



Air pollution exposure monitoring and estimation

Part VI.‡ Ambient exposure of adults in an industrialised region†

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This paper presents methodology and results of a dynamic individual air pollution exposure model (DINEX) that calculates the hourly exposure for each adult in a panel study. Each of over 260 participants, through the use of a diary, provided information used in the model to calculate his/her personal, individualised exposure. The participants filled out the diary daily, hour by hour, over two, two month periods. The exposure assessment model coupled the diary information and results of an indoor/outdoor measurement program, with the results of dispersion modelling on an hourly basis for an industrial area in Norway. The estimated air pollution concentrations from the dispersion model, based on continuous meteorological measurements, were calibrated with air pollutant concentrations measured continuously.

Introduction

It is methodologically challenging to assess the health impact of exposure to concentrations of air contaminants, especially those lower than air quality guidelines.

The effect of exposure to ambient air pollution needs to be quantified and separated from other known factors that influence health status, such as age, smoking habits, nutrition, pre-existing disease and/or genetic constitution. The measurement or estimate needs to describe the fluctuations in concentrations individuals are exposed to, as a result of their movements in different microenvironments.¹

Grenland, the study area, is a heavily industrialised area in southern Norway. Pollutants here originate from several geographically distinct sources. This allows them to vary independently of each other, facilitating their individual identification and quantification. Grenland is well known for its industrial haze leading to reduced visibility. Industrial emissions of hydrochloric acid, ammonia and chlorine lead to the formation of this haze, even though humidity is not high enough to lead to normal fog. This phenomenon occurs mainly on warm summer days in conjunction with the land-sea breeze. In the winter, industrial haze does not usually occur.

Typically important contaminants in the study region are: sulfur dioxide, nitrogen oxides, carbon monoxide, chloride, ammonium, hydrocarbons, photochemical oxidants such as ozone and peroxyacetyl nitrate (PAN), polycyclic aromatic hydrocarbons (PAH), and traces of chlorinated organic compounds such as dibenzofurans and dioxins.

This paper presents a dynamic model used to estimate exposure to a series of air pollutants in a panel investigation, designed to identify the compound or components, if any, responsible for adverse short-term health effects. The dynamic individual pollution exposure model (DINEX) has also been used in other studies. This paper is presented mainly to discuss the method, since major improvements in pollution abatement and the closing of one of the factories has reduced pollution

in the region in the period after the field study was completed (1988).

Materials and methods

Exposure estimating

Exposure estimating must account for people's movements in areas varying substantially in pollution concentrations.

The spatial distribution of concentrations served as a basis for estimating each individual's exposure. An exposure assessment model estimates exposure for each compound, for each hour and for each participant, using information collected from the diary on where each individual was at given time points.

An ambient pollution dispersion model for the entire geographic area combined information on emissions, with information on meteorological conditions in the study area. Such a model estimated hourly concentrations of the different compounds in a square kilometre grid.^{1,2} The model estimated outdoor concentrations of pollution at each individual's home, place of employment or places visited. This method is described in more detail elsewhere.³

People generally spend so much of their time indoors, that it is of importance to know indoor air quality. It is important to quantify how much of outdoor air pollution penetrates into the home, and to describe possible indoor sources of air pollution. Norwegian homes do not use gas cooking or heating, and therefore do not possess this important indoor source of nitrogen oxides. Tobacco smoke is the single most important factor for indoor pollution in Norwegian homes. Indoor measurements at home were made at selected homes, and algorithms derived from these measurements were used in the individual exposure estimating.

An exposure assessment model estimated each individual's pollution exposure for each hour. For each of the pollutant compounds, the model took into account the following major elements: (1) geographic location, (2) proximity to traffic, (3) being indoors or outdoors, (4) shopping, and (5) travelling.

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‡For Part V, see ref. 14.

