Dispersion and Movement of Pollutants".

The first phase of the project was to adapt the KILDER modelling system for long term average concentration estimates into CPCB's computer, carry out training and present the first model estimates based on the limited data available on emission and meteorology.

This report contains the first estimates of dispersion calculations for Delhi, which is the first of three phases in the project. During the next phases, four local State Pollution Authorities (Talcher, Chambur, Visakhapatnam and Dhanbad) will adapt the KILDER system and carry out similar calculations in these areas.

The model calculations in Delhi were carried out for four source categories (industrial point sources, traffic, small industry and domestic coal consumption) and for three compounds; sulphur dioxide (SO_2), nitrogen oxides (NO_x) and suspended particulate matter (SPM). The averaging period considered was the winter season.

The model calculations were based upon emission data and meteorological data collected by CPCB personell. The evaluation of input data and the results were carried out on CPCB's computer by NILU in collaboration with CPCB.

2 EMISSION INVENTORY

The Central Pollution Control Board has carried out the first emission inventory for Delhi for this study. This contains consumption data of fossil fuels for the source types small industry, power plants and domestic coal consumption. In addition, traffic countings has been used to estimate the traffic work and traffic emissions for the area. The emission data has been collected over a period of about 10 years and will be revised in the next phase.

2.1 THE MODEL GRID AREA

The model grid area for Delhi is 22x24 km^2 as given in Figure 1, which shows the main road net, railways and measurement stations in Delhi. The grid is taken from Delhi Guide Map 1:25000, Third edition 1985, which is the most detailed map we could obtain. A new edition of the map will be issued in the autumn of 1992.

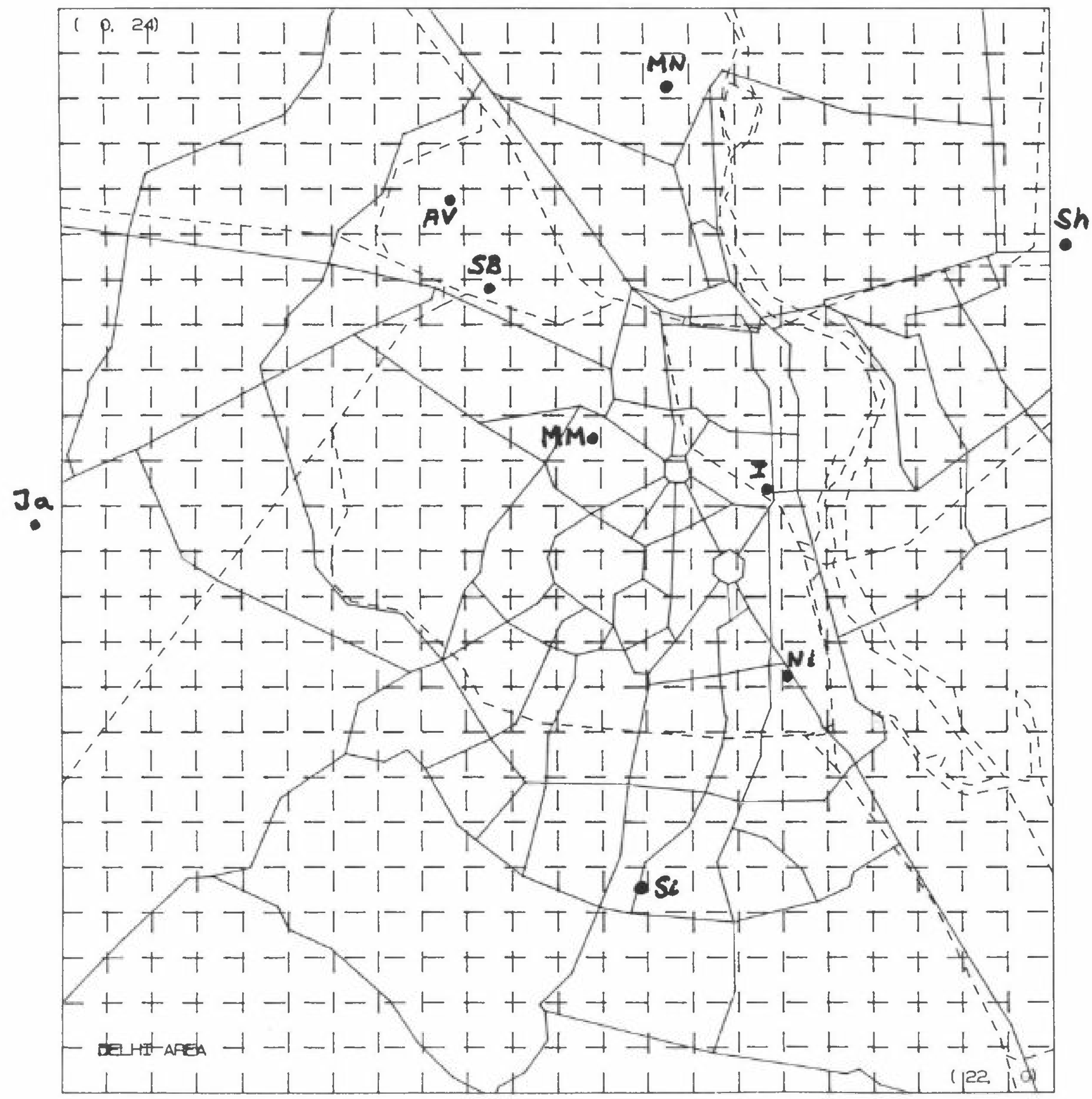

Figure 1: The model grid area for Delhi and measurements stations.
AV = Ashok Vihar, Ja = Janakpuri, I = ITO,
MM = Mandir Marg, MN = Mukherji Nagar,
Ni = Nizamuddin, SB = Shahzada Bagh, Si = Siri Fort
Sh = Shadara.

2.2 SMALL INDUSTRY

There is about twelve well defined industrial areas in Delhi having a wide variety of industrial activities, such as chemical, engineering, rubber and textile. Combustion of coal in hand fired coal units leads to emissions of sulphur dioxide and particles, especially. The emission inventory for the twelve industrial areas were carried out in 1982-83 and the location of the small industry areas is given in Figure 2.

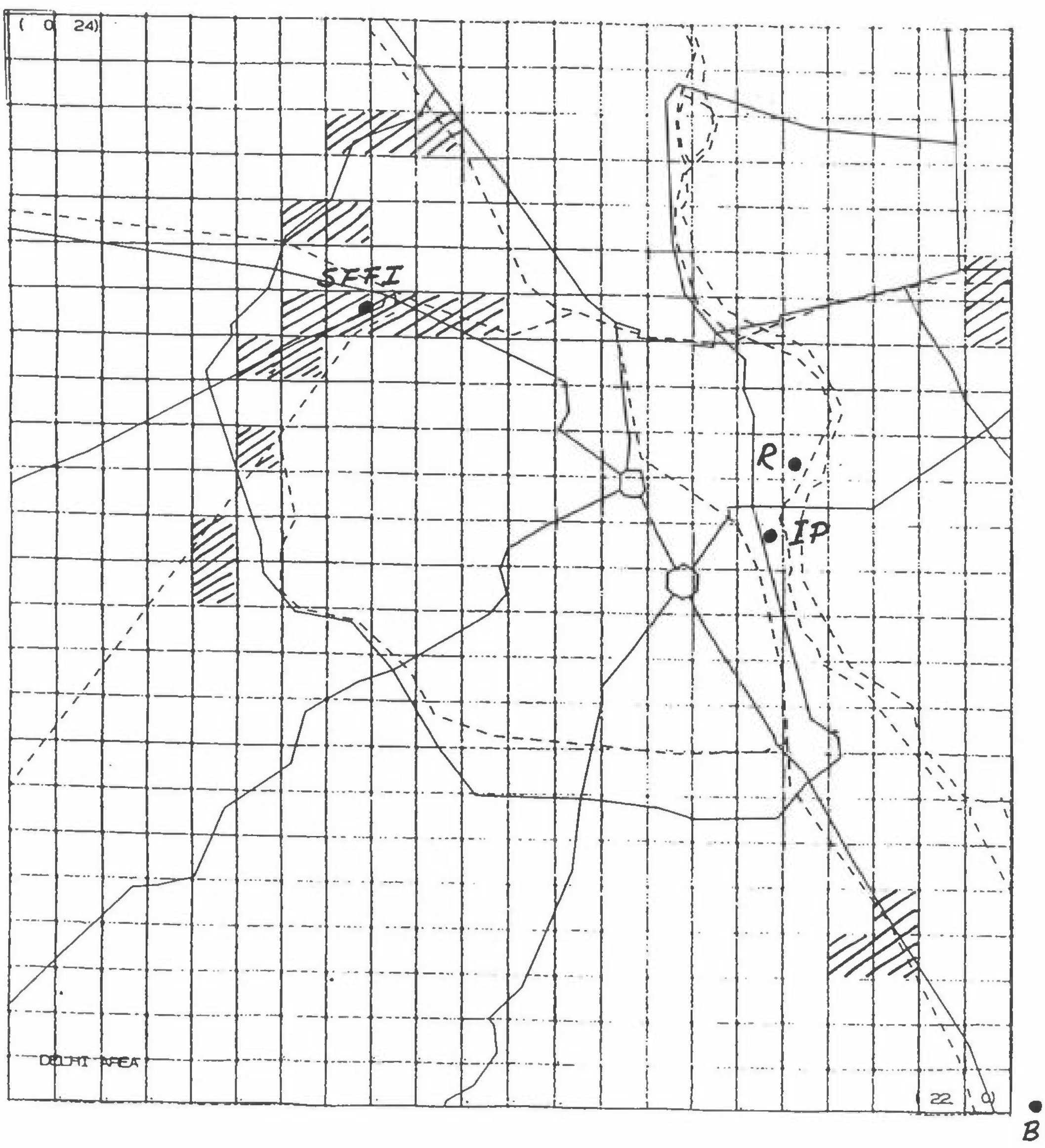

Figure 2: Location of the major point sources and the small industry in Delhi.

Based on consumption data of coal and the emission factors for small industry given in Table 1, the estimated emission rates of SO_2 and NO_x within the grid were 245 kg/h and 46.6 kg/h, respectively. For SPM, separate emission data performed by CPCB gave total emissions of SPM from small industry of about 2 600 kg/h. The emission fields of SO_2 and SPM for small industry is given in Appendix A.

Table 1: Emission factors in kg/tons for small industry (hand fired coal unit).

Source type	SO_2	SPM[2]	NO_x
Small industry	8.0[1]	10.0	1.50

1 Sulphur content: 0.4% S.
2 Not used for small industry.

2.3 INDUSTRIAL POINT SOURCES

The industrial point sources defined at this stage are three power plants and one chemical factory. The power plants are Badarpur, Indraprastha and Rajghat Power Station. These power stations consumes about 4.4 million tonnes of coal each year. The Shriam Foods and Fertilizer Industries (SFFI), located in the north west part of Delhi, has a captive power plant of 22.5 MW. The location of the stacks are shown in Figure 2 and the emission data are given in Table 2.

Table 2: Emission data for the point sources in Delhi.

Name	Utmx km	Utmy km	Hs m	DS m	TG C	VG m/s	SO_2 kg/h	NOx kg/h	SPM kg/h
Badarpur 1	22.50	0.02	154.	6.5	125.	25.	1142.5	1100.0	602.1
Badarpur 2	22.52	0.00	154.	6.5	125.	25.	1328.0	1210.0	914.2
IP 1	16.60	12.73	61.	3.28	150.	7.3	100.8	117.0	183.8
IP 2	16.62	12.75	61.	3.96	110.	14.5	325.4	378.0	52.5
IP 3	16.64	12.77	61.	3.96	125.	13.7	297.4	345.0	48.75
Rajghat	17.22	14.35	160.	3.30	130.	20.0	590.8	600.0	323.3
S.F.F.I. 1	8.02	17.65	32.	1.60	140.	12.0	248.8	86.1	18.2
S.F.F.I. 2	8.01	17.66	32.	1.60	140.	11.8	387.9	86.1	28.4
S.F.F.I. 3	8.03	17.64	32.	1.60	135.	11.6	189.6	86.1	13.9

2.4 TRAFFIC

In the recent years there has been a sharp growth in manufacture and use of automobiles. The fuel consumption in Delhi city in the year 1989 was 244 000 tonnes of petrol and 449 000 tonnes of high speed diesel. The composition of petrol and diesel exhaust is characterized by large amounts of carbon monoxide, hydrocarbons, oxides of nitrogen, particulates and sulphur dioxide. In the absence of any control of the emissions from automobile sources, exhaust gases contribute significantly to urban air pollution.

CPCB har carried out traffic countings for 15-20 major roads in Delhi. Based upon these limited data and local experience in the traffic pattern in Delhi, an emission field of sulphur dioxide from traffic has been established. These emission rates must be taken as preliminary due to the small number of countings carried out so far.

The emission factors used in the model calculations are given in Table 3 (CPCB, 1982). These emission factors are based upon the US EPA factors of 1970. The average emission factors given in the table are estimated by using a relative composition of 65%, 25% and 10% for light, medium, and heavy traffic, respectively.

Table 3: Emission factors (g/km) of pollutants for vehicles in Delhi.

Type of vehicle	SO_2	NO_x	Particulate
Motor cycles (LTV)	0.02	0.07	0.2
Petrol driven cars (MTV)	0.08	3.2	0.33
Diesel driven cars (MTV)	0.39	0.99	0.45
Heavy duty diesel (HTV)	1.5	21.0	0.75
Average values*	0.19	2.89	0.29

* Composition LTV: 65%, MTV: 25%, HTV: 10%.

Figure 4 shows the SO_2 emission field from traffic based upon the traffic countings performed by CPCB and the emission factors given in Table 3. The total emission rates of SO_2 , NO_x and SPM from traffic are estimated to 448 kg/h, 6 815 kg/h and 681 kg/h , respectively.

24	0	0	0	0	10	0	8	12	15	6	0	0	3	4	10	0	0	2	0	0	0	1
23	0	0	0	0	8	0	8	10	20	20	15	6	12	8	20	15	13	12	12	10	6	0
22	0	0	0	6	6	12	8	20	20	14	25	20	15	8	10	0	0	8	6	4	6	0
21	0	8	13	8	10	12	12	12	12	12	12	12	15	15	12	0	0	5	6	2	12	0
20	8	8	2	2	5	8	18	8	12	6	6	15	15	15	20	0	0	5	6	2	6	0
19	4	12	8	10	10	15	15	15	15	15	15	15	15	8	15	4	0	5	6	5	6	0
18	4	15	10	10	12	15	15	10	12	3	15	12	25	30	25	20	10	12	20	20	15	8
17	8	6	15	20	20	25	25	15	12	15	30	25	25	20	30	30	12	0	20	20	10	4
16	8	6	8	12	15	20	15	12	12	20	20	25	20	25	25	30	30	0	6	10	10	8
15	10	6	15	15	15	15	12	5	5	12	12	8	20	25	25	20	15	0	0	8	6	10
14	8	6	6	10	12	15	12	6	6	5	5	20	25	35	30	25	15	0	0	10	10	6
13	4	10	10	10	10	5	5	5	0	5	0	18	30	25	25	30	10	8	0	0	8	2
12	4	8	12	10	10	10	10	6	0	5	0	10	20	20	20	25	0	8	0	0	6	12
11	4	6	6	4	4	6	6	6	10	8	15	15	10	15	15	15	15	10	0	0	0	10
10	2	6	6	6	8	8	6	6	15	12	15	10	15	15	15	15	6	6	6	0	0	6
09	6	6	4	4	8	4	6	6	15	15	10	10	10	12	10	10	10	12	12	0	0	4
08	3	4	4	6	6	6	6	6	10	10	10	15	15	15	10	15	15	15	15	6	0	2
07	2	2	0	0	2	4	2	2	6	10	8	10	15	12	8	15	15	15	12	12	6	0
06	0	0	0	0	2	2	0	0	6	10	10	10	15	12	6	15	12	12	15	12	4	0
05	0	0	0	0	0	0	0	0	0	8	8	15	15	12	10	15	12	12	15	4	2	0
04	0	0	0	0	0	0	0	0	0	4	4	8	10	10	8	12	12	10	8	12	2	0
03	0	0	0	0	0	0	0	0	0	0	0	8	8	10	4	4	4	6	8	8	8	0
02	0	0	0	0	0	0	0	7	0	4	8	4	6	6	8	4	2	2	0	4	6	8
01	0	0	0	0	0	0	0	2	8	8	4	0	0	2	8	10	10	12	10	2	2	8
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

Figure 4: Estimated emission field of sulphur dioxide (0,1 kg/h) from traffic in Delhi.

