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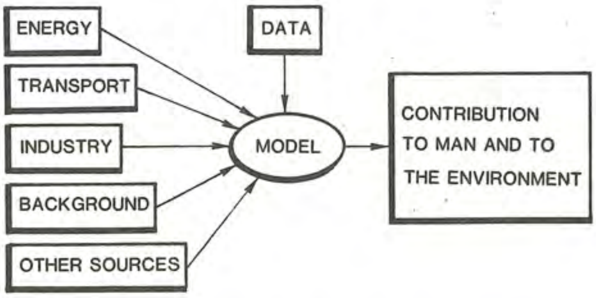

Environmental research under the Nordic Ministerial Council

MIL 4

The relative importance of pollution from different sources to man and to the environment.

Population exposure to SO_2 and NO_x from different sources in Stockholm

by Sten Laurin

SMHI SWEDISH METEOROLOGICAL AND HYDROLOGICAL INSTITUTE

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Abstract

A model for calculation of population exposure to air pollution is developed. With the aid of an existing dispersion model, SO_2 and NO_x concentrations are calculated in a network of gridpoints covering the Greater Stockholm area. Emissions from traffic and stationary sources are treated in the model. A simple model is constructed in order to improve the population data initially given. It is thereafter possible to take into account exposure at work as well as at home for the working part of the population.

Key words

Dispersion model, sulphur dioxide, nitrogen oxides, exposure, population dose

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1. INTRODUCTION

The work reported here was part of a larger inter-Nordic projekt, MIL 4, granted by the Nordic Ministerial Council. The aim of the project was to determine the impacts on man and environment from various sources of air pollution.

The present study is concerned with to what degree the inhabitants of Stockholm are exposed to SO_2 and NO_x, in particular the relative contributions from various sources is studied.

As tools for this kind of calculations numerical dispersion models can be used. Chimney emissions are treated with the so called city model [1], a Gaussian multiple-source model for point sources and area sources. Traffic emissions can be treated with a model for concentrations of air pollution in street environments [2]. This model is a modification of an american model, APRAC-1A [3]. However, this model is not used since it operates with a very small length-scale, concentrations are normally calculated in the range 5 - 30 metres away from the traffic. Here concentration gradients are large, in horizontal as well as vertical direction. Considering that population data are given for squares of 500 x 500 m^2 a higher degree of resolution for traffic pollution can not be properly used. Therefore the traffic has been treated as area sources in the city model.

Population data consists of number of inhabitants and number of people working in each 500 x 500 m^2 area.

2. MATHEMATICAL MODEL

The model describes dispersion in a mixing layer of depth H. The concentration at point xyz (where the x-axis is along-wind) is expressed as

$$\chi = \frac{Q}{2Hu} \exp\left(-\frac{t}{\tau}\right) \frac{\exp(-y^2/2\sigma_y^2)}{\sigma_y\sqrt{2\pi}} \left[\theta_3\left(\frac{h-z}{2H}, \frac{\sigma_z^2}{2H^2}\right) + \theta_3\left(\frac{h+z}{2H}, \frac{\sigma_z^2}{2H^2}\right)\right]$$

where

$$\theta_3(v,w) = \frac{1}{\sqrt{\pi w}} \sum_{k=-\infty}^{+\infty} \exp\left(-\frac{(v+k)^2}{w}\right)$$

and
Q is emission ($g\,s^{-1}$)
u is the wind speed ($m\,s^{-1}$)
τ is the decay time (s)
$t = x/u$ is travel time (s)
$h = h_0 + \Delta h$ is effective stack height (m)
σ_y and σ_z are the dispersion parameter value for the actual stability class and downwind distance x.
H is mixing depth or height to ceiling limiting dispersion upward

To each hour belong four numbers which give classes of wind direction ϕ (36 classes), stability s (four classes), wind speed u (five classes) and mixing depth H (seven classes). The concentration fields are calculated for all existing classes (779 classes in the period tested). In each calculation point (points spaced in the 500 m grid) the concentrations from the various sources are added together and the class concentration map is stored. This has been done separately for area sources and point sources since the methods are different for these two groups.

The emission, Q, is depending on outdoor temperature (daily mean) and the time of day, when heat producing units are considered. Sources with non-variable emissions are also present in the model. This category consists of industrial processes and base production of electricity and heat.

For computer capacity reasons it is not desirable to store all hourly concentration fields. Therefore the hourly fields are added to form daily average fields, which in turn are used to calculate a winter half-year field and a field which for each grid-point gives maximum of the daily values.

In order to calculate not only concentrations but also to what degree people are exposed to those concentrations, the latter two fields are processed together with the daytime/nighttime distribution of the population. Obviously, some accuracy is lost in this operation, since no diurnal variation of concentrations exist when daily averages are used. This will be discussed later.

Calculations were performed for various source types and sizes separately and for all sources together to find out the relative contributions. The results are given as number of people exposed to concentrations exceeding certain predecided values. A population dose is also presented together with the percentage coming from the various source types.

3. INPUT DATA

3.1 Emission data

Emissions from stationary sources have been calculated from data supplied by STOSEB, the joint organization of energy companies in Greater Stockholm. STOSEB also had population data on a suitable form, a network coinciding with the grid-net for the city model. Traffic sources: See section 3.1.2 below.

3.1.1 SO_2 emissions

For stationary sources the emissions are calculated from oil consumption and sulphur content of the oil. Data are given for individual emitters for units consuming more than 400 m^3 of oil per year. This corresponds approximately to a 1 MW unit. Smaller units are grouped together to form area sources.

The inventory shows that area sources in the inner parts of the city give 32% of the emissions, in the suburbs 40% and as an average for the entire area 35%. Some parts of the city are almost entirely connected to district heating systems, others have only individual household heating.

The total emissions of SO_2 during a winter half-year are 24 350 tonnes.

Traffic emissions of SO_2 will give a small contribution to concentrations at roof-level and have thus been omitted.

