

NILU : OR 57/2000
REFERENCE : E-91029D
DATE : NOVEMBER 2001
ISBN : 82-425-1225-6

**Evaluation of urban scale
time-dependent
dispersion model with
subgrid elements
in Oslo, Norway**

**Knut Erik Grønskei, Frederick Gram,
Steinar Larssen and Sam-Erik Walker**

Contents

	Page
Summary	3
1. Introduction	5
2. The establishment of the test data base	6
3. Description of the dispersion model.....	9
4. Evaluation of the NO_x model.....	15
5. Deviation from photochemical balance on an urban scale in Norway	19
6. Evaluation of the chemical balance conditions at the different stations ...	24
7. Description of the NO₂-model.....	28
8. Evaluation of the NO₂- and O₃-models	29
9. References.....	32
Appendix A Description of model evaluation parameters	35

Summary

Hourly data on emission, wind and dispersion conditions are used to calculate hourly NO_x -concentrations in a 1 km grid system based on a time dependent finite difference dispersion model in three horizontal layers.

The local pollution contributions from roads and from point sources within 1 km distance are accounted for by a subgrid model based on Gaussian line source and point source models.

Results of concentration calculations are evaluated by using data from eight stations for four winter months (1.11.1991-29.2.1992) and from the three main stations for two summer months (1.5.-30.6.1992).

The time variation of calculated concentrations, as a result of variations in emissions and/or dispersion conditions, is compared with observed variations. On an hourly basis nearly all fluctuations are reproduced in the calculated values. The amplitudes of the fluctuations may be different as a result of inaccurate input data and model simplifications.

In the centre of the city the correlation coefficient is close to 0.8 during the winter months, 0.5-0.6 during the summer months. In the suburbs the correlation is lower (0.6-0.7) during the winter months.

The evaluation show a tendency to overestimate the NO_x -concentration by the calculation procedure. In particular the overestimation of monthly mean values is more than 100% during summer months.

- The subgrid-model overestimates maximum concentrations close to roads during low wind conditions.
- The finite difference model overestimates concentrations in the centre of Oslo.

The relative importance of processes affecting the NO_2 -concentrations in an urban area as a function of advection time from a line source are discussed. A balance between NO , NO_2 and O_3 is found when the advection time is larger than 600-1000 s. The current calculation procedure leads to an overestimation of long-term averages of NO_2 close to lane sources (roads). It is of importance to improve the model, since it affects the assessment of NO_2 relative to the EU and Norwegian limit values.

The segregation between regional scale ozone and local scale NO has to be accounted for in a realistic NO_2 -model. The combination of a subgrid line-source model and a grid model has been applied as a first approximation of the segregation process. The calculation procedure for NO_2 was proposed by Yamartino and Wiegand in 1986.

Evaluation of urban scale time-dependent dispersion model with subgrid elements in Oslo, Norway

1. Introduction

Results from monitoring of air pollution concentrations in cities in Norway have shown that nitrogen dioxide (NO₂) is one of the compounds which most often, and to the largest extent, exceeds current air quality guidelines (Hagen, 1992; Larssen and Røstad, 1993). This is the case both in city streets and in the urban atmosphere in general. In Norway, the highest NO₂ concentrations occur during the winter months, in connection with "episodes" with poor dispersion. In the general urban atmosphere, high 24-hour average values are of greatest concern relative to Air Quality Guideline (AQG), while in the street atmosphere, very high peak (hourly) concentrations may be the most important problem.

This paper describes the testing of an urban scale, time varying dispersion model under development at the Norwegian Institute for Air Research (NILU), to calculate, as a function of time and space, NO_x and NO₂ concentrations in a grid (length 500 m-1 km) and in receptor points within the grid by means of integrated subgrid models. Input to the model are time-varying gridded fields of emissions and dispersion parameters.

The urban scale time dependent model has been used to describe the spatial distribution of air pollution in other urbanised areas (Grønskei et al., 1990, 1993), and the model has been further developed to account for subgrid variations as a result of emissions along roads and streets in Oslo. The subgrid model is based on HIWAY-2 (Petersen, 1980). This model has been modified to account for emission conditions in Oslo by Larssen et al., 1990.