2.5 DOMESTIC COAL CONSUMPTION

A major fuel for domestic heating and cooking in Delhi are coal. In the model calculations, an annual consumption of 363 000 tonnes is assumed. The domestic coal consumption are distributed homogeneously within six different areas. These areas have been given a ratio of the total annual consumption based on way of living. The major consumption of coal for domestic use was assumed to be in Old Delhi and Shahdara, while no consumption of coal were assumed in the south west part of Delhi. The consumption distribution of coal is given in Appendix B.

The emission rates of SO_2, SPM and NO_x were estimated based on the emission factors of hand fired coal units. The total emissions of SO_2, SPM and NO_x from domestic coal consumption within the grid was 331 kg/h, 415 kg/h and 62 kg/h, respectively.

3 METEOROLOGY

3.1 WIND SPEED AND WIND DIRECTION

The model calculations should be carried out for the whole winter season. Based on statistical evaluations of five years of wind measurement in Delhi (Murty and Tangirala, 1990), measurements at Mukherji Nagar in January 1989 were selected as the most representative month for the winter season. The wind direction frequency distribution within twelve wind sectors for daytime hours and for the whole period is given in Figure 5.

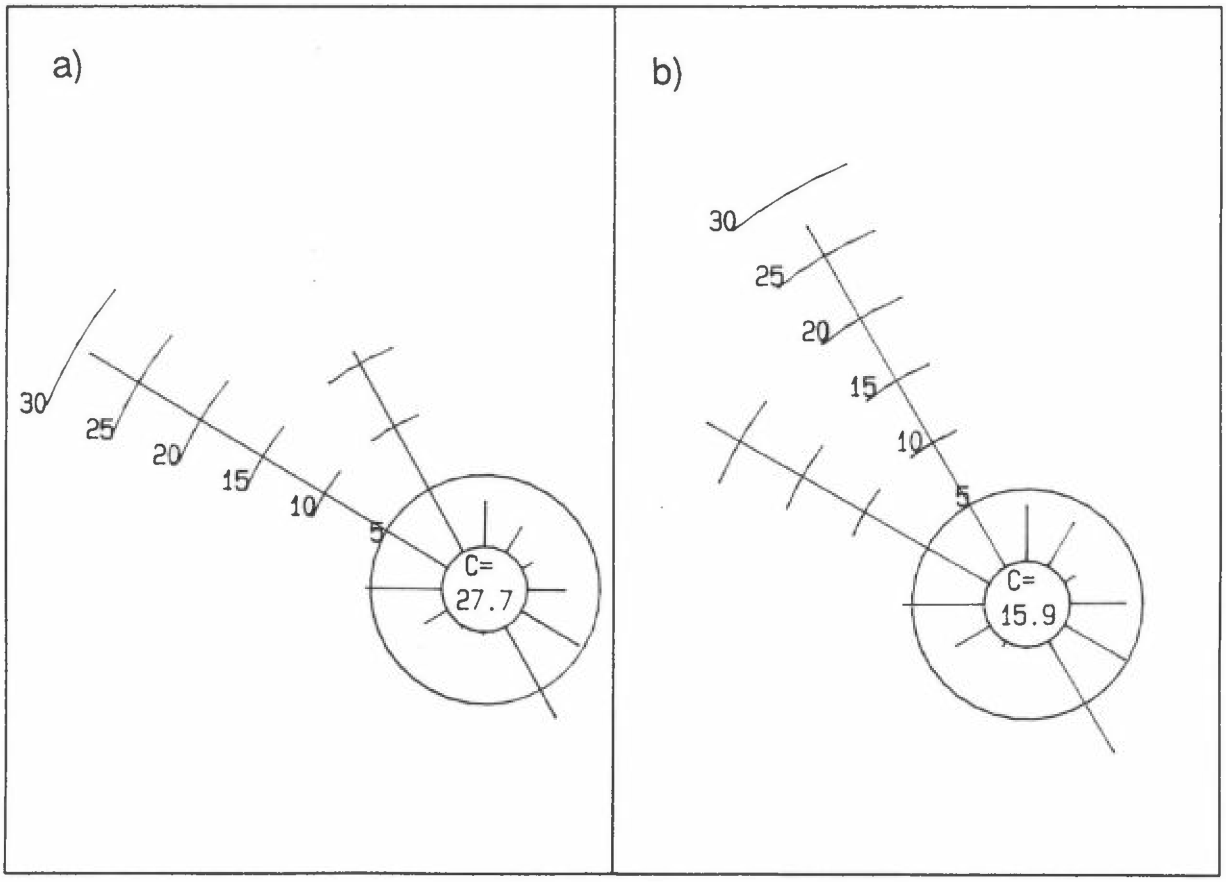

Figure 5: Wind direction frequency distribution for January 1989 at Mukherji Nagar within 12 wind sectors.
a) All hours included.
b) Daytime hours (08-19).

Figure 5 shows that the main wind direction during the winter season are wind from around north west (300°-330°) in about 45% of the period. Winds from south and south-southwest (180°-210°) occurred less than 0.2% of the period. The highest wind speed occurred during the afternoon hours with average values of 3.3-3.6 m/s. The highest wind speeds occurred during winds from north and west (330°) with average windspeed for the period of 3.7 m/s. The average wind speed for the whole month was 2.6 m/s. The daytime averaged windrose gave higher occurrence of wind from north-northwest (330°) compared to the whole period. Statistical evaluation of wind speed and wind direction for January 1989 is given in Appendix C.

3.2 STABILITY DISTRIBUTION

The stability distribution was evaluated by using the Pasquill-Gifford scheme. Based upon information of wind speed and time of the day, hourly classification of stability into four classes were estimated for January 1989. The average diurnal variation of stability within the four stability classes unstable, neutral, slightly stable and stable for January 1989 is given in Figure 6.

The figure shows a clear diurnal variation of stability, with 70-80% occurrence of unstable before noon, 50-60% neutral in the afternoon and 80-40% stable condition between sunset and sunrise. Averaged for the whole month, the occurrence of unstable, neutral, slightly stable and stable conditions was 25.0%, 23.5%, 16.8% and 34.7%, respectively.

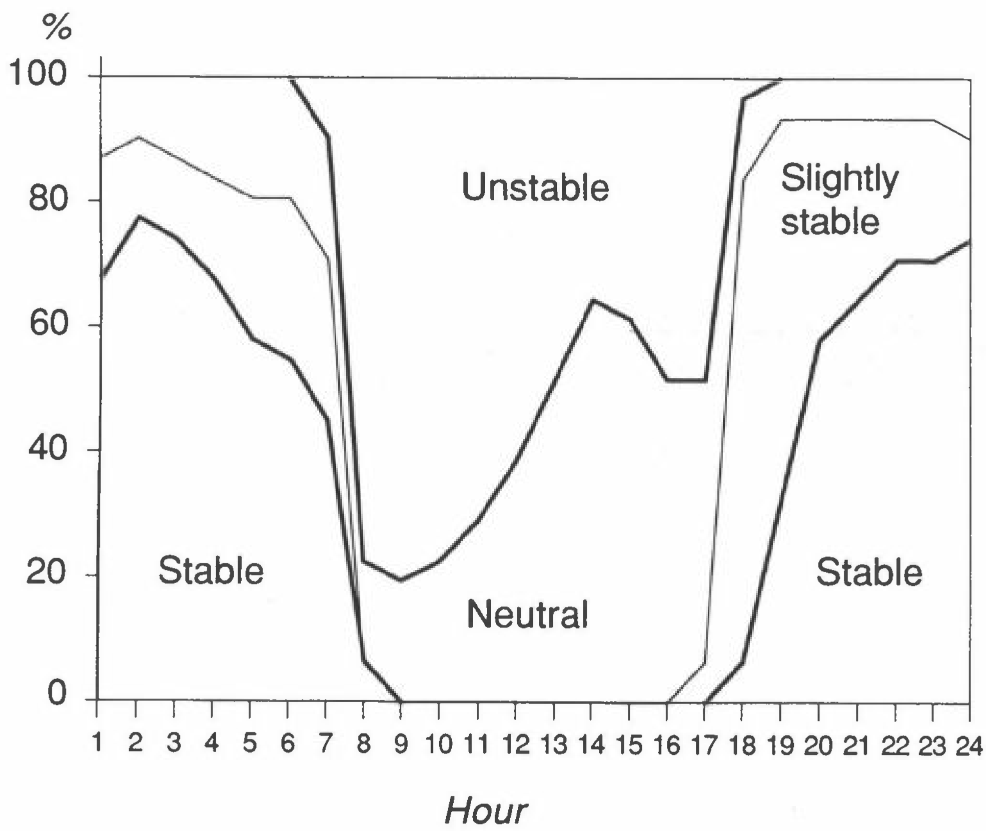

Figure 6: Estimated diurnal variation of stability in Delhi January 1989.

4 AIR QUALITY MEASUREMENTS IN DELHI

CPCB has carried out air quality measurements at several places in Delhi. A monitoring programme of six stations of the compounds SO_2, NO_x, and SPM in the period 1987-89 was used for model evaluation. The measurements have been carried out between 0600 and 2200 and with about 7-10 daily measurements at each location per month. The location of the monitoring stations are given in Figure 1.

The average winter concentrations of SO_2, NO_2, and SPM for the period 1987-1989 are given in Table 4. The monthly averaged values for each station is given in Bøhler, 1990.

Table 4: Winter averaged concentrations of SO_2, NO_2 and SPM at six stations in Delhi in 1987-1989. (Maximum monthly value in parentesis.)

Station	SO_2	NO_2	SPM
Ashok Vikar	5.5 (8)	20 (24)	493 (900)
Janakpuri	9.4 (20)	20 (27)	329 (440)
Nizamuddin	14.0 (19)	17 (30)	375 (485)
Shahdara	16.0 (20)	23 (30)	362 (560)
Shahzada Bagh	27.0 (60)	28 (35)	600 (900)
Siri Fort	3.5 (4)	20 (31)	320 (370)

The highest concentration of SO_2 were observed at Shahzada Bagh, located in between Wazipur (northwest) and the industrial areas south of the railway. The SO_2-concentrations measured at Ashok Vihar were low taken into account the high SPM-values and the location east-southwest of the Wazipur industrial area. The SO_2-values at Siri Fort were also very low. The reason for this might be the influence of lime dust from the stone crushing industry in the analyzing results. Continuous monitoring of SO_2 at Siri Fort indicates that the measurements in 1987-1989 was too low.

The NO_2-concentrations shows small variations within the model area. This indicates that traffic is the main source and that ozone probably is the limiting factor of conversion of nitrogen monoxide to nitrogen dioxide.

Measurements of particulates (SPM) shows the highest concentration around the small industry (Shahzada Bagh and Ashok Vihar). The seasonal average SPM-values were all above the air quality guideline of 200 $\mu g/m^3$ recommended by the World Health Organisation (WHO).

5 MODEL CALCULATIONS FOR THE WINTER SEASON

NILU and CPCB has calculated long term daytime average concentrations of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulates (SPM). The KILDER modelling system have been used to perform emission fields from consumption data and to carry out dispersion calculations for point and area sources. The model calculations have been carried out for four source categories; industrial point sources, small industry, traffic and domestic coal consumption. It was assumed continuous emissions from the industrial point sources. For traffic, coal and small industry it was assumed that 80% of the emission takes place during day time hours (08-19) and 20% in the night time (20-07).

5.1 THE KILDER MODELLING SYSTEM

The model system KILDER consists of a series of programmes to estimate

- emission rates
- dispersion from:
  - point sources
  - area sources
  - volume sources
  - line sources
- concentration distributions.

In this part of the project we have estimated the seasonal average ground level concentration due to emissions from point and area sources in the area.

The dispersion from point sources are treated by the Gaussian plume equations. For estimation of long term average concentrations, sector average concentrations are assumed in the lateral direction. Vertical spread is simulated by a diffusion parameter defined as the standard deviation of the

normal concentration distribution.
When vertical wind fluctuation measurements (turbulence) are not available, the diffusion parameters are taken from empirical data as a function of downwind distance (x):

$$\sigma_z(x) = bx^q$$

where b and q are empirical constants given for the four classes of stability described in Chapter 3.

The wind speed variation with height above the surface is estimated from a simple power law profile:

$$\bar{u}(z) = \bar{u}(z_1)\ (z/z_1)^m$$

where z_1 is the anemometer height above the ground, m is an empirical wind profile exponent given as a function of stability.

The effective source height is taken as the sum of the stack height and a plume rise estimated from the equations given by Briggs. Building turbulence and stack downwash can also be included in these calculations.

An area source represents the emission from several small sources within a grid square, mostly from domestic heating, small industries and road traffic. The emission field is often calculated from fields with coal and oil consumption or traffic work.

In the program AREA-KILDER the pollution contribution from an area source is taken into account by considering 100 point sources evenly distributed over the square-km. The contribution from an area source is tabulated as a function of distance, wind speed and dispersion conditions. Actual concentration values are calculated by linear interpolation between tabulated values.

Each area source is assigned to a box class, which defines the height of the initial vertical turbulence elements, which again is a function of the average building height in the grid square considered. A detailed description of the models is given in separate users guides. (Gram and Bøhler, 1992).

5.2 THE METEOROLOGICAL FREQUENCY MATRIX

The model calculations were carried out as daytime averages to be compared with the daytime averaged measurements carried out in 1987-89. The daytime joint frequency distribution of four wind speed classes, four stability classes and twelve wind sectors for January 1989 is given in Table 5.

Table 5: Daytime joint frequency distribution of wind speeds, stability and wind directions at Mukherji Nagar in January 1989.

JOINT FREQUENCY DISTRIBUTION OF STABILITY, WIND SPEED AND WIND DIRECTION

Class I: Unstable
Class II: Neutral
Class III: Light stable
Class IV: Stable

Wind-direction	.0- 1.0 m/s				1.0- 2.0 m/s				2.0- 3.0 m/s				over 3.0 m/s				
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	Rose
30	2.2	.0	.3	.0	1.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	3.5
60	.3	.0	.0	.0	.3	.0	.0	.0	.3	.0	.0	.0	.0	.0	.0	.0	.8
90	.8	.0	.3	.0	.3	.0	.3	.0	.3	.0	.0	.0	.3	1.6	.0	.0	3.8
120	.3	.0	.3	.3	1.3	.0	.3	.0	.5	.0	.3	.0	.3	1.3	.0	.0	4.8
150	2.2	.0	.0	.0	2.2	.0	.3	.0	2.7	.0	.0	.0	.0	1.6	.0	.0	8.9
180	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
210	.0	.0	.0	.0	.3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.3
240	1.3	.0	.3	.3	.5	.0	.0	.0	.3	.0	.0	.0	.0	.0	.0	.0	2.7
270	1.6	.0	.8	.0	1.3	.0	.5	.0	.5	.0	.0	.0	.0	.8	.0	.0	5.6
300	2.7	.0	1.1	.0	2.7	.0	.8	.0	2.2	1.1	.0	.0	.8	11.3	.0	.0	22.6
330	1.9	.0	.3	.0	4.3	.0	.8	.0	3.2	1.6	.5	.0	.3	14.5	.0	.0	27.4
360	.5	.0	.3	.0	.3	.0	.3	.0	.3	.3	.0	.0	.0	1.9	.0	.0	3.8
Calm	9.9	.0	1.6	4.3													15.9
Total	23.7	.0	5.1	4.8	14.5	.0	3.2	.0	10.2	3.0	.8	.0	1.6	33.1	.0	.0	100.0

The matrix gives similar wind direction distribution compared to the whole month, with main wind direction around northwest in about 50% of the period. The occurrence of calm, however, have been reduced from 26% to 12%. The average wind speed for the day time hours was 2.9 m/s compared to 2.6 m/s when all hours are included.