3.1.2 NO_x emissions

NO_x emissions from stationary sources are calculated from oil consumption and the following emission factors provided by the Energy Company of Stockholm:

point sources	6.47 kg NO_x/m^3 of oil
area sources	3.75 kg NO_x/m^3 of oil

Data on traffic work [vehicle-kilometres] from the Traffic and Street Department of Stockholm, for a 64 km^2 area covering the inner city (but only a small fraction of the suburban area) have been combined with emission factors [g/veh km]. The emission factors have been worked out by the Swedish Environment Protection Board (valid at 0°C ambient temperature):

passenger cars, petrol	2.4 g/veh km
- " - , diesel	1.0 g/veh km
lorries, light	7.5 g/veh km
" , medium	12.0 g/veh km
" , heavy	20.0 g/veh km

For a typical inner-city traffic mix in Stockholm the resulting emission factor will be 2.5 g/veh km. On the large by-pass road E4, heavy traffic constitutes a larger percentage. Here the emission factor is estimated to be 3.5 g/veh km.

Total NO_x emissions during a winter half-year are 9 650 tonnes out of which 1 740 tonnes are from the traffic (18%). The deviation from the often quoted figure that the traffic stands for 60% of total NO_x emissions, is a result of the following three factors:

1) The 60% is for a year. During the summer half-year NO_x emissions from chimneys are approximately 30% of the winter half-year emissions, while the corresponding value for traffic emissions is 80 - 90%.

2) The 60% is for the entire country. Since a certain part of traffic work is done on country roads where travel distances are long, and industrial areas on the other hand often are localized to city areas, the 60% probably is a over-estimate for a city.

3) Traffic emission data are missing for the suburbs, as mentioned earlier.

3.1.3 Classification of sources

In order to obtain the relative importance of various sources, and to make results from similar studies in the Nordic countries comparable, the following classification of sources was agreed upon.

The main division is between industrial sources, heating sources and traffic. A sub-division of heating sources was also made (less than 5 MW, 5 - 30 MW and more that 30 MW, values referring to average power during the coldest month). The number of sources in each group are for Stockholm: 177 small, 51 medium, 14 large and 9 industrial. Strictly, the group of small sources contains units of 1 - 5 MW. Units smaller than 1 MW are already grouped together to form area sources of which there are more than 500. In the following, area sources plus units of 1 - 5 MW are taken as one group.

3.2 Population data

By studying the age distribution of the population and making some assumptions about the degree of employment for the different age groups, one can make a crude estimate of a movement pattern for the population:

1) 0 - 16 years of age. In care of parents, nursery schools or elementary schools. Assumed to spend all day in their home environments. 23% of the total population.

2) 17 - 24 years of age. "Pre-marriage group". Working or studying at university. Highest unemployment degree, almost 20% in 1980 (model year). 12% of the total population.

3) 25 - 40 years of age. "The age of bringing up children". 30% of this group assumed being at home. 25% of the total population.

4) 41 - 65 years of age. "Back to work". This group is assumed to be employed to 90%. The 10% staying at home are, apart from unemployed, elderly house-wives or people suffering from chronical illness. 25% of the total population.

5) Over 65 years of age. Retired. 15% of the total population.

Large variations exist between different areas. In the inner parts of the city, for instance, 30% are over 65 years of age, while the percentage of children is far below the values for the entire community.

By making a budget of the values above one can deduce that roughly 50% of the population are employed. This is in good agreement with official statistical figures, in the community of Stockholm there are 650 000 inhabitants out of which 320 000 are employed. The corresponding figures for Greater Stockholm are 1 290 000 and 650 000 respectively.

Based on the findings above a simple model has been formulated. 50% of the population is supposed to stay in their home environments all day. The 50% travelling to work are treated in the following way: the number of travellers from remote suburbs is reduced by the number of available employment in the same areas (meaning an assumption that these works are occupied by local inhabitants), the rest are distributed over the inner city and the closer suburbs in the same proportion as the numbers of employment are distributed over this area. This model should give a fairly realistic picture of the movement pattern for the population.

3.3 Meteorological conditions

From a climatological point of view, the winter 1979/80 was close to normal. The mean temperature October - March was 1°C below the mean for the period 1931 - 60, the largest deviation for monthly means was during February, which was 2.3°C colder than normally. The distribution of wind directions was normal (winds from the sector south to west are dominating in Southern Sweden) while mean wind speed was somewhat higher than normally.

4. METHOD FOR EXPOSURE CALCULATIONS

For each category of sources a separate model run is made and after that a run with all sources together, so that relative contributions to concentrations can be found. The model output consists of two fields, maximum of daily means for each grid-point and winter half-year mean for each point. The winter half-year means include a value for regional background, 8 $\mu g/m^3$ for SO_2 as well as for NO_x. This value is estimated from the OECD study on long range transport of air pollution [4].

Calculations of number of people exposed to concentrations within certain pre-defined intervals and of total population dose are first made for the part of the population spending all day at home. Next, calculations are performed for the people travelling to work. This is done as weighted means between exposure values at home and at work. This group is assumed to spend 40% of the day away from home. Exposure along the route of travel is not considered although high concentrations of NO_x may occur. Exposure times to the highest concentrations are however short, at least in comparison with the finest time resolution of the City model, which is one hour.

5. RESULTS

Calculated winter half-year concentrations of SO_2 and NO_x are shown in figures 1 and 2, long range transport not included.

In order to describe the variation of the relative contributions from various source groups, the following areas have been chosen:

I Area with highest SO_2 levels, central Södermalm. Densely populated part of the inner city, with a large percentage of individual heating and small point-sources.

II City, the central part of Stockholm, dominated by administration, business, shops and cultural activities. Dense traffic.

III Farsta, a suburb 10 kilometres south of the city center.

IV Sollentuna, a suburb 15 kilometres north of the city center.

V Gustavsberg, a suburb 20 kilometres east of the city center.

These five areas are used in tables 1 and 2.

TABLE 1. Relative contributions (%) to mean concentrations (winter half-year) of SO_2 from various source-types.

Area	Source-type				
	Heating			Industry	Long range transport
	< 5 MW	5 - 30 MW	> 30 MW		
I	83	4.5	4.5	1	7
II	75	9	6	1	9
III	60	10	7	3	20
IV	42	8	12	4	34
V	35	10	10	5	40

TABLE 2. As table 1, but for NO_x.