The model evaluation is based on measurements of air quality, wind and dispersion conditions in Oslo in the period October 1991-June 1992 (Hagen et al., 1993).

The research carried out during the project, to develop and test the model with sub-grid elements, includes the following:

- Development of a data base for testing of the model for the city of Oslo, including an emission inventory and continuous measurement of NO, NO₂, O₃ and dispersion parameters at a number of locations in Oslo during winter and summer periods (described further in chapter 2).
- Model development (described further in chapter 3).
- Model testing and modification (chapter 4).

2. The establishment of the test data base

Description of the Oslo area

Oslo is situated at the end of the 100 km long Oslofjord (Figure 1). Surrounded by hills of height 200-500 meters, the city topography is bowl-like with valleys protruding between hills, the main valley rising from the fjord and city centre towards the Northeast. The area has a continental-type climate, normally with relatively cold winters (mean winter temperature: -3.9°C) and local drainage winds from the hill valleys, dominated in the city centre by the drainage down the main Northeast valley.

Oslo is largely a commercial city. There are only a few minor industrial emission sources and power plants. Car traffic is by far the dominating source of air pollution emissions, while space heating by oil (low-sulphur) and, in cold periods, wood burning, also contributes notably to the air pollution.

Emission inventory

The emission survey covers the urban part of Oslo, the eastern part of Bærum and the northern part of Nesodden, within a grid of $22 \times 18 \text{ km}^2$. As the model is using data on area sources as well as subgrid point and line sources, it is important to present the emission data on different levels for the dispersion model. The main source of nitrogen oxides in the Oslo area is road traffic, so the major work was performed on the calculation of traffic emissions (Gram, 1994).

Road traffic. Data for traffic intensity for the main roads were available for the morning and afternoon rush, plus for "low traffic" conditions. The data were provided by the traffic authorities in Oslo by using the TRIPS model. (The "low traffic" corresponds to the period at noon, not night traffic.) The average daily traffic is calculated as $(2 * \text{morning} + 2 * \text{afternoon} + 14 * \text{low})$, assuming low traffic during 6 night hours. From these 3 data sets plus average traffic, emissions of CO, NO_x , NO_2 and VOC within each km^2 were calculated, using routines from the NILU traffic model RoadAir (Torp and Larssen, 1993), with emission as a function of the driving conditions. Table 1 shows emission data for the main roads in Oslo in 1991. The driving conditions were different for the three scenarios, and for the average traffic. The total length of the main roads within the area was 458 km.

In addition to the emissions from the main roads, emissions were estimated for 954 km local roads to 1160 kg CO/h, 100 kg NO_x /h, 7 kg NO_2 /h and 112 kg VOC/h. The emission of the nitrogen oxides from the small roads corresponds to the fraction of the traffic work, 10-12 %, but due to a lower speed on the local roads, the emissions of CO and VOC were about 25 % of the total.