5.3 THE INITIAL BOX HEIGHT FOR THE AREA SOURCES

The KILDER area source dispersion model contains an initial dilution of the area sources which is representative for the obstructions within each source grid. For buoyant emissions, an average plume rise must be added to the average building height in each square grid. The average building height or typical obstruction heights in each grid were estimated and the four box codes were distributed as shown in Appendix D. The height for the box codes is given in Table 6.

Table 6: Initial box height for the area sources.

Area type	Code	Box height	Emission height
Rural	1	10	10 (2)*
Urban, small	2	20	20 (2)*
Urban, high	3	30	30 (2)*
Small industry	4	25 (15)*	25 (2)*

* Traffic emission.

The box code distribution in Appendix D reflects that the highest buildings occurred around Connaught place, while at the edges of the grid, especially in the southwest part, there were open flatland or small buildings which gave the lowest box height of 10 m.

5.4 AVERAGE SO_2-CONCENTRATIONS FOR THE WINTER SEASON

By using the emission inventory presented in Chapter 2 and the joint frequency matrix for daytime hours given in Chapter 5.2, averaged SO_2-concentrations for the winter season were calculated for each source category. The total SO_2-concentration distribution for all source categories is presented in Figure 8. The impact of sulphur dioxide from each source category is given in Appendix E.

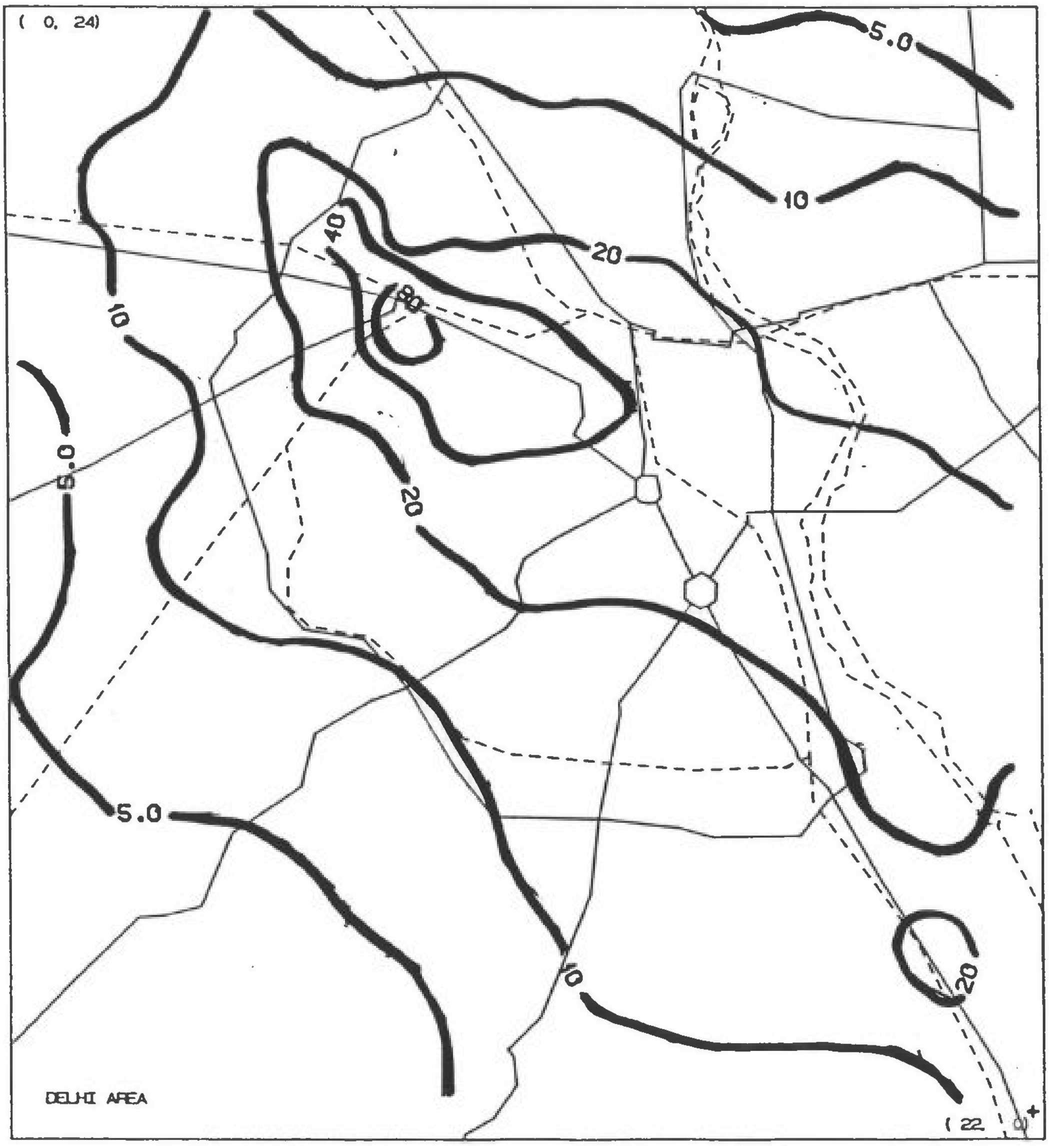

Figure 8: Concentration distribution of sulphur dioxide (µg/m³) from all source categories for the winter season.

The highest impact of sulphur dioxide occurred southeast of the SFFI chemical factory in Delhi. The average SO_2-concentrations for the winter season in this area was around 80 $\mu g/m^3$. The chemical industry contributed with around 85% of the impact of sulphur dioxide in this area.

The domestic consumption of coal lead to maximum SO_2-concentration of 5-8 $\mu g/m^3$ in old Delhi for the winter season. The small scale industry gave similar contribution (5-10 $\mu g/m^3$) in the grid squares were they were located. Emissions of sulphur dioxide from traffic gave maximum impact of around 5 $\mu g/m^3$ southeast of Connaught Place.

5.5 AVERAGE NO_x-CONCENTRATIONS FOR THE WINTER SEASON

The two main sources to nitrogen oxides (NO_x) are traffic and the industrial point sources. The concentration distribution of NO_x from all source categories for the winter season is given in Figure 9. The impact of NO_x from each source category is given in Appendix F.

Figure 9 shows that the highest impact of NO_x occurred southeast of Connaught Place. The average NO_x-concentration in this area was around 100 $\mu g/m^3$. The contribution from traffic to the total impact of nitrogen oxides in this area was about 95%.

The highest NO_x-concentration contribution from small industry and domestic coal consumption was around 1 $\mu g/m^3$. NO_x-emissions from the point sources gave winter average concentrations up to about 15-20 $\mu g/m^3$.

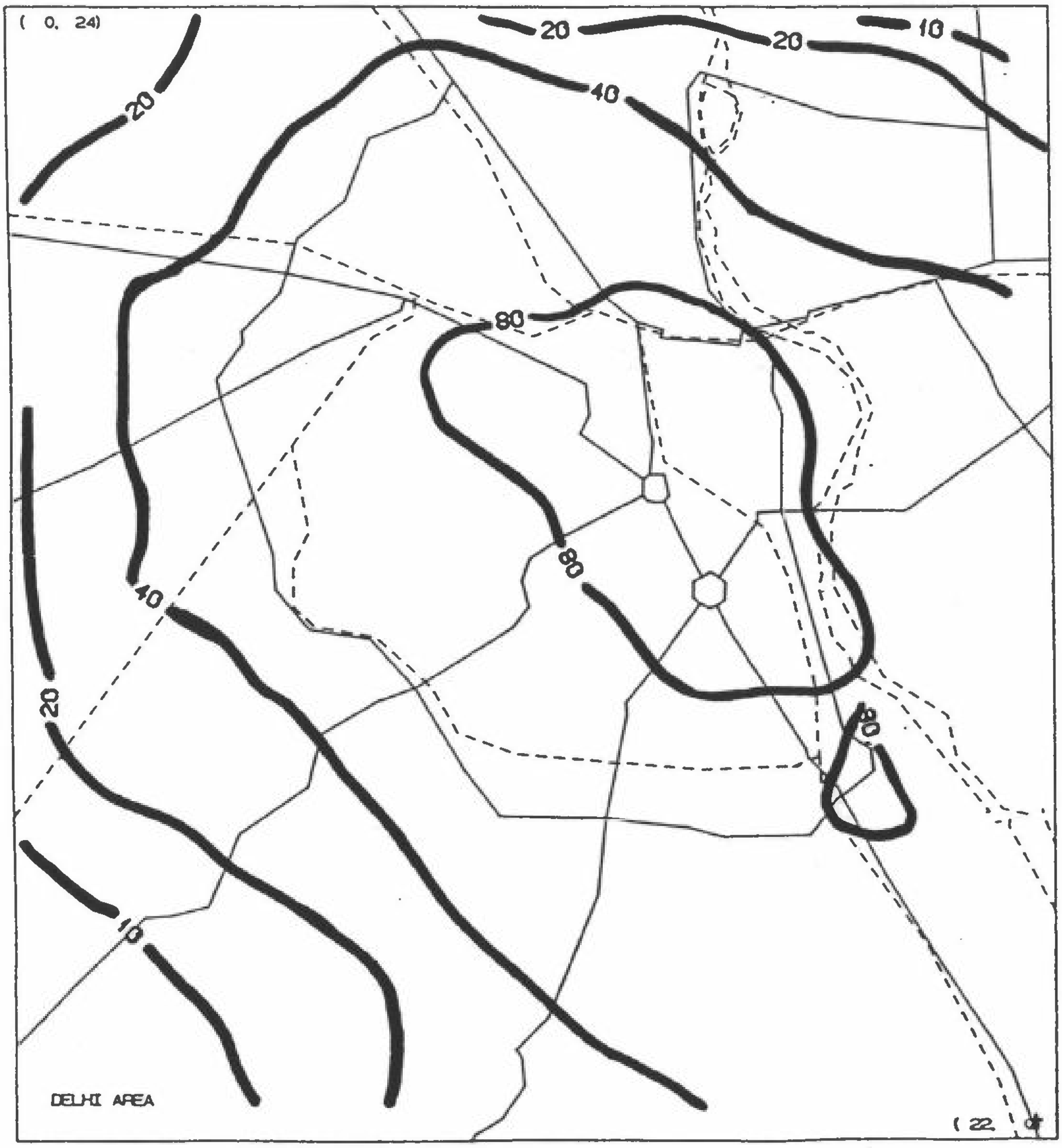

Figure 9: Concentration distribution of nitrogen oxides (µg/m³) from all source categories for the winter season.

5.6 AVERAGE SPM-CONCENTRATIONS FOR THE WINTER SEASON

The main sources for emissions of particles are the industrial point sources and small industry. The emission factors for particles for traffic is probably too low, taken into account the old and not adjusted engines in the vehicles in Delhi. The concentration distribution of SPM from all source categories for the winter season is given in Figure 10. The impact of NO_x from each source category is given in Appendix G.

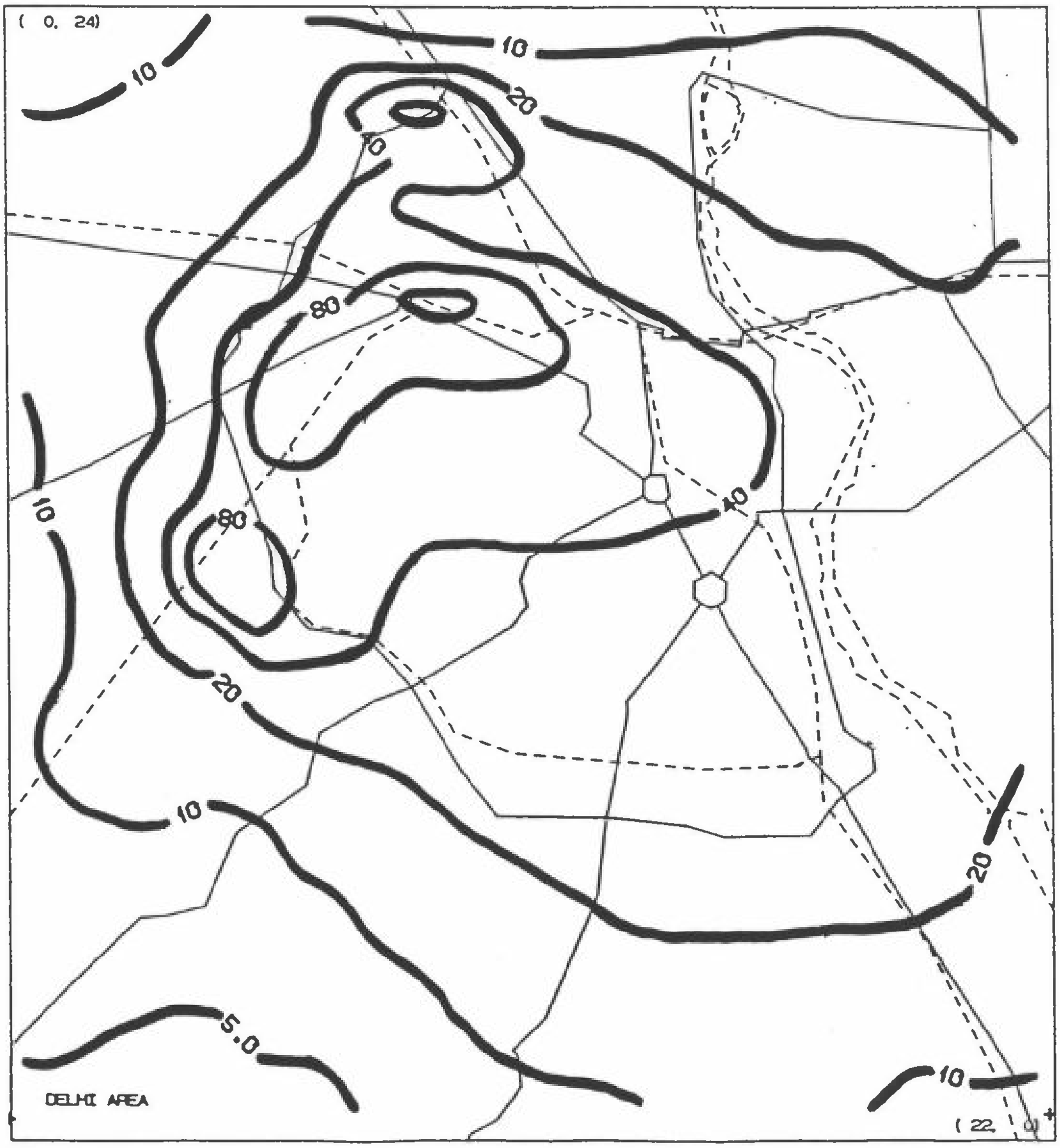

Figure 10: Concentration distribution of SPM ($\mu g/m^3$) from all source categories for the winter season.