Area	Source-type					
	Heating			Industry	Traffic	Long range transport
	< 5 MW	5 - 30 MW	> 30 MW			
I	45	3	3	0	37	12
II	30	3	4	0	52	11
III*	38	6	6	0	12	38
IV*	21	7	7	0	7	57
V*	20	8	8	0	4	50

*Values for traffic are under-estimated in suburban areas because of missing traffic emissions. Consequently, the values for other sources are overestimated.

From table 1 can be seen that minor heating sources contribute most to the SO_2-levels of the inner city area. This source-type is responsible for approximately 80% of the SO_2 concentrations although it stands for only 45% of the total emission. The contribution decreases with growing distance to the city center. The same thing is valid for the absolute SO_2-levels, which is reflected by the fact that long range transport gradually increases in relative importance, going outward from the city.

For NO_x, the traffic gives contributions that are of the same magnitude as minor heating sources. These two source-types therefore are dominating causes for the inner-city NO_x levels, as can be seen from table 2. For the suburbs, no reliable conclusions can be drawn because of missing traffic data.

Tables 3 and 4 present the ratios between percentage of concentration and percentage of total emission for the various source-types. A value larger than 1.0 thus points out an "over-polluting" source group. Long range transport is not included since it would give a division by zero (no emissions inside the model area).

TABLE 3. Ratios between percentage of concentrations and percentage of total emission for various source-types. Based on winter half-year means of SO_2.

Area	Source-type			
	Heating			Industry
	< 5 MW	5 - 30 MW	> 30 MW	
I	1.83	0.36	0.14	0.12
II	1.66	0.72	0.18	0.12
III	1.32	0.80	0.21	0.36
IV	0.93	0.64	0.36	0.48
V	0.77	0.80	0.30	0.60

TABLE 4. Same as table 3, but for NO_x.

Area	Source-type				
	Heating			Industry	Traffic
	< 5 MW	5 - 30 MW	> 30 MW		
I	1.25	0.28	0.11	0	2.06
II	0.83	0.28	0.14	0	2.89
III*	1.05	0.57	0.22	0	0.67
IV*	0.58	0.66	0.25	0	0.39
V*	0.55	0.75	0.29	0	0.78

*See remark to table 2

A cautious interpretation of tables 3 and 4 is recommended, since they express ratios between concentrations in local areas and emissions for the entire calculation area. A part of the city where heat is produced by a heating central might have the major part of the air pollution from area sources at some distance, while at the same time air pollution from the heating central goes to another part of the city.

It is thus possible to find a large "benefit factor" (a value > 1) for reducing emissions from minor heating sources in a particular area, only to find that this source-type is not very common in this area.

Calculations of exposure and population dose have also been made. The results are shown in figures 3 - 6, showing the number of people that are exposed to concentrations of SO_2 och NO_x (winter half-year mean and maximum of daily means) exceeding the values denoted on the abscissae of the figures. Figures 7 - 10 show the percentages of the total population dose that come from various source groups.

From figures 3 and 5 can be seen that in the case of exposure to SO_2, the minor heating sources give the largest contributions. Figures 4 and 6 show that the same sources are of great importance in the NO_x case, but also that the traffic is of an equally great importance although a large part of its emissions was missing in the model run.

The relative population doses in figures 7 - 10 are confirming this picture, but furthermore show that for long-term means, and particularly in the NO_x case, long range transport is of great importance.

6. LIMITATIONS AND UNCERTAINTIES IN THE CALCULATIONS

Originally the intention was to include exposure to traffic pollution on a local scale, within the street canyons. It was also intended to calculate NO_2 values, not only NO_x.

Since neither traffic data nor population data were available with the resolution needed for such calculations, this idea was abandoned.

The NO_2 calculations also had to be left out. It was believed when the project was originally drawn up, that NO_2 on a local dispersion scale in winter conditions could be treated purely as an effect of dispersion of directly emitted NO_2. Later findings have shown that atmospheric chemistry must play important role also in those cases.

The calculations that actually have been performed also suffer from some weaknesses:

- Traffic data missing for suburbs. The error because of this is probably not too large, since the traffic work per unit area here is much less than in the inner city. Furthermore, the major roads in suburban areas often are built at some distance from the living areas.

- Although concentrations are calculated for individual hours with the City model, these can not be used for exposure calculations. Therefore daily means have been treated as if they were consisting of 24 equal, hourly values. This might be important for the results, since contributions from various source-types are at maximum on different hours of the day. Model calculation implicates that maximum concentrations caused by stationary sources occur mostly during night-time hours, but for traffic in day-time hours.

- Divisions between different source-types are not strictly done. In the model an industrial source is defined as an emission with no variation during the day. For practical reasons some heating sources have been treated as industrial sources. This concerns some electricity production and also units producing a base-load of heat. On the other hand there are industries with no emissions caused by the manufactoring process but with a combustion unit to supply their buildings with heat. These industries have been brought to heating sources.

7. SUMMARY AND CONCLUSIONS

The results of the calculations show that the small stationary sources (< 5 MW) are of major importance to the SO_2 levels in Stockholm. When NO_x is considered, the same source type has a great influence on the concentrations. Here traffic also largely contributes to the NO_x levels, in spite of the fact that only part of the traffic emissions has been available as data input.

In order to reduce the population exposure to SO_2 and NO_x, obviously one should start with the two source types mentioned above. Apart from a direct reduction by emission restrictions, introduction of new long-distance heating systems and traffic restrictions could be useful tools for this purpose. Traffic restrictions might be either permanent or initiated temporarily by an air pollution forecast.

In future work one should try to specify how much short-time exposure to high pollution levels contributes to the population dose. It would also be desirable to include diurnal variation of concentrations in the exposure calculations.

8. ACKNOWLEDGEMENTS

This work has been supported by the Nordic Ministerial Council. I have very much appreciated meeting and discussing with colleagues from the other Nordic countries and especially Bjarne Sivertsen at the Norwegian Institute for Air Research who has been co-ordinator for the MIL-4 projects. I am also very grateful to miss Christina Lindgren for her skill in handling large computer programmes and to miss Yvonne Björkman for typing the manuscript.