The dispersion model

Grenland (see Fig. 1) lies in a long and relatively wide valley opening to the sea. It is a highly industrialised locality of $16 \times 23 \text{ km}^2$. The topography combined with climate creates local temperature inversions in the winter, with poor atmospheric dispersion conditions, often leading to higher concentrations of several types of pollutants. The land-sea breeze primarily influences pollutant dispersion from most industrial sites in the valley in the summer and inversions in the winter. In the summer, the land-sea breeze leads the wind into the valley during the day and out to sea at night.

The main sources of air pollution in Grenland are local emissions from industry, vehicular traffic, domestic heating and boat traffic.

For modelling, the entire Grenland area was divided into a square kilometre grid system. Each participant's home and work/school address was coded to the nearest km^2 . The code also indicated proximity to a major road.

The dispersion model (EPISODE) estimated the concentration of each compound in each grid square (km^2) using meteorological conditions measured continuously at two stations. Measured ambient pollution concentrations at 5 stations were used to control the concentration field.^{1,2} The dispersion model usually functions by dispersing known emissions at specified locations. For SO_2 , and NO_x , emission inventories

were available. Emissions were assessed for elemental chlorine and model calculations were performed for Cl_2 and did not account for chemical reactions.

However, emissions were not known for all compounds. Ozone concentrations within the model area were assessed from background concentrations, ozone depletion by NO_x and ozone formation based on the dissociation of NO_2 . Long-range transport that may at times contribute around 30% of the concentrations of NO_x was also accounted for.

For sulfates, nitrates and suspended particles, emissions were again not known, and an appropriate model did not exist. Therefore, the model for suspended particles distributed measured total suspended particles over a twelve hour period according to continuous measurements of visibility.

Fig. 2 gives an overview of the relative importance of various sources of emissions. Information on emissions from industry and from both boat and car traffic was collected immediately prior to the field study. Efforts were made to collect emissions on an hourly basis.

A separate model using traffic counts estimated pollution concentrations along the major roads for different hours of the day and under different meteorological conditions.

For a more complete discussion of the elements included in the dispersion model, the uncertainties in the model and tests of the validation of the model, see other articles in this series.^{2,3}

Air quality measurements

Outdoor measurements. The principal compounds measured were sulfur dioxide (SO_2), nitrogen oxide (NO), nitrogen oxides (NO_x), ozone (O_3), sulfates (SO_4), nitrates (NO_3), particulate matter ($\text{PM}_{2.5}$) and pollen. Nine air quality stations in the area measured air quality and meteorological parameters during the two investigation periods. Fig. 1 shows the measuring sites for air quality and meteorological parameters.

Indoor measurements. People in general spend most of their time indoors. If in addition windows and doors are closed, air quality indoors can be substantially different from outdoors. Opening of windows for ventilation can for some compounds, influence indoor air quality. Using simultaneous measurements made indoors and outdoors, a set of algorithms was developed to estimate pollution concentrations indoors. Most notably, exposure to suspended particles was increased when people smoked or were exposed to passive smoking, or nearby traffic.