The highest impact of SPM in the winter season occurred around the small industry south of the northern railway. The highest SPM-concentrations in this area were around 150 µg/m^3. The contribution from small industry to the total impact in this area was around 90%.

The emissions of SPM from domestic coal consumption and traffic lead to highest impact up to about 10 µg/m^3 at Old Delhi and southeast of Connaught Place, respectively. The contribution from industrial point sources gave highest impact of SPM of about 5-10 µg/m^3 southeast of the chemical factory and 2-3 km southeast of the I.P. Power Station.

6 SOURCE CONTRIBUTION AND MODEL EVALUATION

The four source categories considered in these first estimates of impact of SO_2, NO_x and SPM in Delhi were industrial point sources, small industry, traffic and domestic coal consumption. The total emissions of the three compounds SO_2, NO_x and SPM from each source category within the grid area are given in Table 7.

Table 7: Annual averaged emissions (kg/h) of SO_2, NO_x and SPM from each source category.

Source type	SO_2	NO_x	SPM
Traffic	448.0	6 814.0	686.0
Small industry	245.0	46.6	2 596.0
Point sources	4 611.0	4 008.0	2 185.0
Coal consumption	332.0	62.4	415.0
Total	5 637.0	10 931.0	5 881.0

The industrial point sources contribute with 82% of the total SO_2-emissions and 37% of the total NO_x- and SPM-emissions. The major source for NO_x-emissions was traffic, which contribute with around 62% of the total emissions.

The source contribution to the total impact in the areas with highest concentrations for each compound is given in Figure 11. The location of the maximum impact areas is shown in figures 8-10.

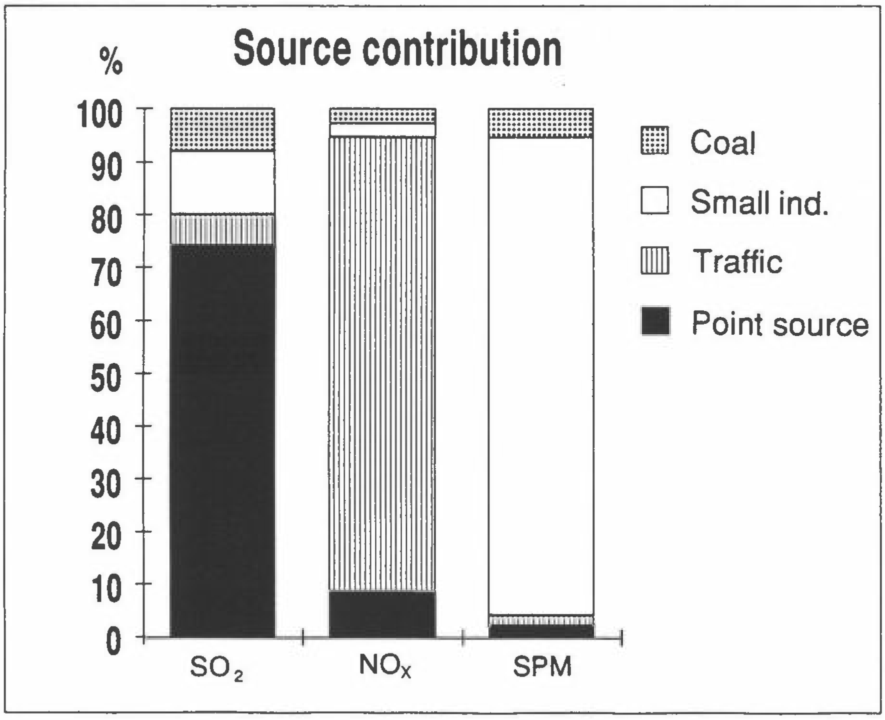

Figure 11: The impact of each source category in the areas for highest concentrations for each compound.

Figure 11 shows that the low sources (small industry and traffic) gave the highest relative impact for NO_x and SPM, while point sources, highest impact of SO_2. While the point sources contributed with 37% of the total SPM- emission, the impact in the maximum area was around 1%. The highest estimated SPM-concentrations from point sources was 5-8 $\mu g/m^3$ which was less than 5% of the highest observed SPM-concentrations.

The maximum impact of sulphur dioxide from industrial point sources was around 75% og the total in the area southeast of the SFFI chemical industry. These stacks are low (32 m) with low exit gas velocity which lead to small plume rise and high impact. The high stacks at the Rajghat and Badarpur Power Plants gave small contributions for all compounds.

The NO_x-emissions from traffic contributed with about 91% of the impact in the highest concentration area of nitrogen oxides. The point sources contributed with about 1/3 of the emissions and gave highest impact around 8% of the maximum NO_x-concentrations for the winter season.

To evaluate the first estimates of averaged concentrations for the winter season, observed and estimated concentrations of SO_2 and SPM for the winter season is presented in Figure 12.

The comparison between observed and estimated values of sulphur dioxide shows good agreement for the three stations Shahzada Bagh, Nizamuddin and Shahdara, while the estimated values were too high for Siri Fort and Ashok Vihar. However, later measurements on these location shows that these values probably were too low. At Janakpuri, which is located at the western edge of the grid area, the observed values was higher than the estimated. The reason for this is that the upwind sources in the main wind direction are outside the grid area and not included in the model calculations. The model itself can handle sources outside the grid area when they are included in the emission inventory.

For SPM, a natural background of 300 $\mu g/m^3$ due to dust was added. The comparison shows that the estimated values were smaller than the observed for all stations, especially in the high polluted areas. The reason for this can be too small emissions factors, especially from domestic coal consumption and traffic.

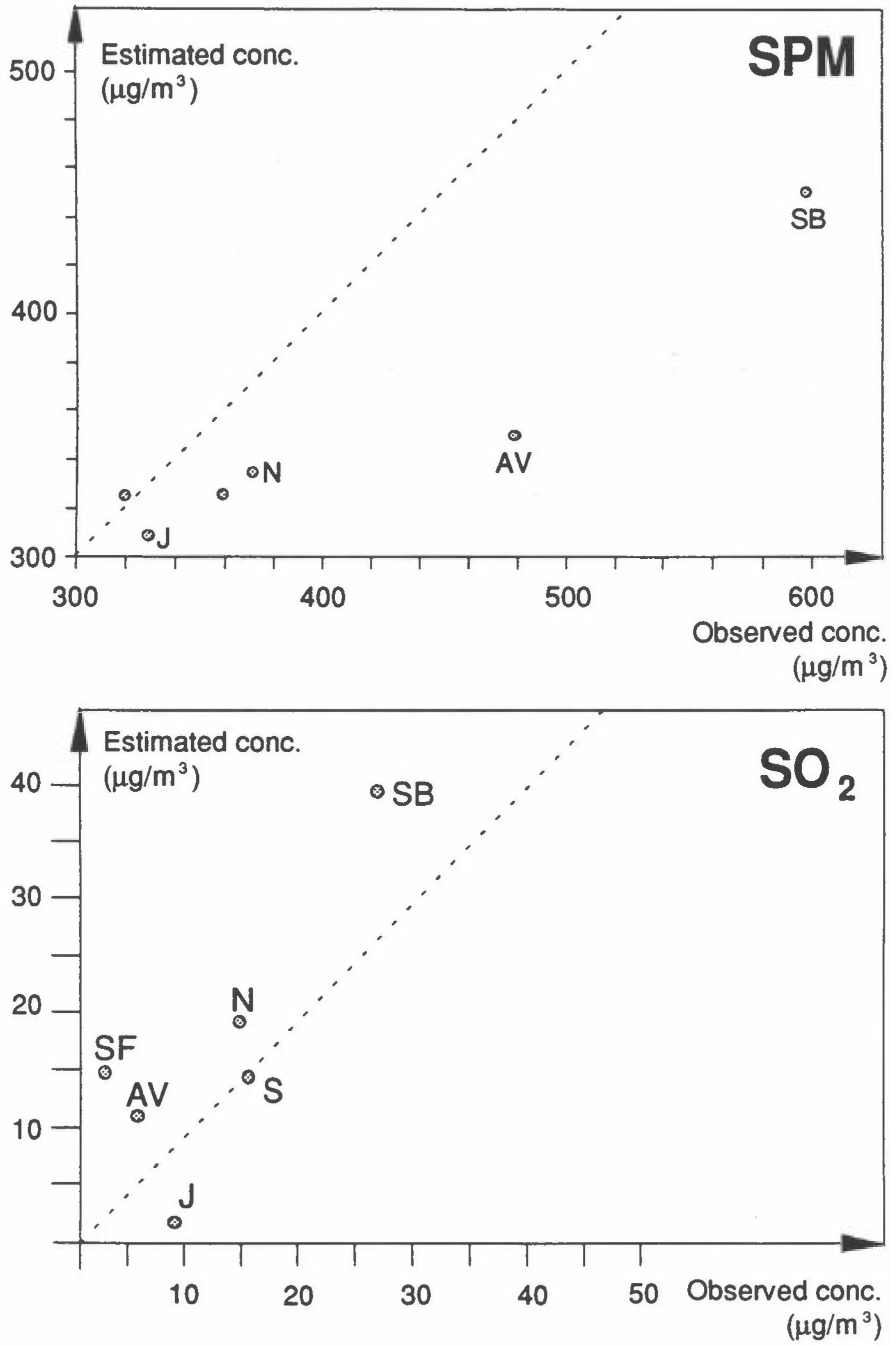

Figure 12: Comparison of observed and estimated concentrations of sulphur dioxide and SPM for the winter season. SPM: Background of 300 µg/m³ is added.

For nitrogen oxides, only the measurements of nitrogen dioxide has been carried out. The observed values of NO_2 varies between 20-30 $\mu g/m^3$, while the estimated NO_x-concentration varies between 60-100 $\mu g/m^3$. The estimated NO_x-concentrations are the maximum values of NO_2 that can be observed dependent on the amount of ozone available and other photochemical activities in the polluted atmosphere over Delhi.

7 DISCUSSION AND RECOMMENDATIONS

NILU and CPCB has in collaboration carried out the first model estimates of long term averaged concentration distribution of SO_2, NO_x and SPM in Delhi for the winter season. These estimates were carried out for training purposes of the NILU KILDER modelling system, and were based on limited information of emissions and meteorology.

The model calculations were carried for four source categories; industrial point sources, small industry, traffic and domestic coal consumption. The major source of sulphur dioxide was the industrial sources (82%). For nitrogen oxides, traffic emitted about 2/3 and point sources 1/3 of the total emissions. For suspended particulate matters, point sources emitted about 45% and small industry about 38% of the total emissions.

The model calculations were carried out for the winter season, and compared with average values at six stations for the period 1987-1989. For sulphur dioxide the model calculations agreed well with the observed values, with the highest concentrations southeast of the chemical industry and around the small scale industries.

For nitrogen oxides, maximum winter averaged concentrations up to 100 $\mu g/m^3$ as NO_2 were estimatetdsoutheast of Connaught Place. The observed NO_2-concentrations at the six stations varied between 20 and 30 $\mu g/m^3$. The conversion of nitrogen monoxide to nitrogen dioxide is dependent in several factors such as the ozone concentrations available and the photochemical activity in the atmosphere.

The model calculations gave winter averaged concentrations of particles much lower than observed. Even after adding a "natural background" dust level of 300 $\mu g/m^3$, the estimated values were still too low, especially in the high polluted areas.

In the next phase of the project, the KILDER modelling system will be adapted to four State Pollution Control Boards (Talcher, Dhanbad, Chambur and Visakhapatnam). In Delhi, the emission inventory and the emission factors have to be improved to obtain better agreement between observed and estimated values, especially with respect to particles.

The model estimates were based on wind measurements only. Hourly data of wind and atmospheric stability should be collected for at least one year to obtain a good description of the meteorological conditions in the area.

The traffic emission fields in the first estimates were based upon countings at 15-20 places in Delhi. Several additional countings will be carried out to improve the resolution of the traffic pattern in the city. The traffic countings and the road description will be entered into datafiles to be prepared further by the KILDER supporting programs.

Detailed consumption data of fossil fuels such as coal, oil, kerosene etc. for domestic use has to be collected. Based upon living standard and population distribution, these data will be distributed within the grid area.

Consumption data and process data for the industry must be improved to better understand the variation and composition of industrial emissions.

Improved emission factors for different types of burning of fossil fuels must be obtained, especially for the particle emissions from domestic use of coal. The traffic emission factors used in these first estimates were based upon the US EPA 1970 standard. The relative old vehicle park in the city and no control of the emissions from the vehicles, indicates that the emission factors will deviate considerably from the factors used, especially for particles.

The quality of the model results strongly depends on the number of well defined industrial point sources. Based on consumption and process data, each major industry with a stack above 20 m should be considered as an industrial point source.

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APPENDIX A

The SO_2 and SPM emission fields for small industry

Sulphur dioxide (kg/h)

SO2 KG/HR ANNUAL AVERAGE DELHI 1000 1.0

24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	6	12	12	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
18	0	0	0	0	0	0	6	8	25	20	12	0	0	0	0	0	0	0	0	0	0	18
17	0	0	0	0	0	20	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	18	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

Particles (kg/h)

(2X,22F3.0)

SPM KG/HR ANNUAL AVERAGE DELHI 1000 1.0

24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	85	169	85	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	55	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
18	0	0	0	0	0	0	64	85	264	211	126	0	0	0	0	0	0	0	0	0	0	10
17	0	0	0	0	0	211	240	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	352	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	18	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

APPENDIX B

Consumption distribution
of coal in Delhi
Unit: 10 tons/year

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
J=24	0.	0.	0.	0.	50.	0.	0.	50.	50.	50.	0.	0.	50.	0.	50.	0.	0.	264.	264.	0.	0.	0.
J=23	0.	0.	0.	0.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	0.	0.	264.	264.	264.	264.	0.
J=22	0.	0.	0.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	0.	0.	264.	264.	264.	264.	264.
J=21	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	0.	0.	264.	264.	264.	264.	264.
J=20	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	0.	0.	264.	264.	264.	264.	264.
J=19	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	50.	0.	0.	264.	264.	264.	264.	264.
J=18	50.	50.	50.	50.	50.	50.	50.	50.	400.	400.	400.	400.	400.	400.	400.	400.	400.	0.	264.	264.	264.	264.
J=17	0.	50.	50.	50.	50.	50.	50.	400.	400.	400.	400.	400.	400.	400.	400.	400.	400.	0.	264.	264.	264.	0.
J=16	50.	50.	50.	50.	50.	50.	50.	50.	50.	400.	400.	400.	400.	400.	400.	400.	400.	0.	0.	264.	264.	264.
J=15	50.	50.	50.	50.	50.	50.	50.	0.	50.	50.	400.	0.	0.	0.	0.	400.	400.	400.	0.	264.	264.	264.
J=14	50.	50.	50.	50.	50.	50.	50.	0.	50.	0.	0.	0.	0.	0.	0.	0.	400.	0.	0.	264.	264.	264.
J=13	50.	50.	50.	50.	50.	0.	50.	0.	0.	0.	0.	0.	0.	0.	0.	0.	400.	0.	0.	264.	264.	264.
J=12	50.	50.	50.	50.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	31.	0.	0.	0.	264.	264.
J=11	0.	50.	50.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	31.	0.	0.	0.	264.	264.
J=10	50.	50.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	0.	0.	0.	264.
J= 9	50.	50.	0.	0.	0.	0.	0.	0.	31.	31.	0.	0.	0.	0.	31.	31.	31.	31.	31.	0.	0.	0.
J= 8	50.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	0.	0.
J= 7	50.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	0.
J= 6	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.
J= 5	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	0.	0.
J= 4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	0.	31.
J= 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.	31.
J= 2	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	31.	31.	31.	31.	31.	0.	31.	0.	31.	31.	0.
J= 1	0.	0.	0.	0.	0.	0.	0.	0.	31.	31.	31.	0.	0.	31.	31.	31.	31.	31.	31.	0.	0.	0.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