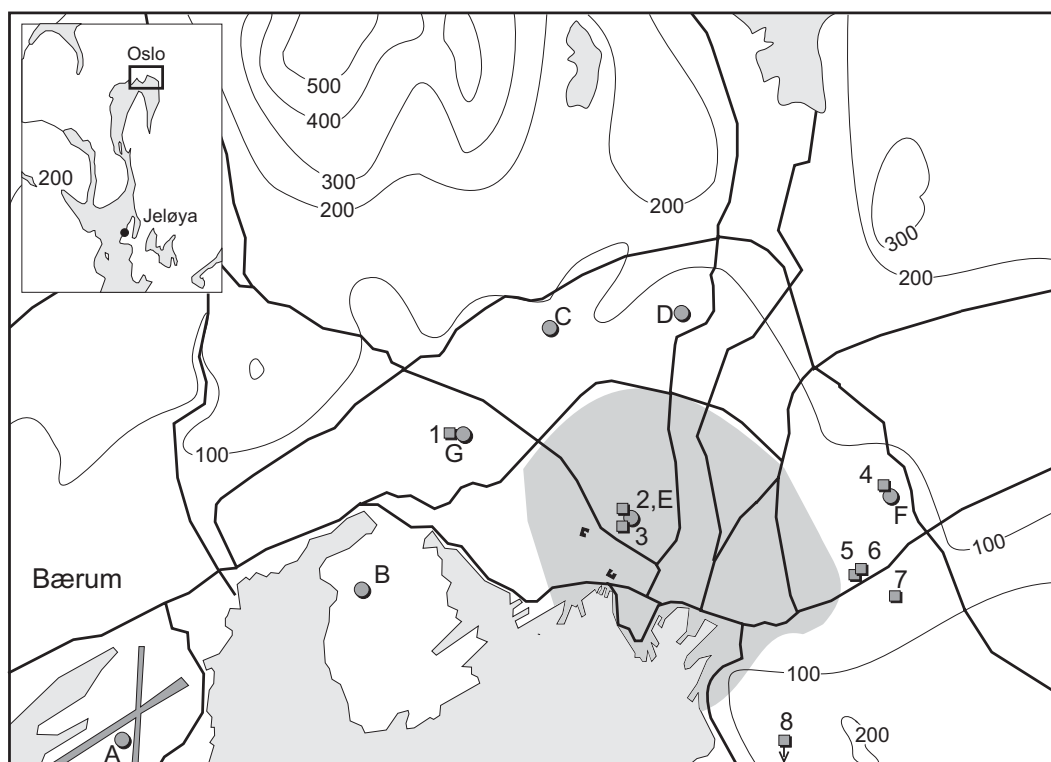


Figure 1: The Oslo area with measurement stations.

Met.stations ○	Air quality stations □
A. Fornebu Airport	1. Skøyen (City regional)
B. Bygdøy	2. Nordahl Bruns street (City regional)
C. Blindern (Norw. Met. Inst.)	3. Pilestredet (Street)
D. Bjølsen	4. Hovin (City regional)
E. Nordahl Bruns street (City centre)	5. Strømsveien (Street)
F. Hovin	6. Fyrstikkalleen (50 m from street)
G. Skøyen	7. Etterstadsletta (City regional)
	8. Holmlia (Suburban residential)

Table 1: Emission data for the main roads in Oslo 1991.

	Traffic work 10 ³ car-km/h	CO kg/h	NO _x kg/h	NO ₂ kg/h	VOC kg/h
Morning	591	11 277	1 979	154	768
Afternoon	596	12 319	2 180	150	776
Low traffic	285	4 167	949	65	364
24 h-average	265	3 245	799	70	330

Other traffic emissions. The calculation of emissions from the harbour traffic and from Fornebu Airport was based upon detailed data about the traffic intensity, specially for the airport.

The harbour traffic is dominated by large ferries with a mean emission of 84 kg NO_x/h. The emission from Fornebu Airport was estimated in 1989 to 39.3 kg NO_x/h as a daily mean value. The airport was closed during the night giving a mean emission of 58.9 kg NO_x/h from 07-23.

Heating. The emissions from industry and the consumption of oil for heating purposes in Oslo are reduced substantially during the last decades, mainly due to low electricity prices, central heating and a fall in the industrial activity. The emission from point sources in Oslo 1991 was estimated to 93 kg NO_x/h, mainly from three incineration plants.

The emission from domestic use of oil and solid fuels was estimated to about 120 kg NO_x/h.

Table 2 shows mean hourly emissions from the Oslo-area for the winter 1991-92.

Table 2: Average hourly emissions of nitrogen oxides from traffic and heating for the winter 1991-92. Unit: kg/h as NO₂.

Traffic		Heating	
Main roads	798.7	Point sources	93.1
Local roads	99.6	Area oil heating	111.5
Harbour	84.0	Solid fuels	8.2
Airport	39.3		
Sum traffic	1 021.6	Sum heating	212.8

Measurement program, NO_x, NO₂, O₃.

A total of 9 measurement stations for nitrogen oxides and ozone were operated during the measurement period starting in October 1991 and ending in July 1992 (Hagen et al., 1993). All stations were not operated simultaneously. The location of the stations within Oslo city boundaries is shown in Figure 1. In addition to these a regional background station was operated, situated in a rural setting on the east coast of the Oslofjord, about 50 km south of Oslo.