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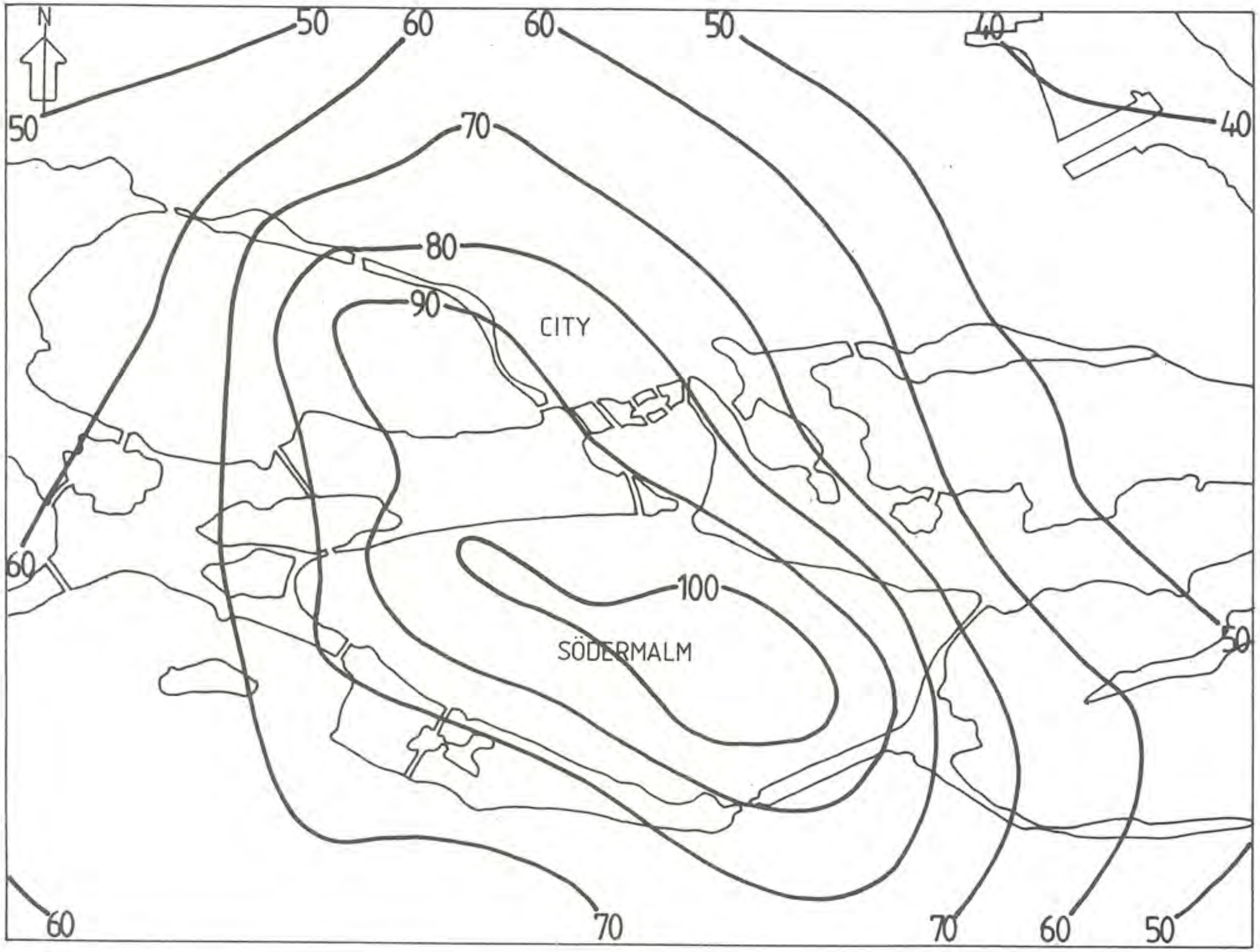

FIGURE 1. Calculated winter half-year means of SO_2 concentrations in Stockholm.