APPENDIX C

Statistical evaluation of the wind measurements
at Mukherji Nagar

Station : MUKHERJI NAGAR
Period : JANUARY 1989

DIURNAL VARIATION OF WIND DIRECTIONS (%)

*) Wind-direction	Hours 01	04	07	10	13	16	19	22	Wind-rose
30	3.3	.0	.0	.0	3.2	9.7	3.2	.0	2.0
60	.0	.0	.0	3.2	.0	3.2	.0	.0	.8
90	3.3	6.5	3.2	3.2	9.7	3.2	.0	.0	2.6
120	.0	.0	9.7	3.2	3.2	3.2	12.9	6.5	4.6
150	6.7	3.2	.0	6.5	12.9	9.7	3.2	6.5	7.2
180	.0	.0	.0	.0	.0	.0	.0	.0	.1
210	.0	.0	.0	.0	.0	.0	.0	.0	.1
240	.0	3.2	3.2	.0	3.2	.0	.0	.0	1.8
270	3.3	12.9	19.4	3.2	3.2	.0	3.2	.0	5.3
300	33.3	29.0	22.6	41.9	12.9	9.7	29.0	41.9	28.9
330	10.0	3.2	.0	9.7	45.2	45.2	12.9	.0	15.9
360	3.3	.0	.0	6.5	3.2	6.5	.0	3.2	3.1
Calm	36.7	41.9	41.9	22.6	3.2	9.7	35.5	41.9	27.7

Wind speed < .20 m/s = calm
Wind direction 0 = 360

Nobs	(30)	(31)	(31)	(31)	(31)	(31)	(31)	(31)	(741)
Average wind m/s	1.3	1.1	1.2	2.1	3.6	3.3	1.1	1.1	1.9

DISTRIBUTION OF WINDSPEED WITH WIND DIRECTIONS (%)

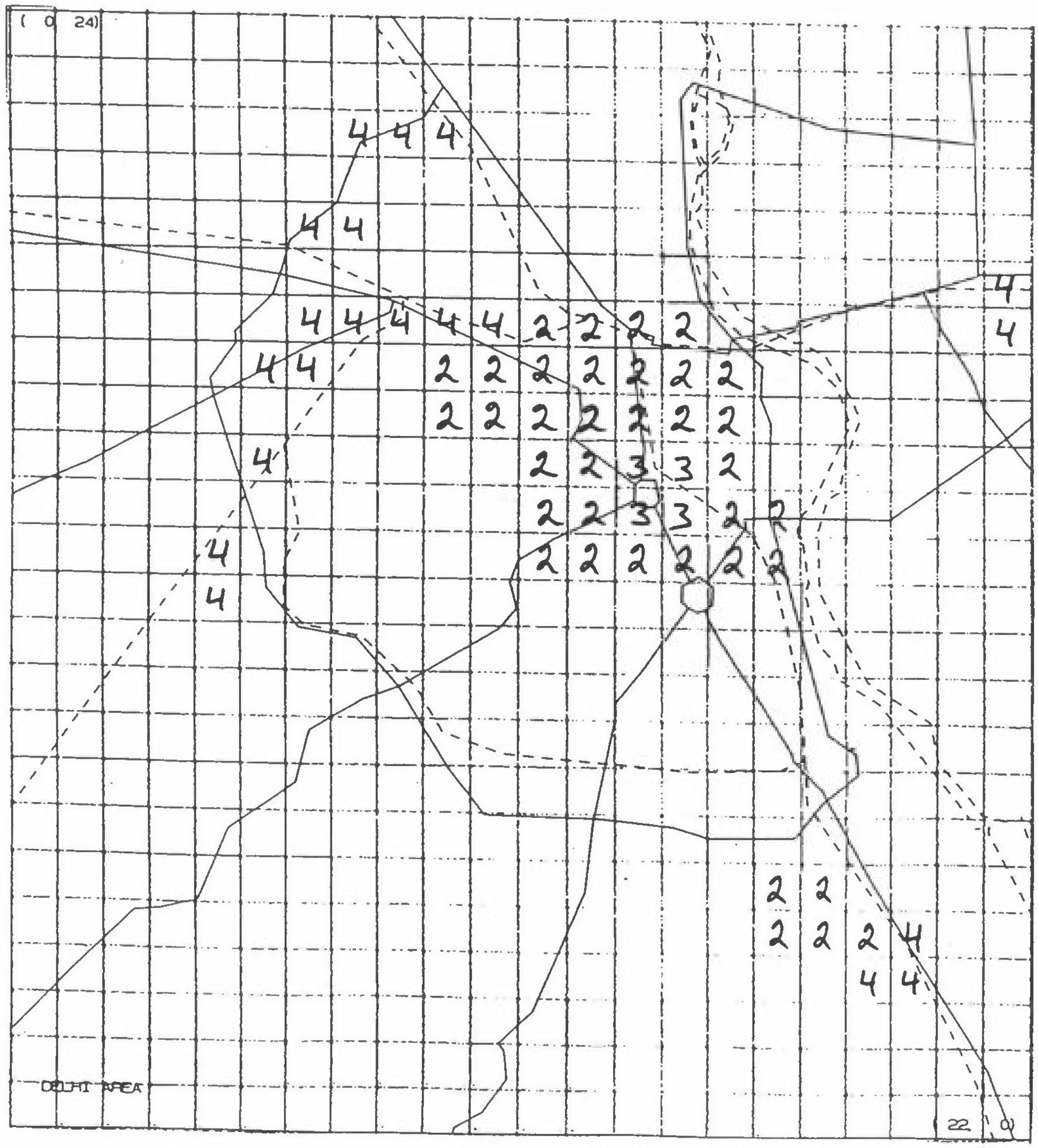
Class I: Windspeed .3 - 1.0 m/s
Class II: Windspeed 1.1 - 2.0 m/s
Class III: Windspeed 2.1 - 3.0 m/s
Class IV: Windspeed > 3.0 m/s

*) Wind-direction	Classes I	II	III	IV	Total	Nobs	Average wind m/s
30	1.5	.5	.0	.0	2.0	(15)	.8
60	.4	.3	.1	.0	.8	(6)	1.3
90	.7	.7	.1	1.1	2.6	(19)	2.9
120	1.2	1.5	.7	1.2	4.6	(34)	2.2
150	1.9	2.4	1.8	1.1	7.2	(53)	2.0
180	.1	.0	.0	.0	.1	(1)	.3
210	.0	.1	.0	.0	.1	(1)	1.5
240	1.1	.4	.3	.0	1.8	(13)	1.1
270	2.4	1.8	.7	.4	5.3	(39)	1.6
300	6.1	6.7	5.9	10.1	28.9	(214)	2.7
330	2.2	3.1	3.0	7.7	15.9	(118)	3.7
360	1.5	.4	.3	.9	3.1	(23)	2.1
Calm					27.7	(205)	
Total	19.0	17.9	12.8	22.5	100.0	(741)	
Average wind m/s	.7	1.6	2.7	4.9			1.9

*) This number indicates central direction of sector

APPENDIX D

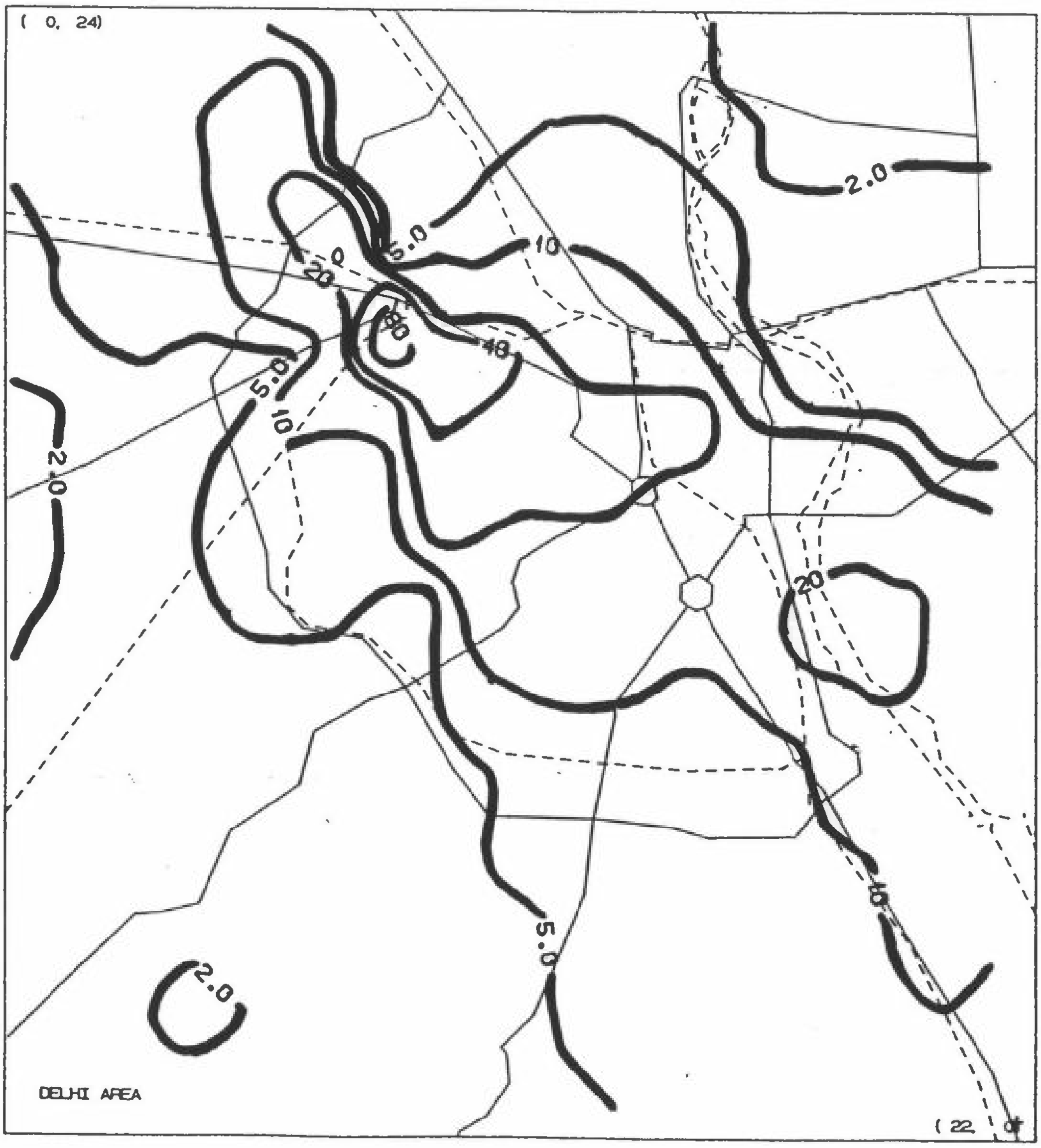
The distribution of
the box codes within the grid area



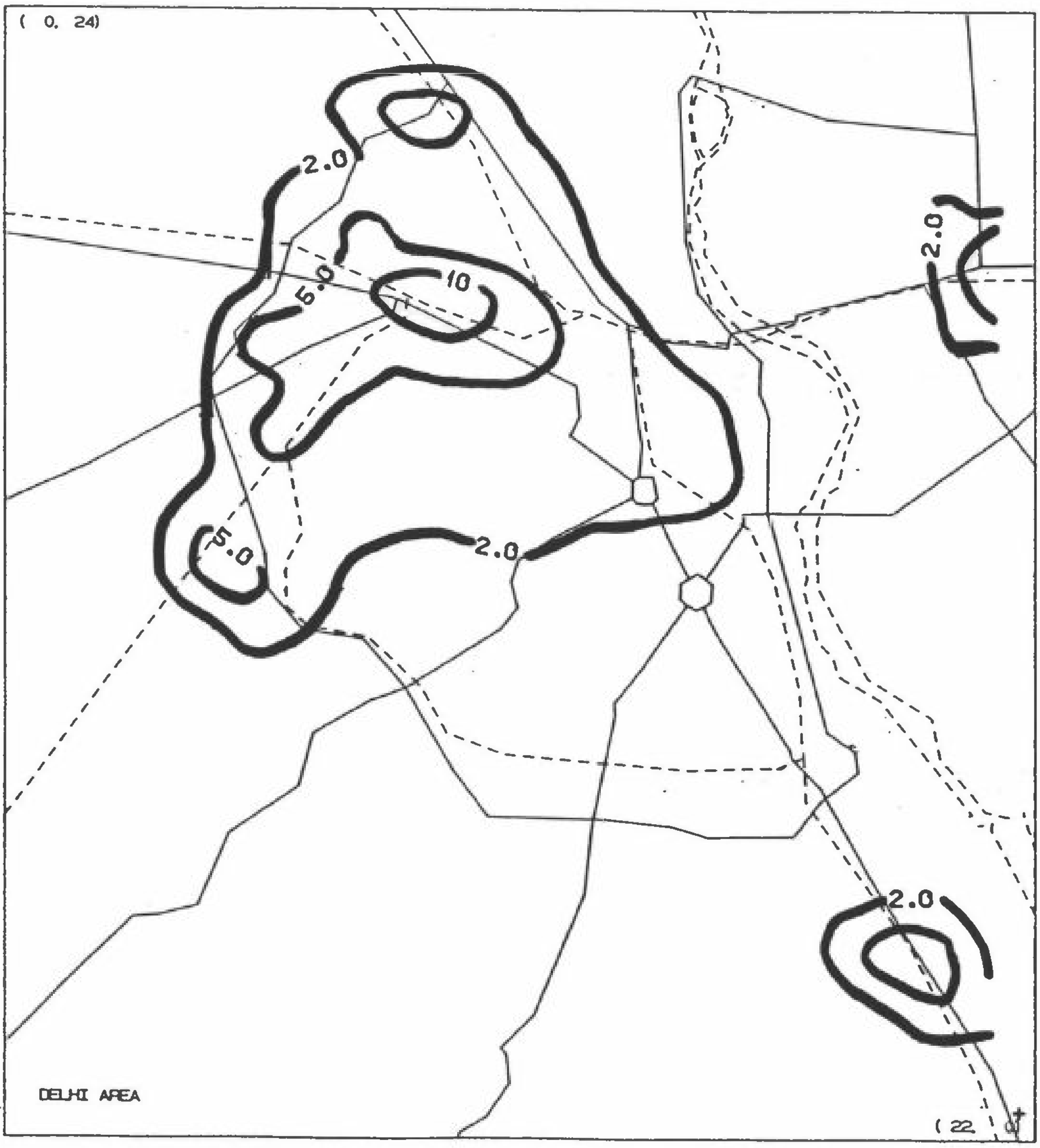
Box codes for KILDER calculations in Delhi
when different from 1.