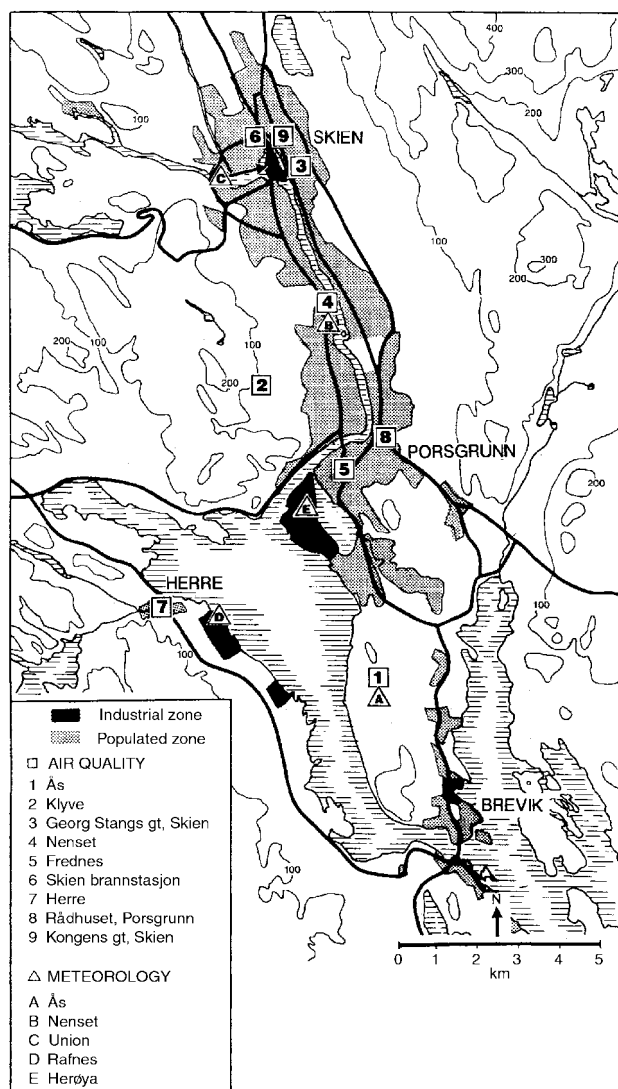


Fig. 1 Location of stations for measuring air quality and meteorological conditions in the Grenland area.

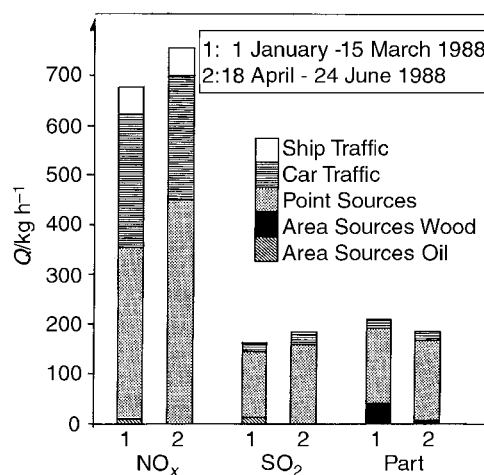


Fig. 2 Average total emission intensity (Q) of SO_2 , total suspended particles (TSP) and NO_x from different source groups in winter and summer.

Simultaneous indoor and outdoor measurements for a three day period for 15 typical homes, determined indoor concentrations due to penetration into the home, and/or indoor sources (e.g. smoking). Measurements were made for three periods per day in each home, for both a winter and summer period.⁴

Data collected from each individual

Over 260 people participated in the study both in winter and summer. Each person filled out a diary, once a day on an hourly basis. Each person was to indicate when and how long he/she was at home, at work or school, or visiting other places (providing address), outdoors, or indoors, with or without open windows. Each address was coded to the nearest square kilometre in addition to noting closeness to major traffic arteries.

Traffic is one of the major pollution sources that contributes to exposure to NO_x and suspended particles. Therefore, it is also necessary to know when people are travelling and how much traffic they are encountering. The participants indicated how many minutes they were travelling in dense, medium or little traffic. These terms were defined.

Each person was also to indicate how many minutes he/she was shopping either in downtown Skien or Porsgrunn (the two major towns in the area) or other places. Skien had at that time an outdoor shopping area that was essentially free of traffic, whereas a major road crossed Porsgrunn. Therefore, the model used an average of the squares that represent the shopping area in Skien and an average of the km² in downtown Porsgrunn, plus an additional factor for vehicular traffic for estimating concentrations when shopping in Porsgrunn.

Results

Time-use information provided by the diary

Results of studies of the health effect of air pollution carried out in different countries where individual exposure has not been measured should be compared with care. Even though pollution levels may be lower in one country, exposure may be higher due to cultural differences in ventilation of homes (i.e. sleeping with windows open) and amount of time spent outdoors. This section summarises such features for the studied Norwegian population.