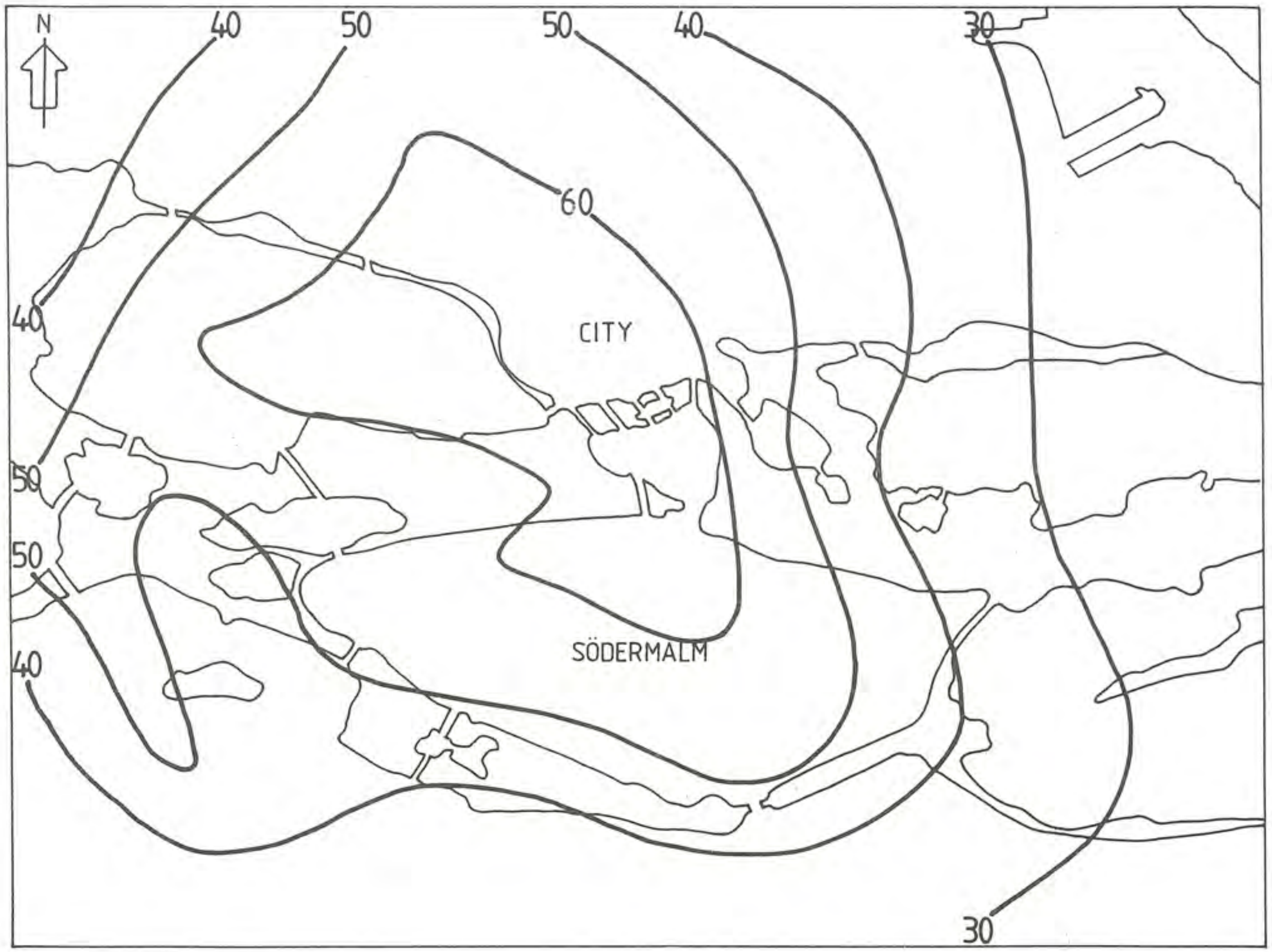

FIGURE 2. Calculated winter half-year means of NO_x concentrations in Stockholm.

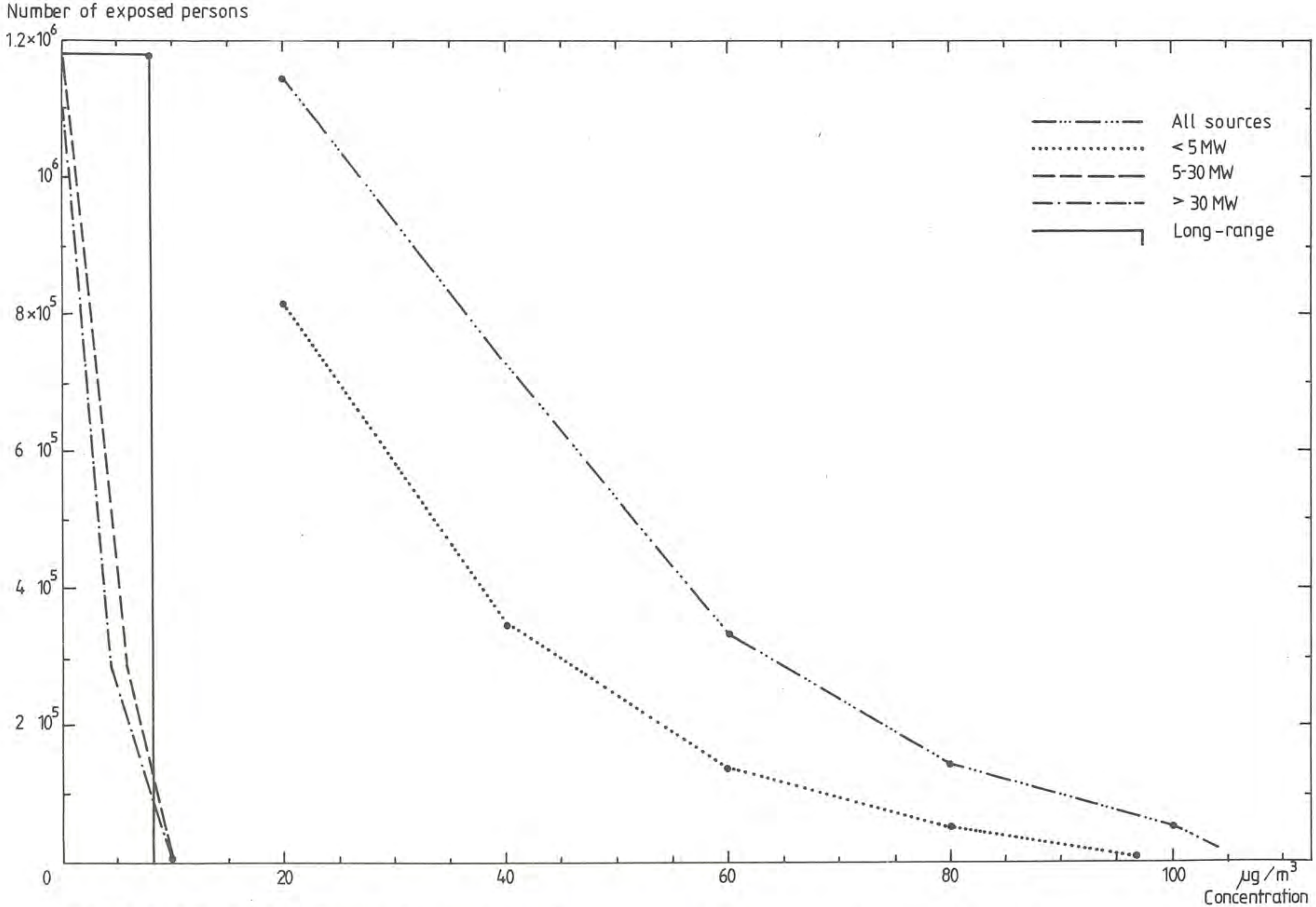

FIGURE 3. SO_2-load in Stockholm. Winter half-year mean. The curves show number of persons exposed to concentrations exceeding values on the abscissa.