APPENDIX E

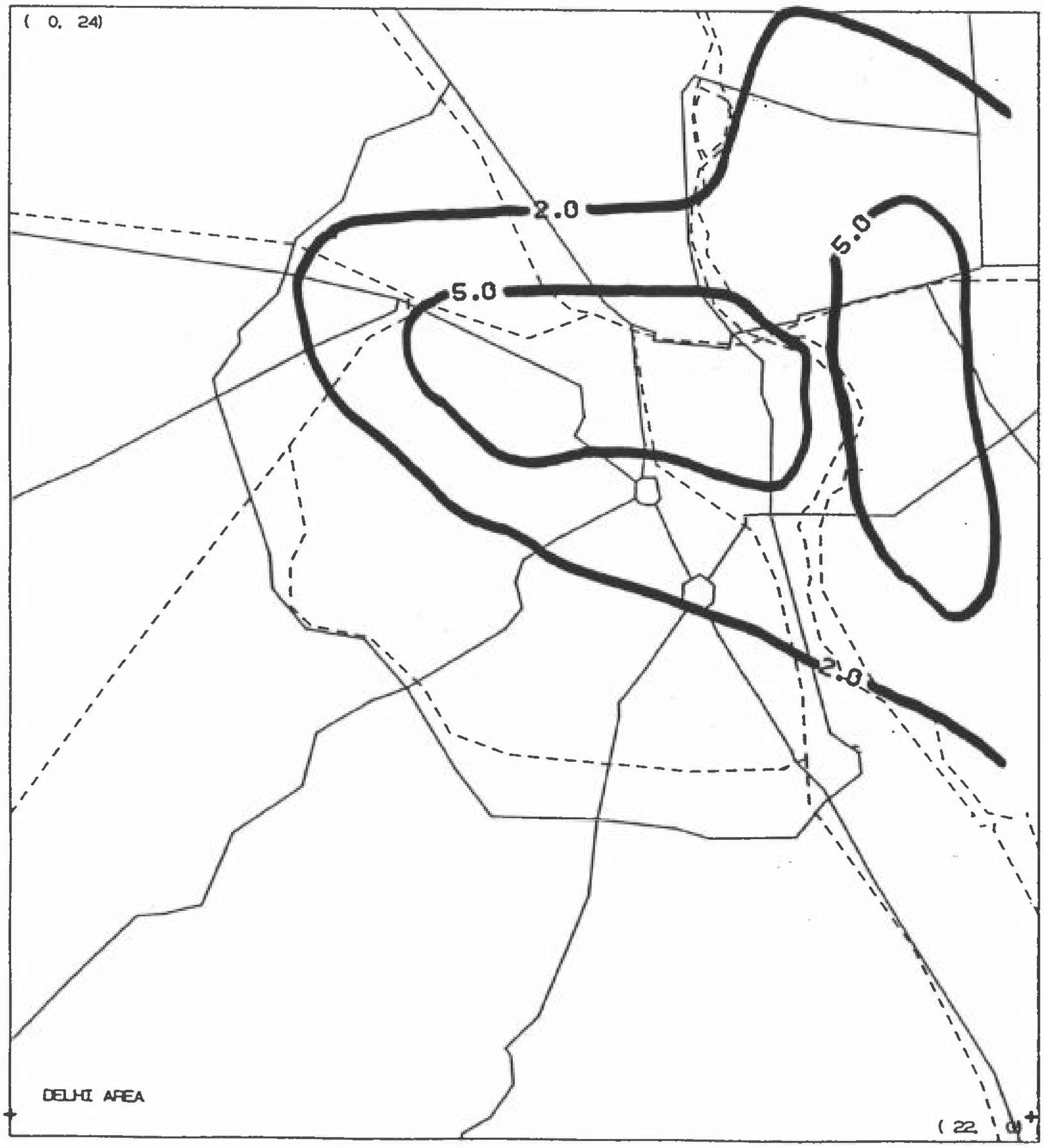
Impact of sulphur dioxide
from each source category



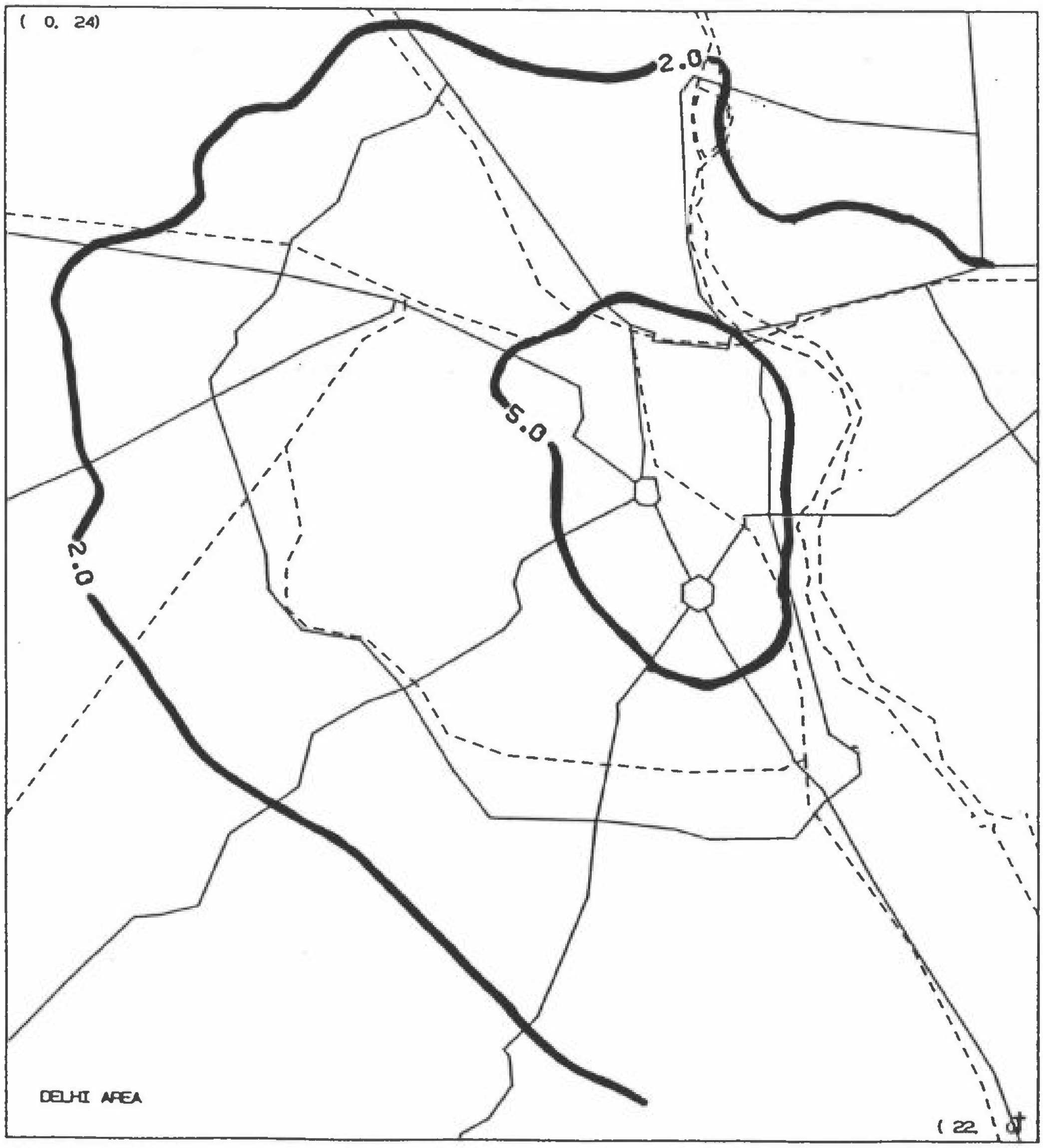
Impact of SO_2 ($\mu g/m^3$) from point sources.



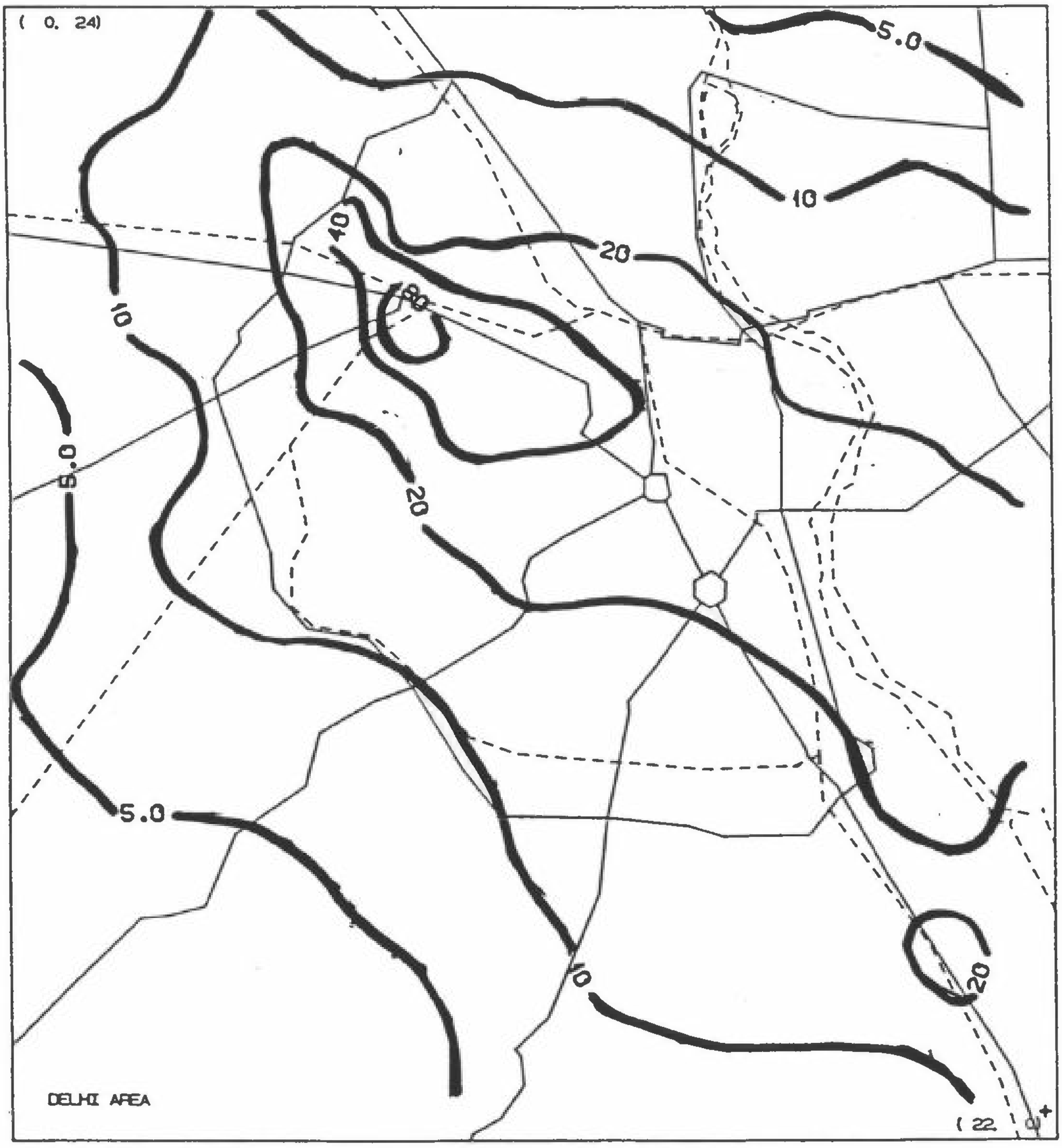
Impact of SO_2 ($\mu g/m^3$) from small industry.



Impact of SO_2 ($\mu g/m^3$) from coal consumption.



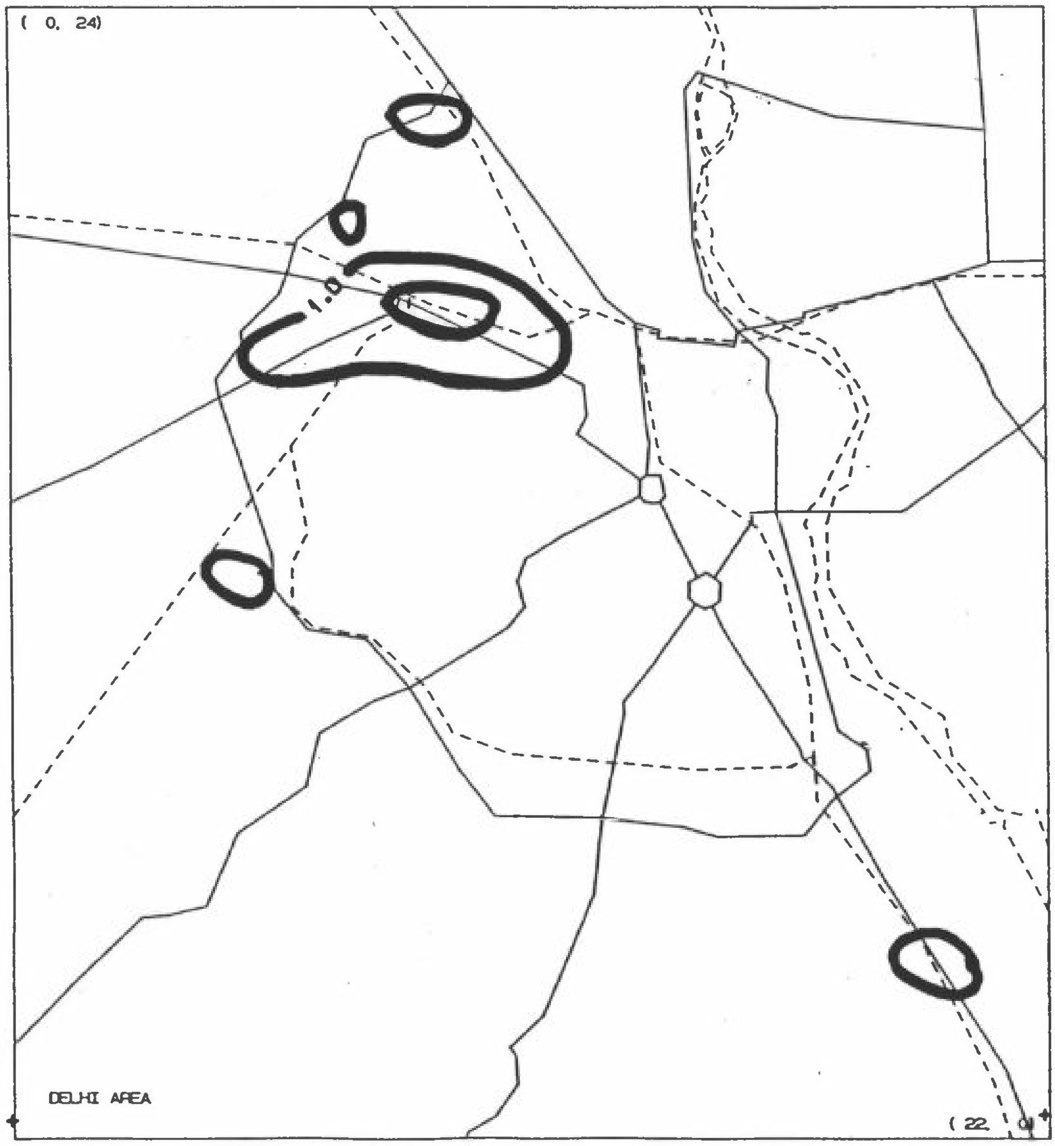
Impact of SO_2 ($\mu g/m^3$) from traffic.