There is a sharp contrast in time spent with the window open, closed or outdoors between winter and summer (Table 1). Even in the winter, people spend an average of 17% of their time in rooms with the window open and 3% of their time outdoors. In the summer, time spent outdoors can be as high as 20%. Children are more outdoors than adults. Women are outdoors less than men, but have the window open more than men. Assuming that a yearly average is a direct mean of the summer and winter values given in Table 1, Norwegians seem to be outdoors more than in most other countries.⁵⁻¹¹ Time spent outdoors in this region does not differ from values estimated for Norway¹² as a whole.

Time spent travelling is stable in both winter and summer. No comparison is available for time spent indoors with or without the window open, since few studies have segregated these parameters. Otherwise it is evident that features of this population reflect a society dominated by working in the factories, with for example shift work influencing wake-up time.

Measured ambient and indoor concentrations

Due to a mild winter, pollution concentrations varied considerably. Increases in sulfates and suspended particles accompanied the two coldest periods that occurred that winter.

Table 2 summarises the maximum values of different air pollution components measured outdoors during the period January to June 1988. Table 3 provides the algorithms used for indoor concentrations based on the measurement programme inside selected homes.

Estimated exposure to different air pollution components in Grenland

Based on information reported in the diary and summarised in the previous section, each participant's exposure to each component was estimated each hour. It was necessary, in order to use these exposure estimates further in assessing the health effects of air pollution, to know how contaminants correlated with each other. It was an *a priori* assumption that the unique geographical features of the region should result in a relatively independent distribution of the contaminants that should allow one to distinguish between the effects of each component. As can be seen in the figures in Part I of this series,³ dispersion model results demonstrated that this assumption was correct.

Interrelations between exposure estimates for individual components are generally stronger in summer than in winter but often of the same general dimension. Important exceptions are relative humidity and sulfates (slight negative correlation in the winter, yet a stronger positive correlation in the summer). O₃ correlates negatively with all compounds other than sulfates in the winter, whereas it correlates positively with all compounds other than CO and chlorine in the summer.

Table 4 indicates where the correlation exceeded 0.25, which is a value chosen to represent a meaningful correlation. With our amount of data, 0.001 significance level is reached for correlation coefficient values under 0.1.

Table 5 summarises participants' exposure. The table shows percentiles of exposure estimates and maximum estimated exposure for winter and summer.

These estimated concentrations could be described as a function of various parameters.

Changes in temperature and humidity during day and night are especially noticeable in the summer, and affect some of the contaminants giving them marked daily variations. Human activities that tend to occur at routine times during the day, that is, driving to work, working, *etc.* can also affect exposure to contaminants.

Fig. 3 shows changes in exposure to the gaseous and particulate air contaminants as a function of hour whereas Fig. 4 shows exposure day by day during the investigation. Exposure to NO is higher in the winter than in the summer and exposure to NO₂ slightly lower in the winter. Concentrations of NO, and to a lesser degree NO₂, show the typical peaks associated with exposure to traffic pollution. These peaks are especially noticeable in the afternoon rush hour and are slightly higher during the winter than the summer. Exposure to SO₂ is only slightly higher in the winter than in the summer and does not vary markedly with time of day. Exposure to O₃ is, as expected, much higher in the summer than in the winter and shows a pronounced daily variation in the winter but not in the summer. Exposure to nitrates and sulfates is lower in the winter than in the summer.

There were only minor differences in exposure between the two sexes. However, exposure to all parameters was either equal or slightly higher in men, except for suspended particles. Men had slightly higher levels of exposure to the nitrogen oxide components. This is especially noticeable in younger men, possibly due to more exposure to traffic pollution. Both older men and women have higher exposure to ozone, due to more time spent outdoors. The higher exposure to suspended particles in women is especially evident in younger women. Younger men, however, have also higher levels of exposure

Table 1 Time spent in different microenvironments by age group of participants. Percent of registered wake-up and go to sleep time in the different participant subgroups