The three main stations for testing of the model are the following:

- Skøyen. Located in a park. Distance to surrounding main streets: about 1 km. City regional station
- Nordahl Bruns street. The location is inside a city block, in a built-up area, 4-8 stories buildings. Distance to streets surrounding the block: 30-50 meters. City centre station
- Hovin. Located in residential area with dispersed 4-stories apartment blocks. Distance to main roads: 250 m to the East, 500 m to the West. City regional station

3. Description of the dispersion model

General description

The dispersion model is a gridded, 3-layer model, as shown in Figure 2.

The procedure for calculation and for specification of boundary values are described by Grønskei et al. in 1993.

The dispersion is partly caused by the time variation of the wind field and partly by turbulent exchange. Wind (\mathbf{V}_h and w) and pollution concentrations (c_i) are divided in one average value in grid elements ($\bar{\quad}$) and deviations from the average values (\prime), i.e.

$$\begin{array}{ll} \text{concentrations} & : c_i = \bar{c}_i + c'_i \\ \text{horizontal wind velocity} & : \mathbf{V}_h = \bar{\mathbf{V}}_h + \mathbf{v}'_h \\ \text{vertical wind speed} & : w = \bar{w} + w' \end{array}$$

For each of the pollution components, the following equation is solved:

$$\frac{\partial \bar{c}_i}{\partial t} = - \underbrace{\bar{\mathbf{V}}_h \cdot \nabla_h \bar{c}_i}_{\text{I}} - \underbrace{\bar{w} \frac{\partial \bar{c}_i}{\partial z}}_{\text{II}} - \underbrace{\frac{\partial (\overline{w' c'_i})}{\partial z}}_{\text{III}} - \underbrace{\nabla_h \cdot (\overline{\mathbf{v}'_h c'_i})}_{\text{IV}} + \underbrace{Q_i}_{\text{V}} \quad (3.1)$$

Processes to be considered in the model are:

- ($\bar{\quad}$) spatial average quantities
- I: horizontal advection, $\bar{\mathbf{V}}_h \cdot \nabla_h \bar{c}_i$
 - II: vertical advection, $\bar{w} \frac{\partial \bar{c}_i}{\partial z}$
 - III: turbulent exchange vertically, $\frac{\partial}{\partial z} (\overline{w' c'_i})$
 - IV: turbulent exchange horizontally, $\nabla_h \cdot (\overline{\mathbf{v}'_h c'_i})$
 - V: emission, Q_i .

The computer codes are developed to include chemical reactions between different compounds, but in this presentation such reactions were not taken into account.

The vertical structure is shown in Figure 2.

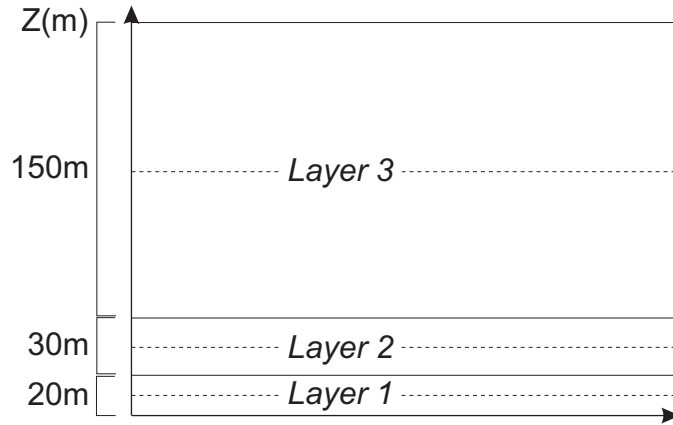


Figure 2: The vertical structure of the three-level model. Emissions from area sources are mixed in layer 1 and layer 2. During inversion situations area source emissions are mixed in layer 1. Point source emissions are located in a layer according to their plume rise.

When sodar measurements were not available in the current study, measurements from station F were used for wind direction in level three. Plume rise above layer three (200 m) was not taken into account.