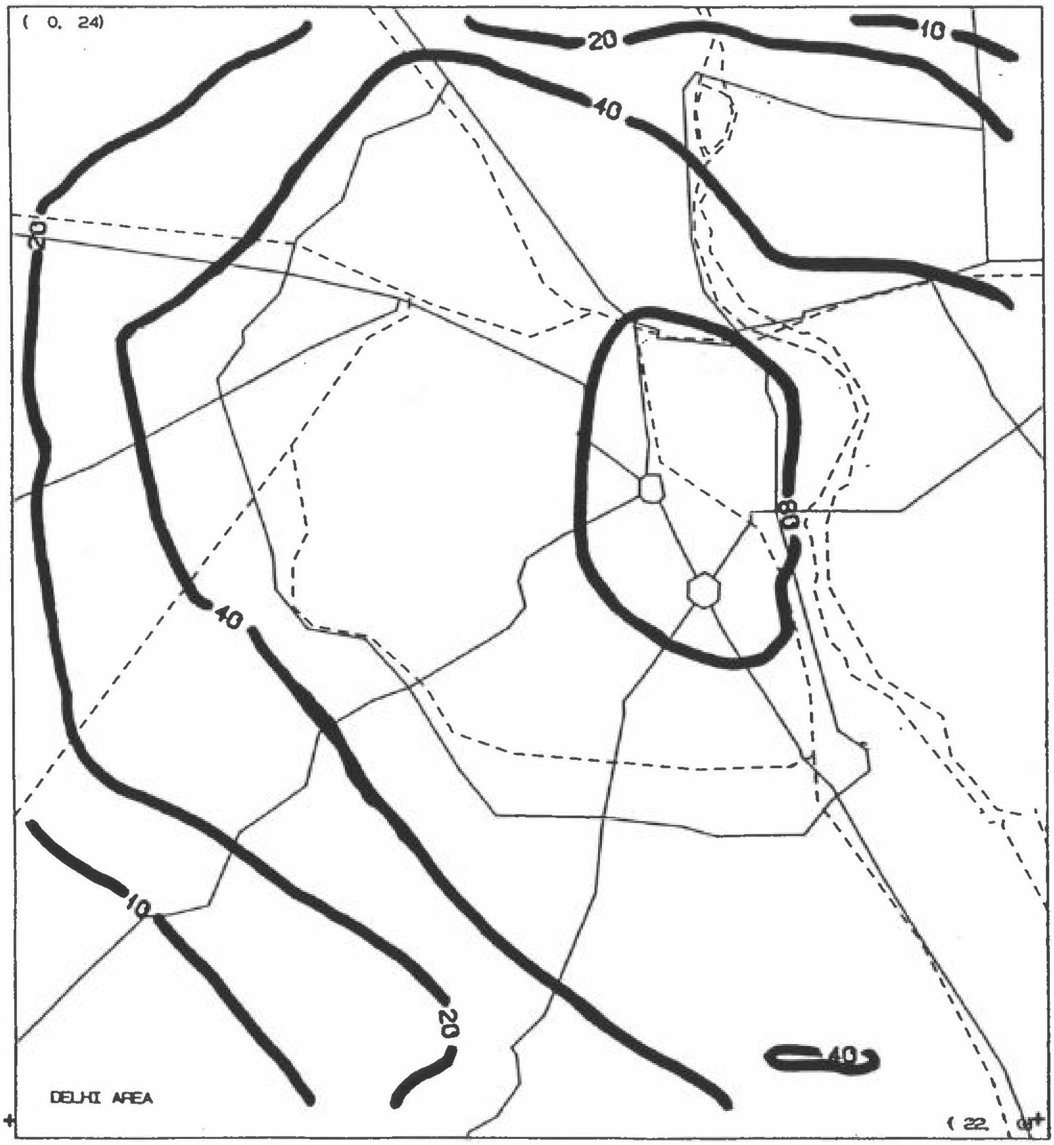
Total impact of SO_2 ($\mu g/m^3$) from all source categories.

APPENDIX F

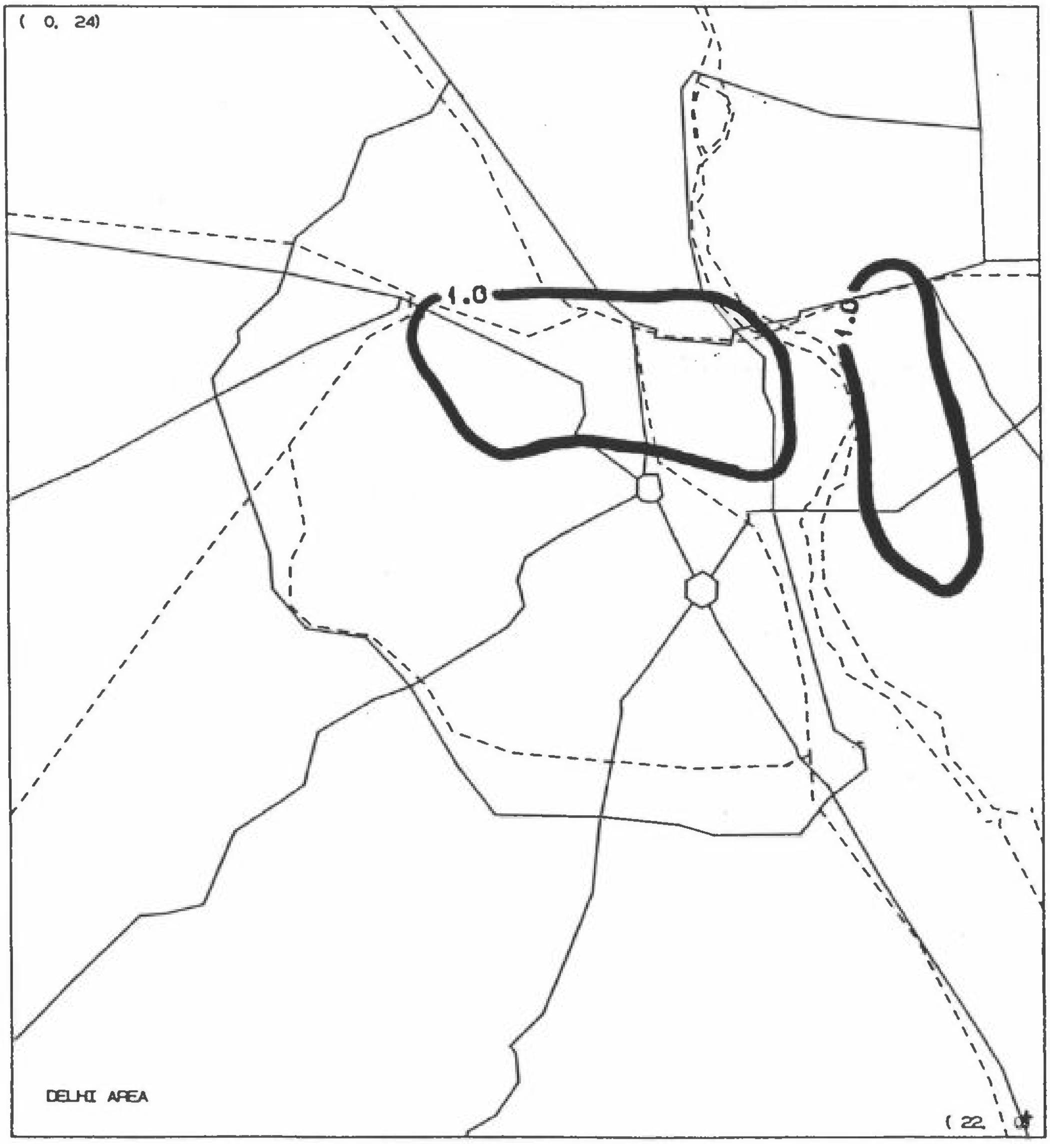
Impact of nitrogen oxides
from each source category



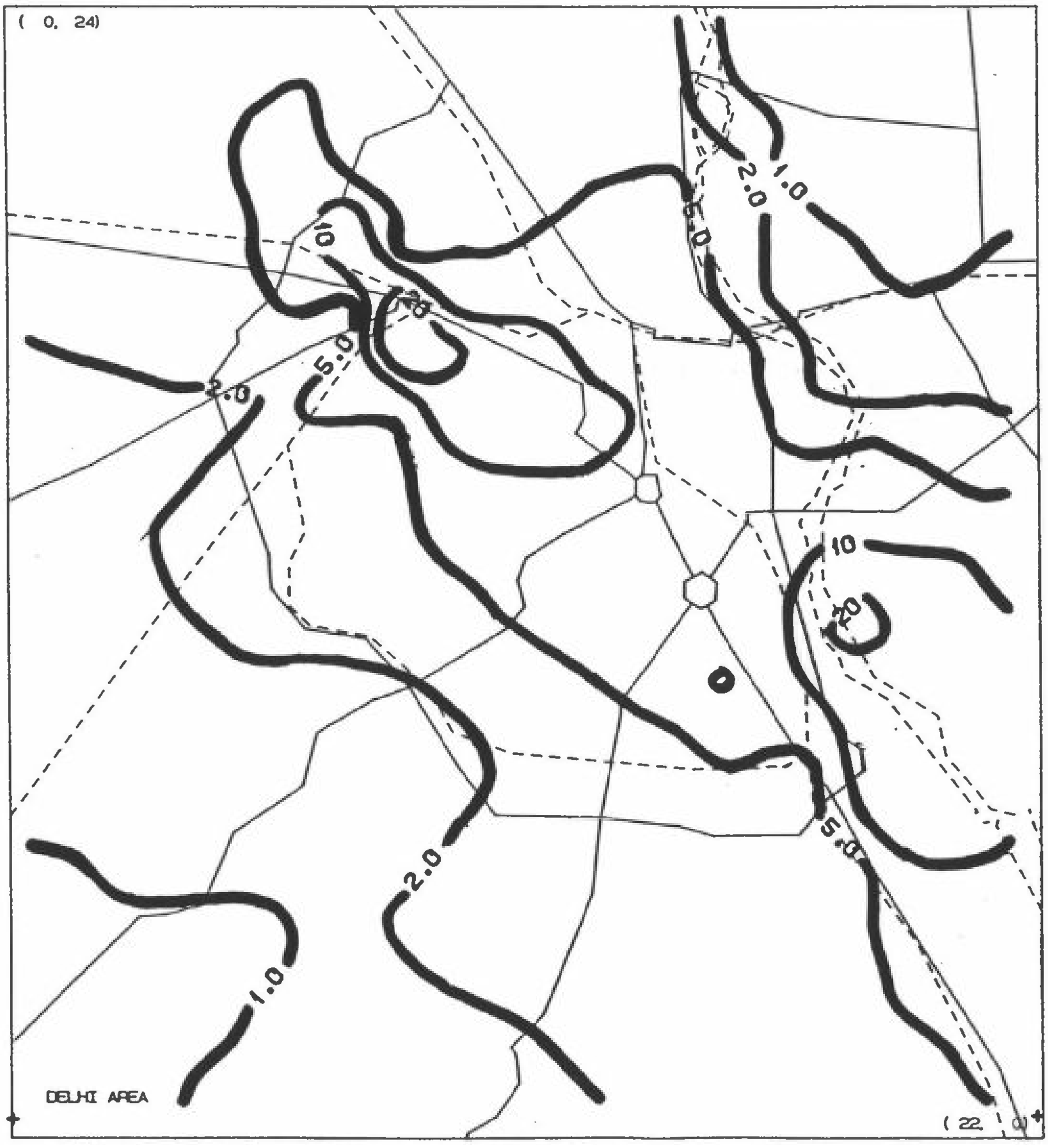
Impact of NO_x ($\mu g/m^3$) from small industry.



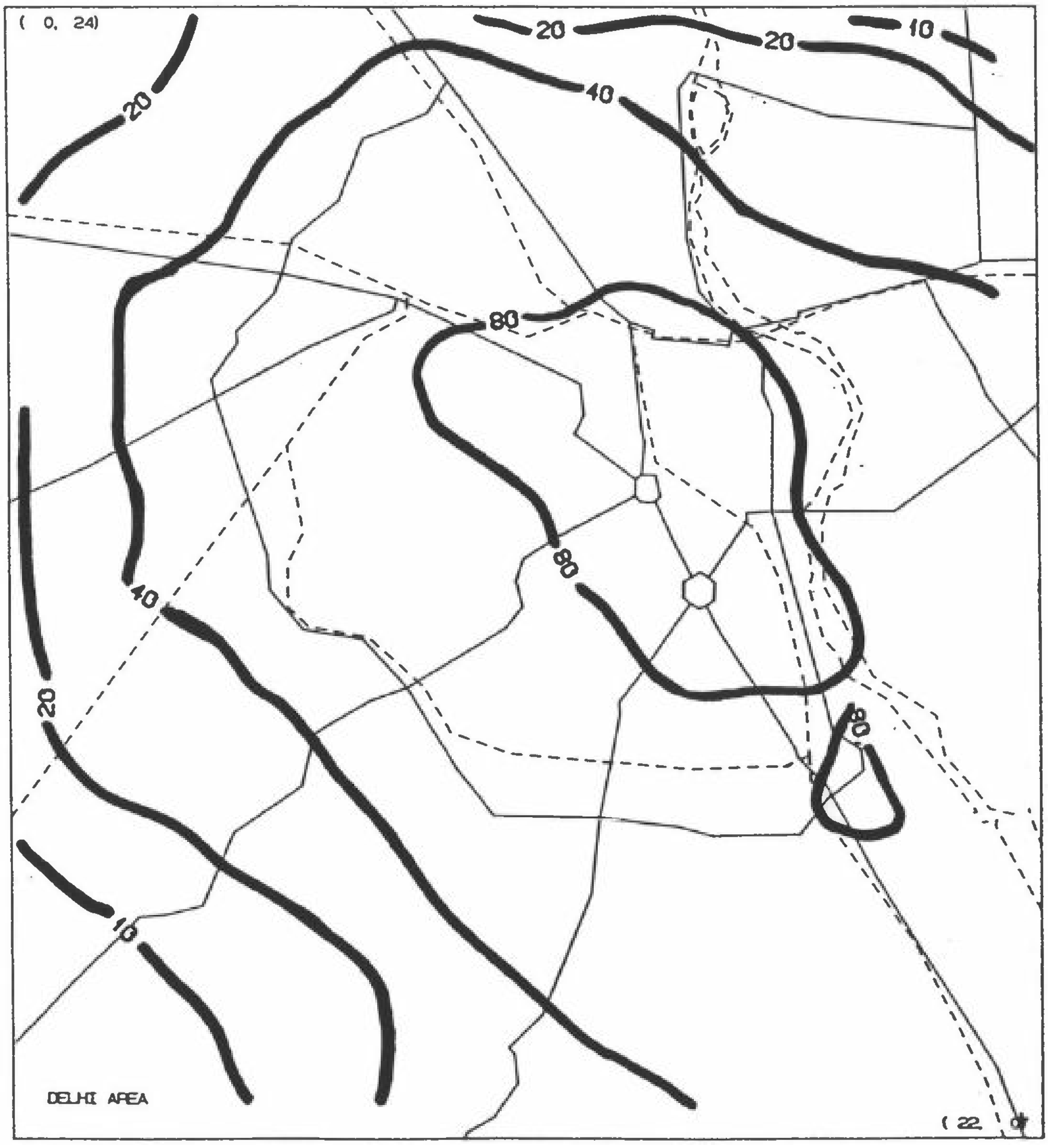
Impact of NO_x (μg/m³) from traffic.



Impact of NO_x ($\mu g/m^3$) from coal consumption.