	Winter			Summer		
	Adult women	Adult men	Children	Adult women	Adult men	Children
Type of location (% of time)						
Home	74.6	67.4	68.6	68.8	62.7	66.4
At work/school/kindergarten	9.7	17.4	12.4	8.7	15.2	10.4
Other places	15.7	15.2	19.0	22.5	22.1	23.2
Indoors window closed	76.5	76.3	81.2	45.5	44.0	54.9
Indoors window open	19.2	16.3	9.9	38.1	33.8	18.9
Outdoors	1.1	3.8	6.5	12.9	18.6	23.0
Travelling whole hour	3.2	3.6	2.4	3.6	3.6	3.2
Number of minutes traveling						
Dense traffic	3.9	6.9	6.9	6.1	8.0	6.2
Medium traffic	19.4	27.6	16.6	20.3	27.9	19.6
Light traffic	20.9	26.9	19.5	21.1	22.7	18.7
Total daily shopping	26.4	23.2	15.2	27.3	21.8	22.4
Type of activity (% of time)						
Sleeping	35.3	33.8	42.4	33.8	32.7	40.7
Daily activity	63.4	64.6	54.8	65.1	65.4	57.8
Hard work/training	1.2	1.5	2.8	1.0	2.0	1.7
Wake up time (% of registered cases)						
06.00–07.00	0.9	3.3	0.7	0.9	4.2	0.1
07.00–08.00	12.4	25.7	4.1	15.1	26.6	2.2
08.00–09.00	26.6	28.6	46.2	29.3	30.5	39.7
09.00–10.00	24.8	17.7	24.7	27.0	19.5	32.2
10.00–11.00	18.0	11.8	12.2	14.9	11.0	15.1
11.00–12.00	6.3	4.0	6.7	5.0	2.7	5.6
12.00–13.00	2.4	1.5	2.2	1.7	1.1	2.3
Sleep time (% of registered cases)						
19.00–20.00	0.1	0.1	0.3	0.3	0.0	0.1
20.00–21.00	0.2	0.2	13.1	0.2	0.1	4.2
21.00–22.00	1.4	2.3	37.0	0.6	1.1	30.8
22.00–23.00	11.8	16.7	20.0	7.1	13.8	23.5
23.00–24.00	35.9	38.8	17.7	34.6	39.1	23.8
24.00–01.00	33.6	28.2	7.6	42.8	35.7	14.2
01.00–02.00	5.2	3.7	0.5	5.3	3.8	0.1
02.00–03.00	2.3	2.0	0.6	2.3	1.4	0.8

Table 2 Summary of maximum values of different air pollution components during the period January to June 1988

Component	Averaging time/h	Ås	Herre	Frednes	Klyve	City hall Porsgrunn	Nenset	G. Stangs gt Skien	Skien Fire st.	Kongensgt
SO ₂ /µg m ⁻³	1	147		338	474		203	872	2027	
	24	32	23	37	55	26	63	134	320	121
NO _x /µg m ⁻³	1	296		761	326		820	463	551	
	24	110		320	104		273	167	229	
NO ₂ /µg m ⁻³	1	192		119	191		125	102	121	
	24	84		70	75		61	47	59	90
Haze/10 ⁻⁶ m ⁻¹	1	764		1061			572			
	24	116		71			58			
O ₃ /µg m ⁻³	1	185		150						
	8	179		141						
Suspended particles/µg m ⁻³	12	69		89	74		93	94		
	12	16.7		16.2	17.8		16.3	15.3		
SO ₄ /µg m ⁻³	12	10.7		9.8	12.7		6.4	5.9		
NO ₃ /µg m ⁻³	12	6.6		4.7	3.3		4.6	5.0		
Cl ₂ /µg m ⁻³	12									
Soot/µg m ⁻³	24	31	30			79				104
Lead/µg m ⁻³	24									1.21
NH ₃ /µg m ⁻³	24	9.6								
NH ₄ /µg m ⁻³	24	8.7	5.3							
Formaldehyde/µg m ⁻³	24				0.7					

than older men. This is due to higher exposure to tobacco smoke in the young as opposed to the elderly, and in women as opposed to men, as seen in the data.