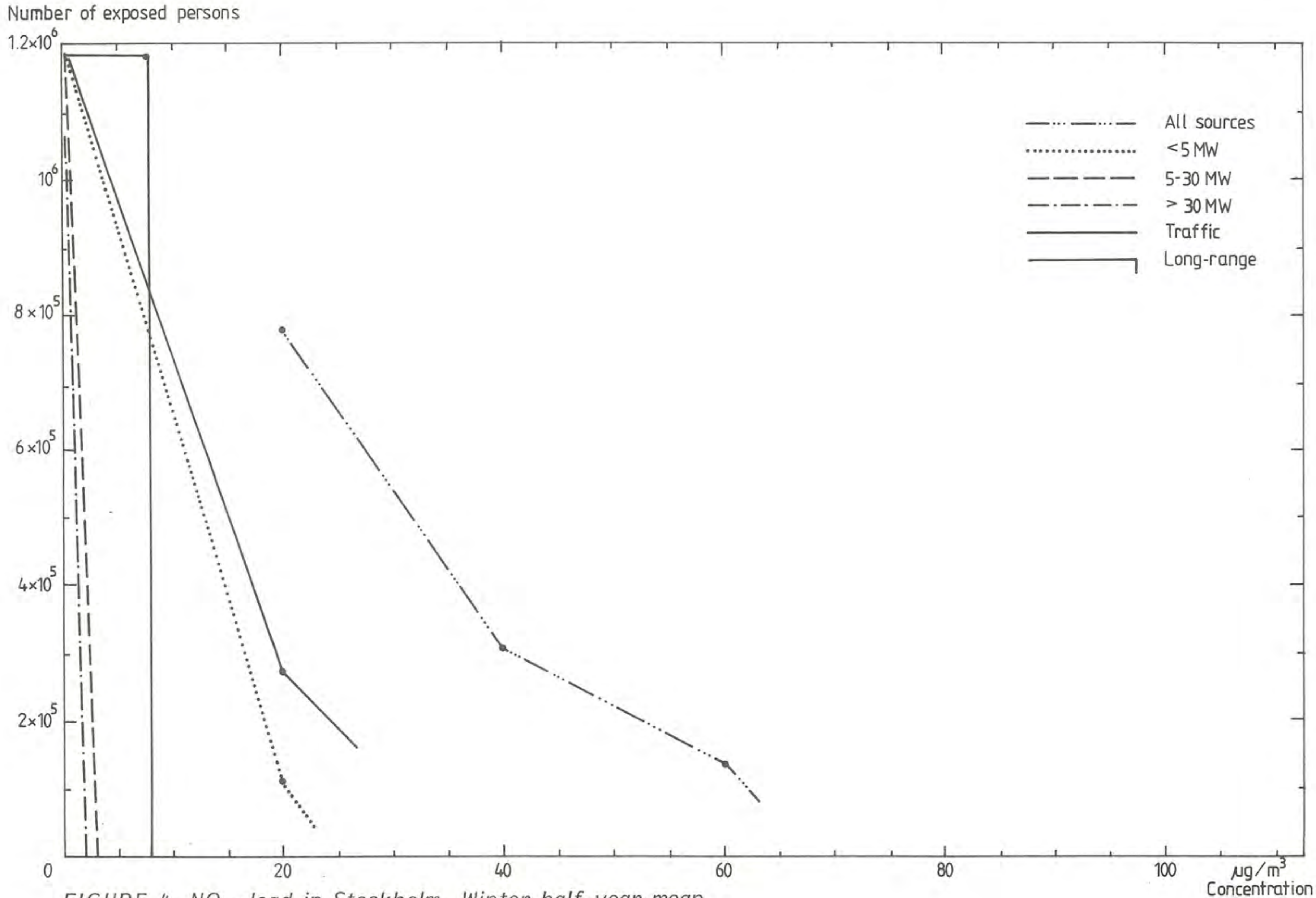

FIGURE 4. NO_x-load in Stockholm. Winter half-year mean.