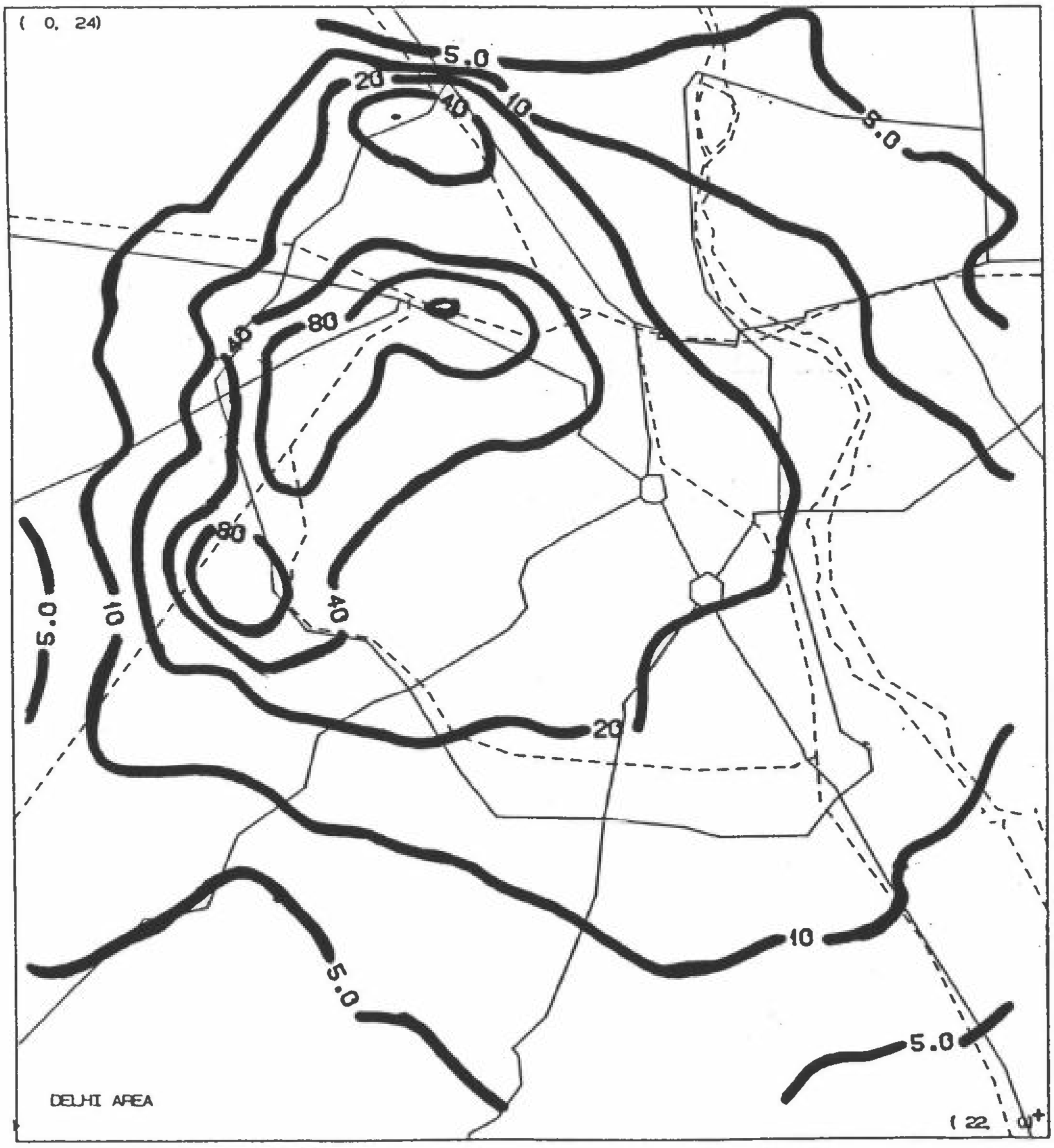
Impact of NO_x ($\mu g/m^3$) from point sources.



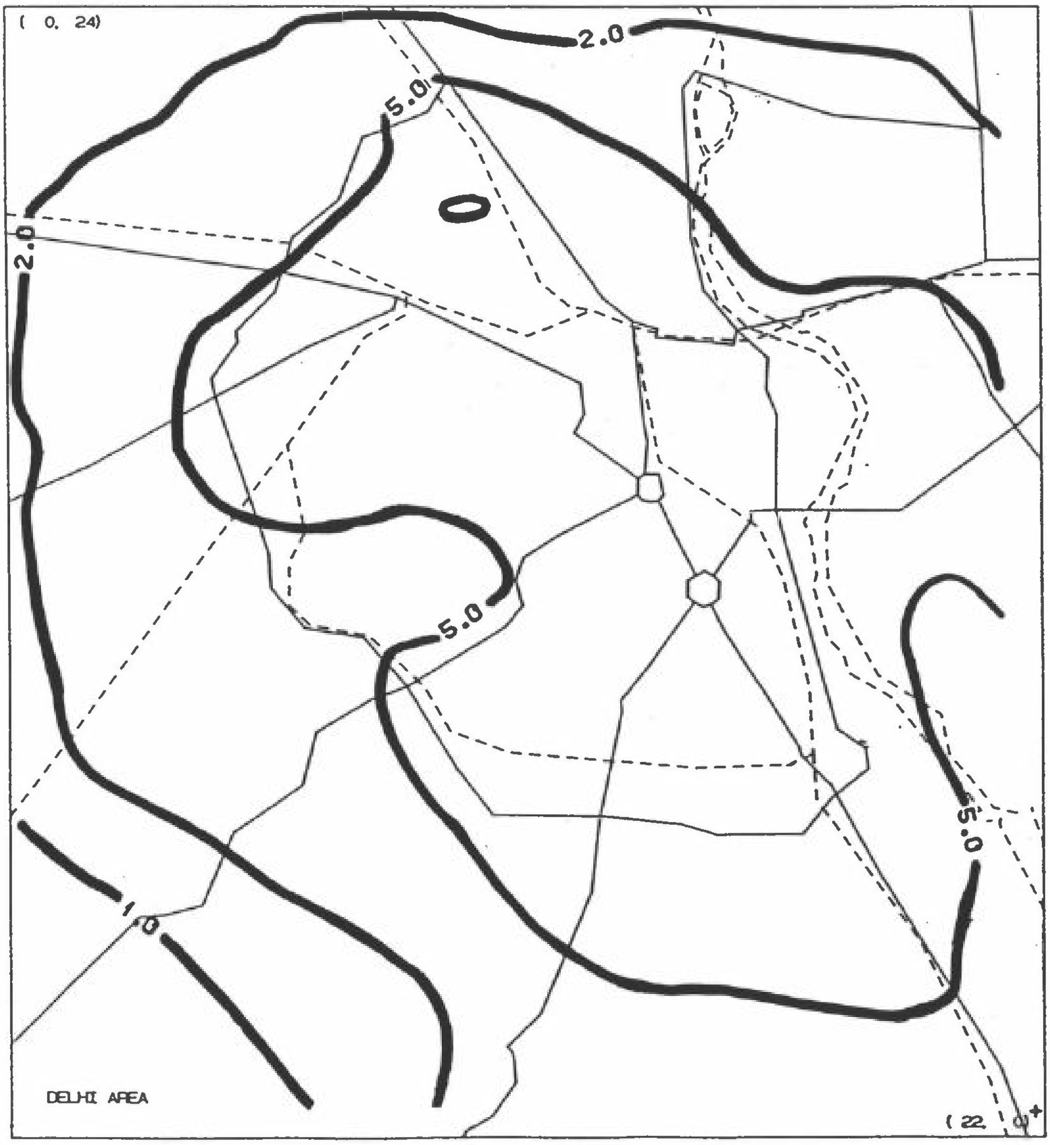
Total impact of NO_x ($\mu g/m^3$) from all source categories.

APPENDIX G

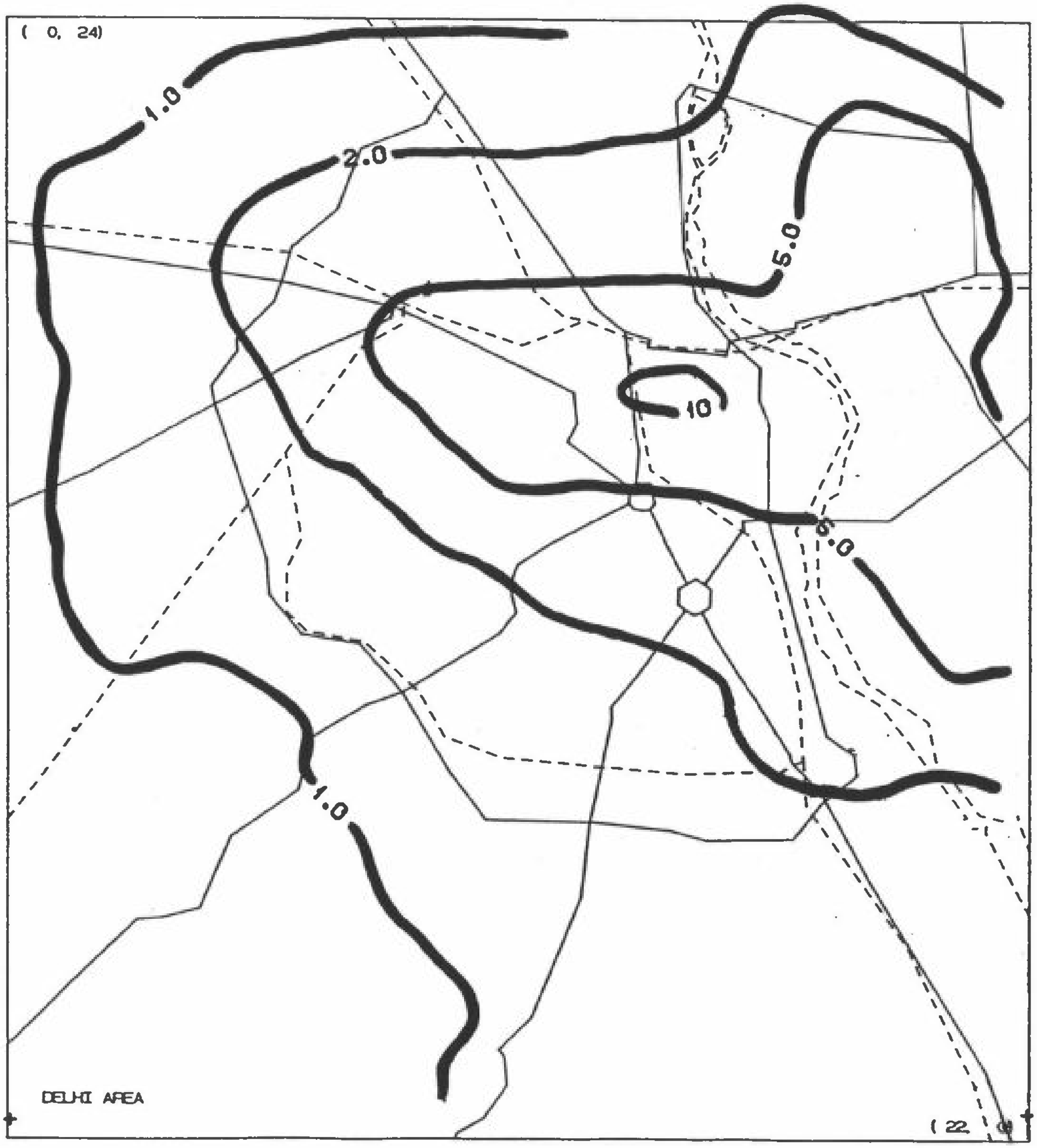
Impact of SPM
from each source category



Impact of SPM ($\mu g/m^3$) from small industry.

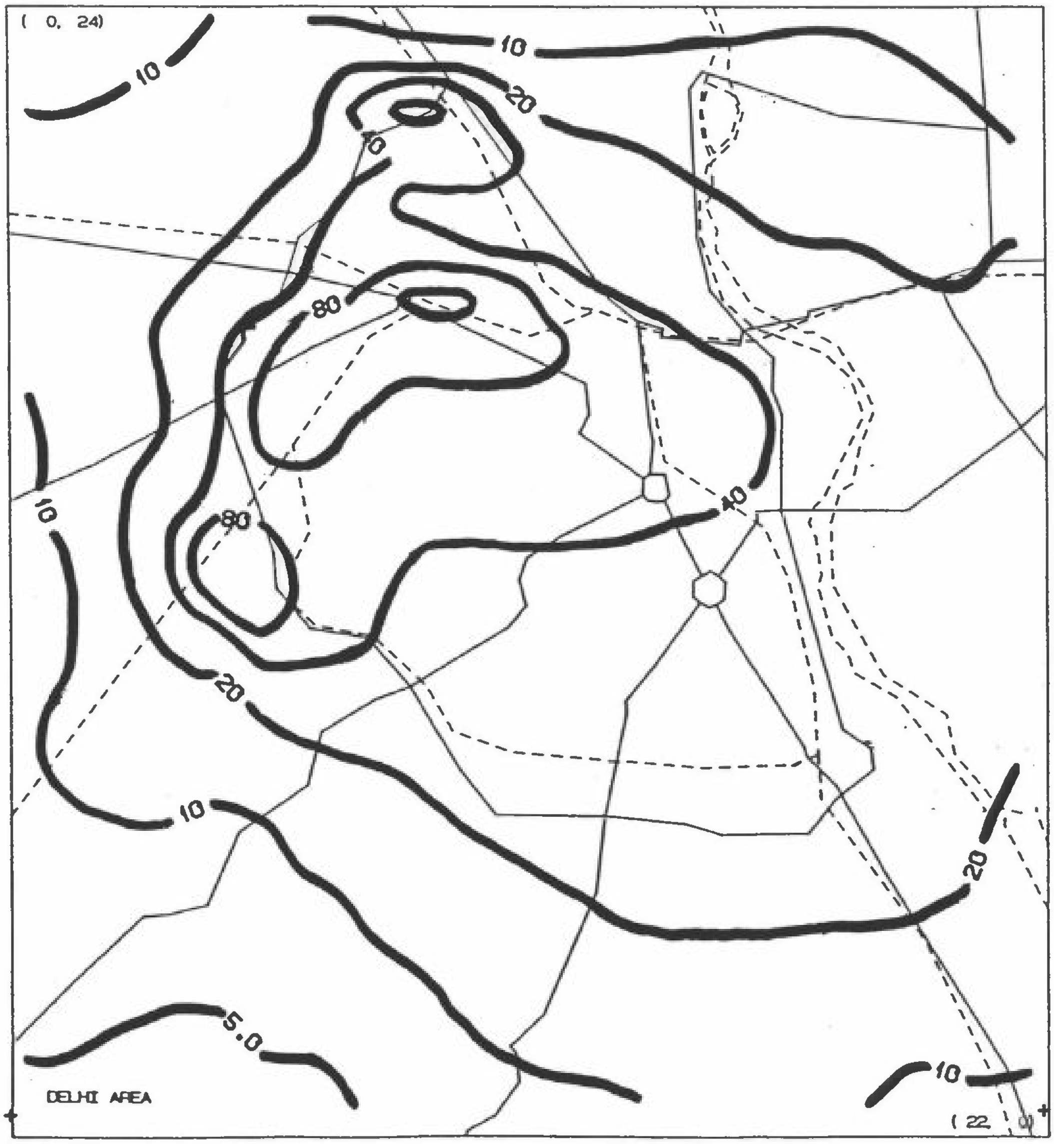


Impact of SPM ($\mu g/m^3$) from traffic.



Impact of SPM ($\mu g/m^3$) from coal consumption.

Impact of SPM (µg/m³) from point sources.



Total impact of SPM (µg/m³) from all source categories.

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		NILU PROSJEKT NR. O-92014	
FORFATTER(E) T. Bøhler, F. Gram and C. Prakash		TILGJENGELIGHET * A	
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TITLE	Model calculation of long term average concentrations of SO_2, NO_x and SPM in Delhi.

ABSTRACT

NILU has in collaboration with CPCB in Delhi carried out the first estimates of long term averaged ground level concentrations of SO_2, NO_x and SPM in Delhi, India. Based on limited information of emissions, these estimates agreed well with observations for SO_2. The winter averaged concentrations of NO_x was above the measured NO_2-concentrations which indicates that ozone in the limiting factor regarding the formation of NO_2. The estimated SPM-concentrations was too low compared to measurements in Delhi. More detailed information of emissions and consumption of fossil fuels and improved emission factors for traffic and coal consumption might improve the modelling results.

* Kategorier: Åpen - kan bestilles fra NILU A
Må bestilles gjennom oppdragsgiver B
Kan ikke utleveres C