Non-smokers are slightly more exposed in the winter than in the summer to particles. The difference between winter and summer is more noticeable in occasional smokers and even

more marked in daily smokers. There is a mean difference of 32 µg m⁻³ exposure to suspended particles in the winter, between non-smokers and those who smoke every day; whereas that difference is only 10 µg m⁻³ in the summer. This is a direct reflection of time spent outdoors or with the window open in the summer as opposed to the winter.

Table 3 Relationships between indoor (C_i) and outdoor (C_o) concentrations of selected pollutants in Norwegian homes in $\mu\text{g m}^3$

Compound	Winter		Summer	
	0800–2000	2000–0800	0800–2000	2000–0800
SO ₂			$C_i = 0.49C_o + 5.05$	
NO ₂	$C_i = 0.21C_o + 10.5^a$	$C_i = 0.28C_o + 6.3$	$C_i = 0.34C_o + 9.55$	$C_i = 0.56C_o + 7.5$
PM _{2.5}	$C_i = 0.73C_o - 0.75^b$	$C_i = 0.7C_o - 3.0^c$	$C_i = 0.75C_o + 0.25^d$	$C_i = 0.72C_o + 5.00^e$
SO ₄	$C_i = 0.73C_o + 0.32$	$C_i = 0.70C_o - 0.23$	$C_i = 0.75C_o + 0.43$	$C_i = 0.72C_o - 0.26$
CO			$C_i = 0.7C_o$	
O ₃			$C_i = 0.2C_o$	

^aFor NO₂ the time intervals are 1600–2400 and 0000–1600. ^bFor PM_{2.5} the values here are for non-smoking homes, the constant becomes additive and increases to 36.75 and 97.75 for homes with smoking of 1 to 10 cigarettes per day and homes with smoking of more than 10 cigarettes per day respectively. ^cFor PM_{2.5} the values here are for non-smoking homes, the constant increases to 23.0 and 60.5 for homes with smoking of 1 to 10 cigarettes per day and homes with smoking of more than 10 cigarettes per day respectively. ^dFor PM_{2.5} the values here are for non-smoking homes, the constant increases to 8.25 and 45.3 for homes with smoking of 1 to 10 cigarettes per day and homes with smoking of more than 10 cigarettes per day respectively. ^eFor PM_{2.5} the values here are for non-smoking homes, the constant increases to 23.0 and 60.5 for homes with smoking of 1 to 10 cigarettes per day and homes with smoking of more than 10 cigarettes per day respectively.

Table 4 Mean weighted Pearson correlation coefficients for the log-transformed air pollution exposure data for winter (under the diagonal) and summer, (above the diagonal) (only values over 0.25 listed). Each season is based on approximately 260 individuals, with 1000 registered hours each

	SO ₂	NO _x	NO ₂	O ₃	PM _{2.5}	Cl ₂	SO ₄	NO ₃	CO	Temperature	Relative humidity	
SO ₂	—	0.78	0.79		0.62		0.44	0.38				
NO _x	0.67	—	0.99	0.28	0.71		0.53	0.43	0.91			
NO ₂	0.67	0.89	—	0.31	0.71		0.53	0.43	0.73			
O ₃				—	0.35		0.31	—	−0.35	0.43	−0.40	S
PM _{2.5}	0.58	0.57	0.56		—	0.29	0.60	0.45	0.60			u
Cl ₂						—						m
SO ₄	0.44	0.35	0.37		0.35		—	0.62			0.33	m
NO ₃		0.40	0.35		0.26		0.43	—				e
CO		0.83	0.68		0.47				—			r
Temperature								0.33		—	−0.53	
Relative humidity				−0.39				0.28		0.26	—	
												Winter

Table 5 Percentiles of the calculated exposure to air pollutants for study population