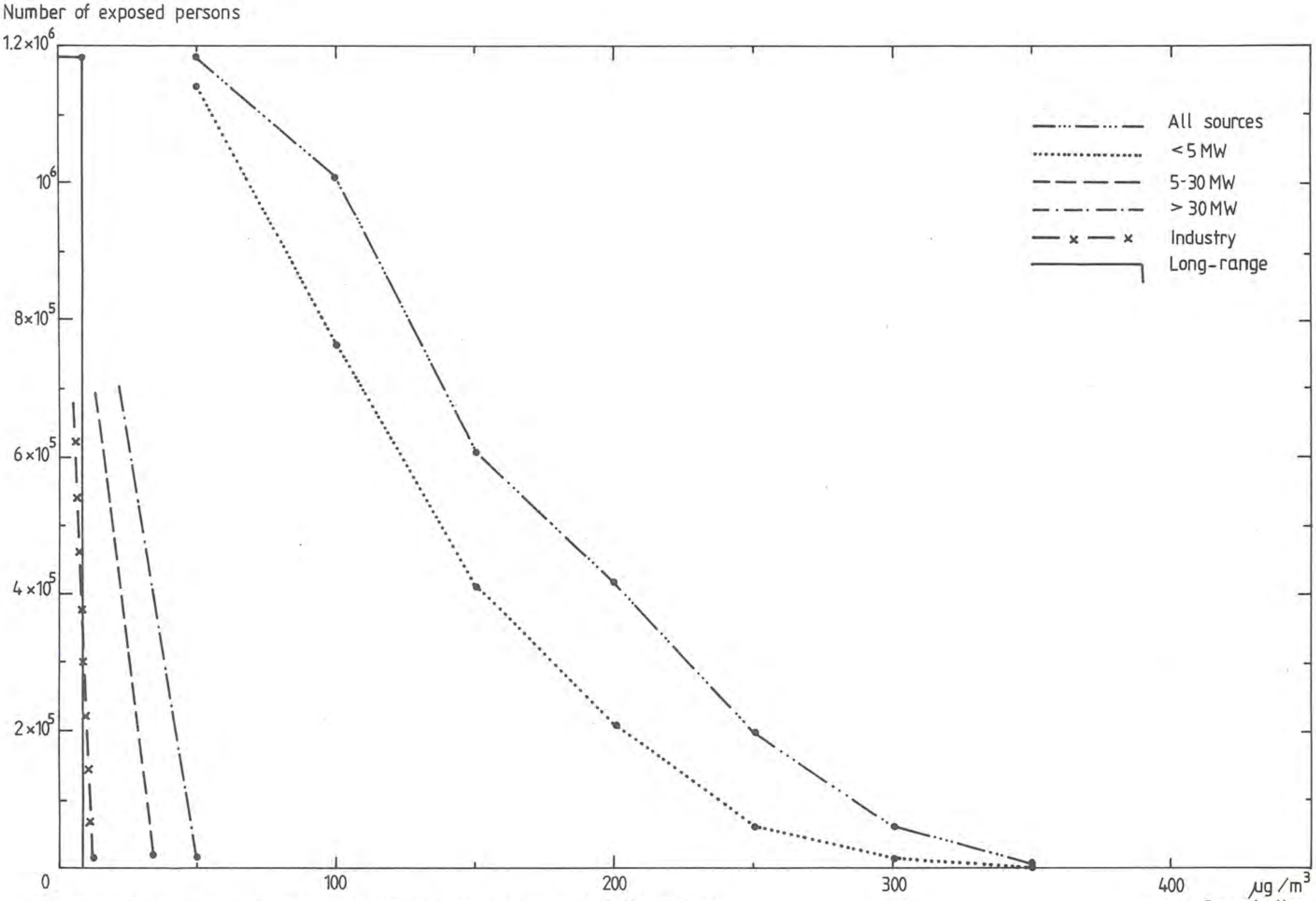

FIGURE 5. SO_2-load in Stockholm. Maximum of daily means.

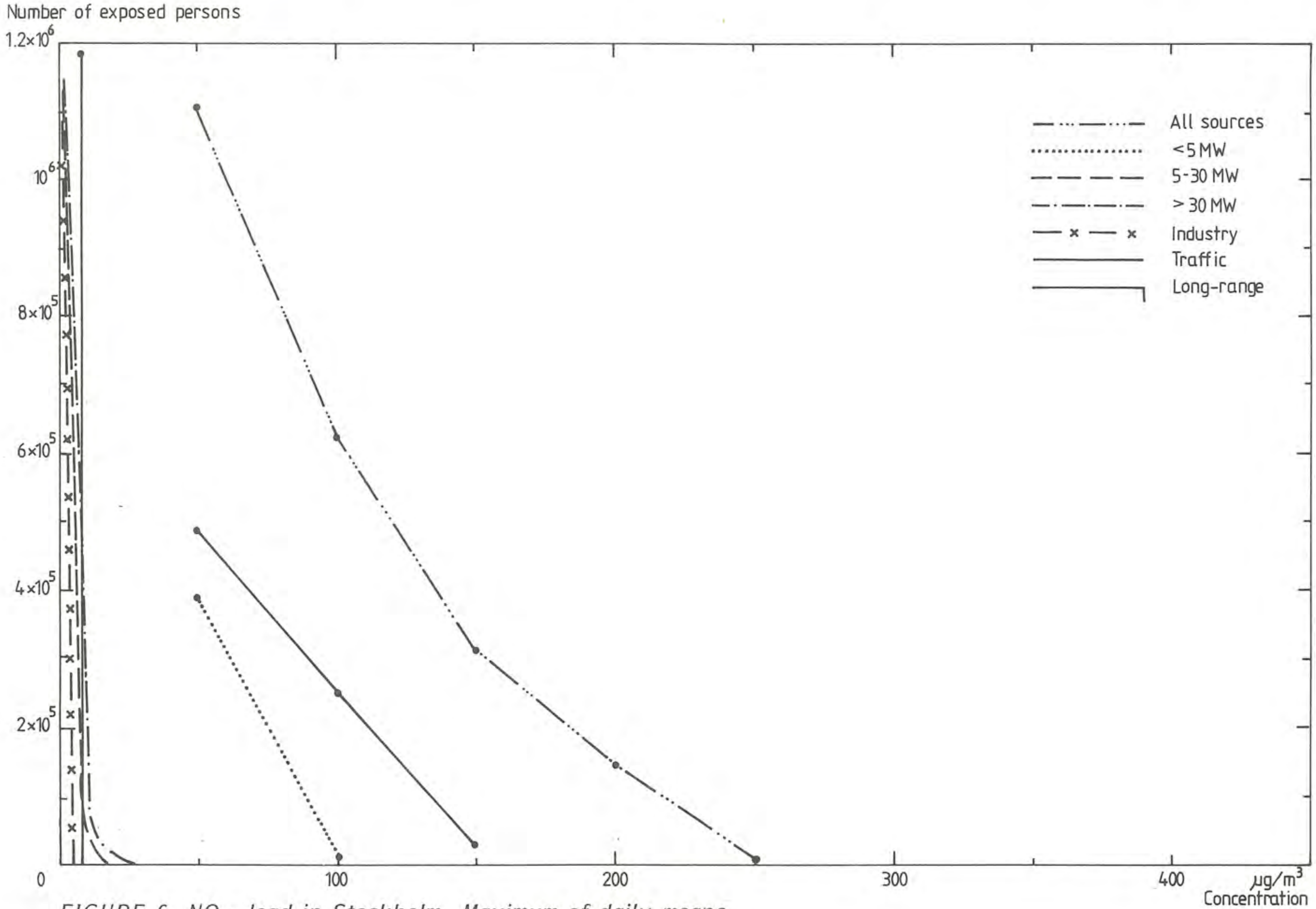

FIGURE 6. NO_X-load in Stockholm. Maximum of daily means.

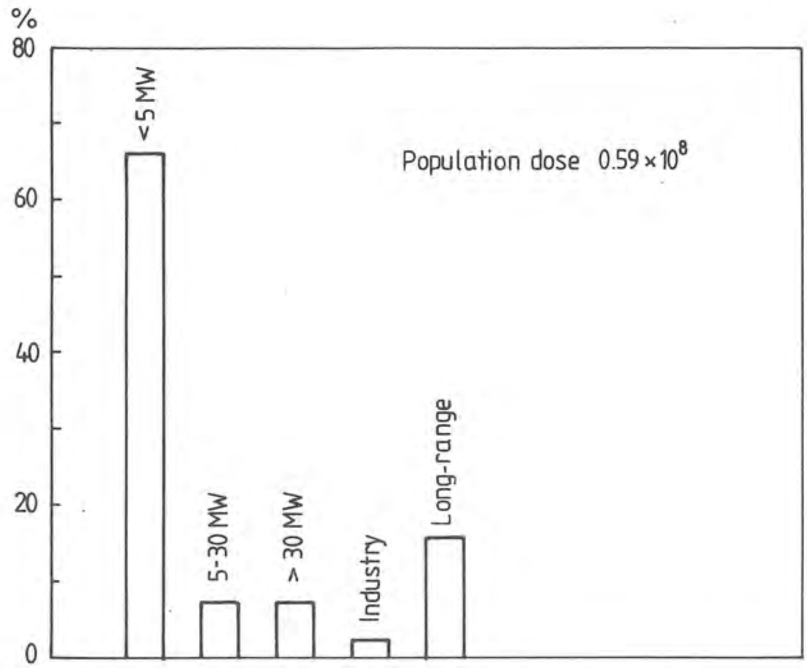

FIGURE 7. Relative contributions (%) to the population dose (µg · man/half-year) of SO_2, winter half-year.

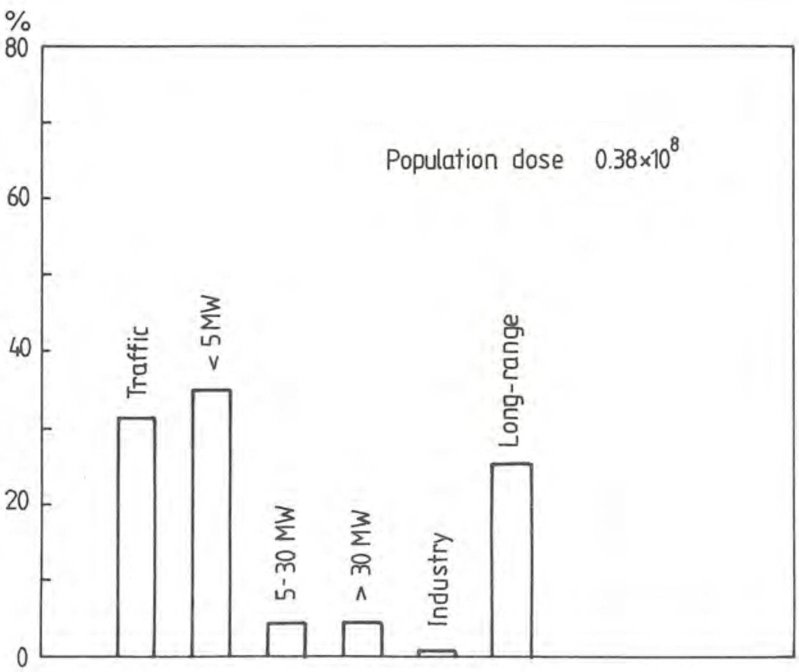

FIGURE 8. As figure 7, but for NO_x.

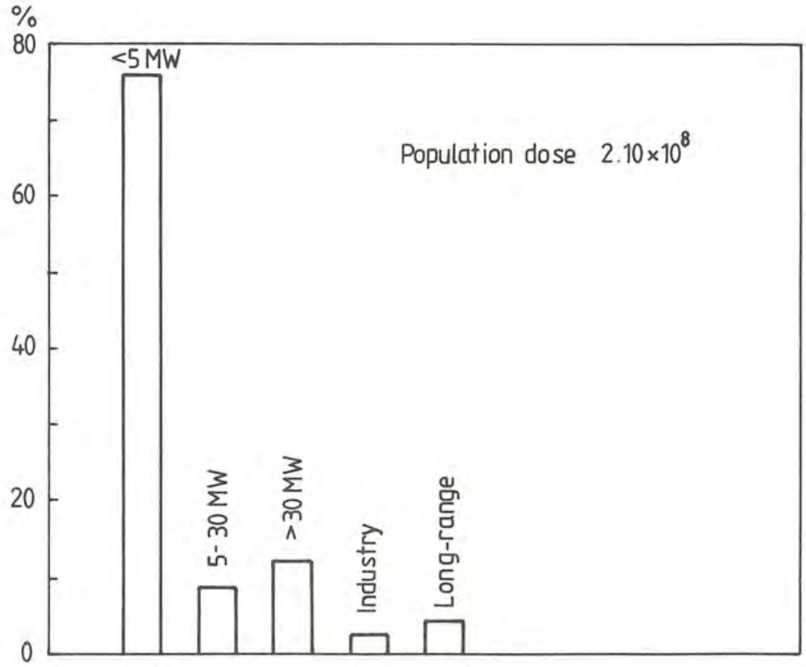

FIGURE 9. Relative contributions (%) to the population dose (µg • man/day) of SO_2, maximum of daily means.

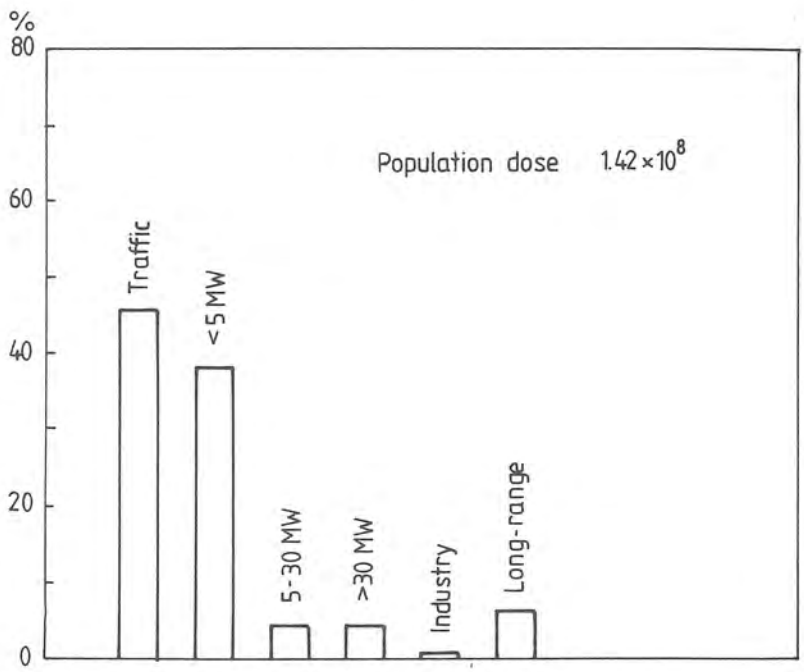

FIGURE 10. As figure 9, but for NO_x.

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