Randomly selected study population	Median	95% quantile	Maximum
Winter^a			
Sulfur dioxide/ $\mu\text{g m}^{-3}$	9	22	900
Nitrogen dioxide/ $\mu\text{g m}^{-3}$	17	85	3065
Ozone/ $\mu\text{g m}^{-3}$	4	41	93
Particles (fine fr.)/ $\mu\text{g m}^{-3}$	17	108	581
Sulfates/ $\mu\text{g m}^{-3}$	2	8	17
Nitrate/ $\mu\text{g m}^{-3}$	0	2	8
Chlorine/ $\mu\text{g m}^{-3}$	0	7	297
Summer			
Sulfur dioxide/ $\mu\text{g m}^{-3}$	7	19	1414
Nitrogen dioxide/ $\mu\text{g m}^{-3}$	16	55	2313
Ozone/ $\mu\text{g m}^{-3}$	24	112	185
Particles (fine fr.)/ $\mu\text{g m}^{-3}$	11	53	614
Sulfates/ $\mu\text{g m}^{-3}$	2	10	15
Nitrate/ $\mu\text{g m}^{-3}$	0	2	9
Chlorine/ $\mu\text{g m}^{-3}$	0	1	55
Birch pollen/pollen m^{-3}	0	47	833
Grass pollen/pollen m^{-3}	0	19	2185

^aNumber of hours registered: Winter: 354 735; summer: 304 697.

Discussion

The most important sources in the area are industrial and high pollution concentrations occur only sporadically (problems in operation of the plants). High exposure mainly occurs for one compound at a time.

Variations in lifestyle (time spent outdoors, keeping windows open) *etc.* were large between seasons and population groups,

showing the need for accounting for these facts when investigating the effects of air pollution on health.

The diary method used in this investigation has proven itself as a feasible basis for estimating personal exposure for an investigation of short-term health effects. It allows one to measure more individuals over a longer time period, divided into shorter time intervals. This method allows one to estimate more pollution compounds than an ideal method using portable pollution measuring equipment could possibly do. However, one can argue that a combination of both these approaches would be advantageous. This was carried out in a later investigation in a region with traffic pollution.¹³

The exposure assessment model DINEX, used here, allowed combining concentrations of pollution measured at fixed site stations with individual differences in behaviour and lifestyle, thus creating a personalised and hopefully more exact exposure estimate.

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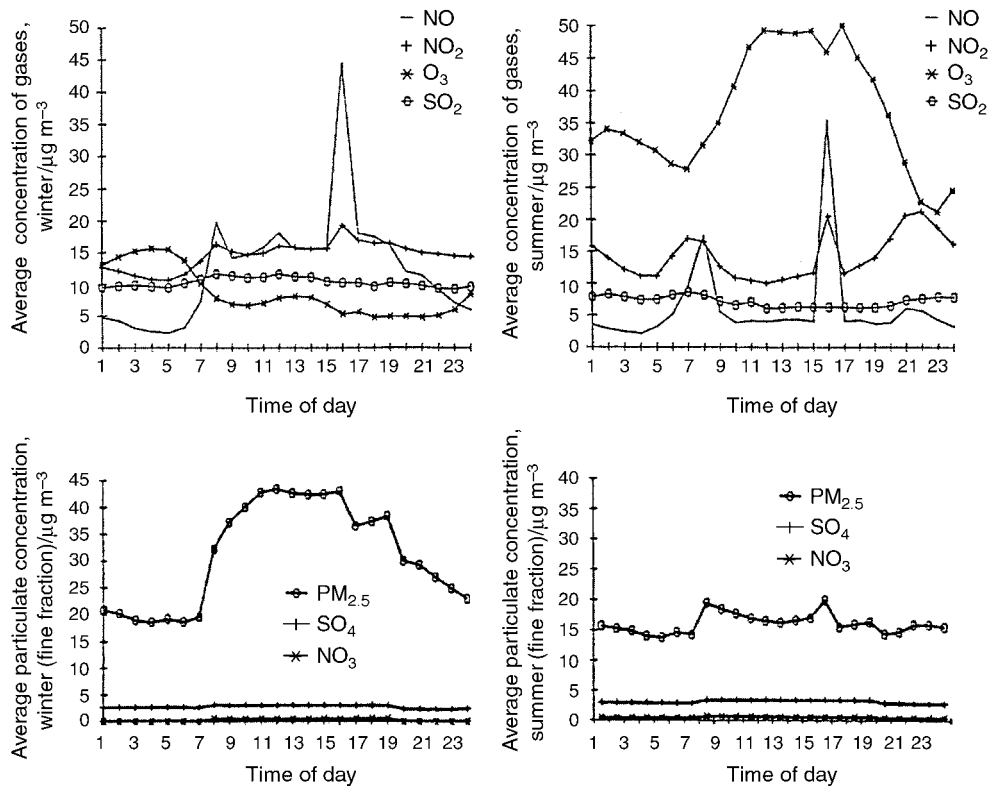


Fig. 3 Variations in concentrations of exposure to the gaseous contaminants (NO, NO₂, O₃ and SO₂) and particulate contaminants (PM_{2.5}, sulfate and nitrate) as a function of time of day and season.

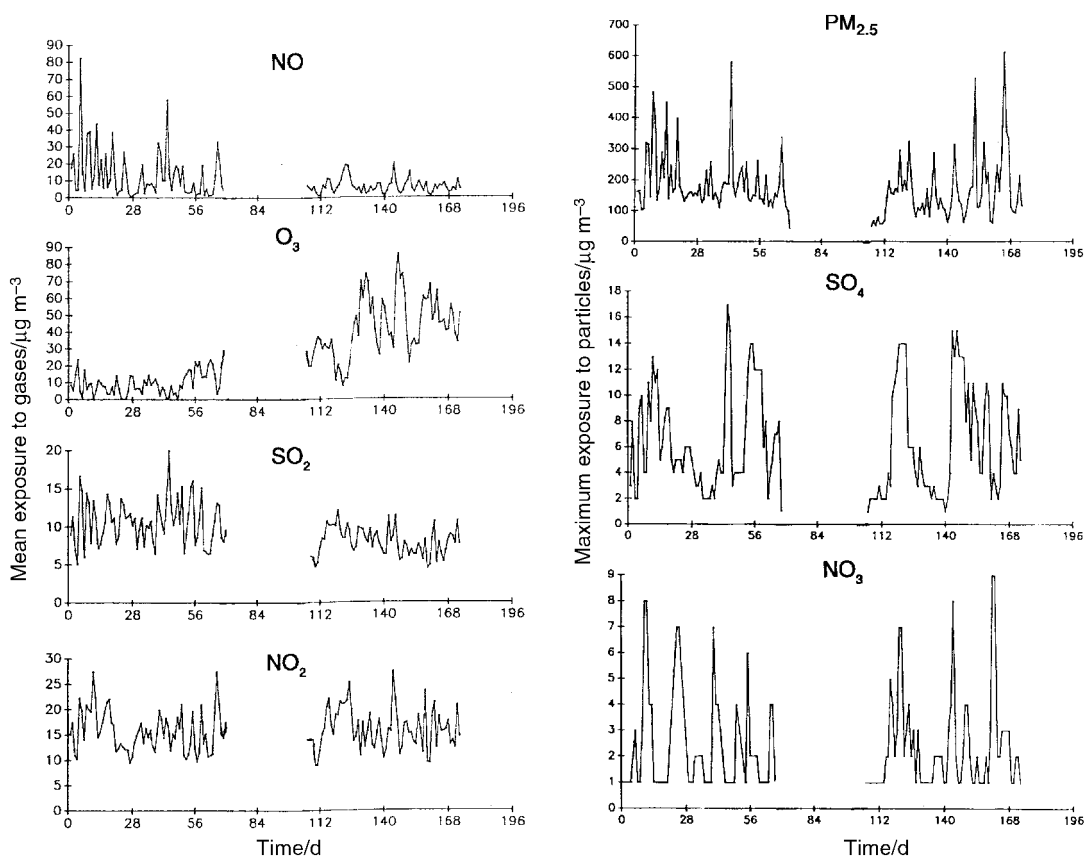


Fig. 4 Concentrations of mean daily exposure of the entire study population to the gaseous and particulate matter (PM_{2.5}) contaminants as a function of day of study. Day 1 = January 2, 1988.

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