Wind fields

Wind measurements close to the ground were used to define a two-dimensional wind field $\mathbf{V}_{h1}(\mathbf{r})$ for layer 1. The wind field is calculated by statistical interpolation as described by Eidsvik (1982):

$$\mathbf{V}_{h1}(\mathbf{r}) = a_1(|r - r_1|)\mathbf{V}_{h1}(\mathbf{r}_1) + a_2(|r - r_2|)\mathbf{V}_{h1}(\mathbf{r}_2) + a_3(|r - r_3|)\mathbf{V}_{h1}(\mathbf{r}_3) + a_4(|r - r_4|)\mathbf{V}_{h1}(\mathbf{r}_4) \quad (3.2)$$

$$\left. \begin{array}{l} \mathbf{V}_{h1}(\mathbf{r}_1) \\ \mathbf{V}_{h1}(\mathbf{r}_2) \\ \mathbf{V}_{h1}(\mathbf{r}_3) \\ \mathbf{V}_{h1}(\mathbf{r}_4) \end{array} \right\} \text{observed velocities at four grid points.}$$

$$\left. \begin{array}{l} a_1(|r - r_1|) \\ a_2(|r - r_2|) \\ a_3(|r - r_3|) \\ a_4(|r - r_4|) \end{array} \right\} \text{factors of proportionality, } a_k, \text{ are determined by spatial covariance functions of } |r - r_k|, \text{ the distances between the points of wind interpolation } (r) \text{ and the respective points of wind measurements } (r_k).$$

Observed time series of wind at four wind stations were used to compute spatial covariance functions. The procedure was based on the “variate difference” method described by Kendall et al. (1983). The method is based on considering deviations from smoothed values of the hourly observations of wind.

The interpolated values of horizontal wind velocities based on hourly average wind observations from four wind stations introduce uncertainties into the calculations of hourly pollution concentrations far from the wind stations, in particular close to the point sources.

The vertical wind component is specified by requiring a three-dimensional non-divergent and mass-consistent wind field in each level:

$$\nabla_h \mathbf{V}_h = -\frac{\partial w}{\partial z} \quad (3.3)$$

In the upper layer 3 homogeneous wind according to hourly averaged sodar measurements (\mathbf{V}_{sod}) is used for advection calculations:

$$\mathbf{V}_{h3} = \mathbf{V}_{sod} (150 \text{ m}) \quad (3.4)$$

In layer 2 the following wind field is used for advection calculations:

$$\mathbf{V}_{h2} = 0.5 (\mathbf{V}_{h1} + \mathbf{V}_{h3}) \quad (3.5)$$

It may not be possible to describe the modes of motion that are important for vertical advection of pollution by using observations of horizontal winds only. Results of flow-field model calculations combined with wind measurements may improve the wind fields for calculation of advection terms considerably.

This source of error is probably more important for dispersion calculation in areas where vertical advection of pollution is important (Eidsvik, 1982).

Description of the diffusion process

Mean concentration distribution as a result of dispersion of emission from a point source may be approximated by a Gaussian plume formula. For the standard deviation in the vertical pollution distribution (σ_z) the following formula applies:

$$\sigma_z = \frac{\sigma_w t}{(1 + t / 2T_L)^{1/2}} \quad (3.6)$$

σ_w : the standard deviation of vertical wind fluctuations.

T_L : Lagrangian time scale

t : time of advection

The formulae is based on the assumption of stationary and homogenous turbulence conditions locally (Csanady, 1973). The variation with respect to advection time is found by derivation of equation 3.6 with respect to time.

$$\frac{d\sigma_z}{dt} = \sigma_z \frac{4T_L + t}{t(4T_L + 2t)}, \quad (3.7)$$

Venkatram (1984) described the length scale of turbulence (l) as a function of height above the ground (z) and temperature stratification ($\partial\theta / \partial z$) by equation (3.8):

$$\frac{1}{l} = \frac{1}{l_n} + \frac{1}{l_s}, \quad (3.8)$$

where $l_n = \alpha z$ provided $z_0 \ll z \ll H$,

$$l_s = \gamma^2 \frac{\sigma_w}{N},$$

$\alpha = 0.36$, $\gamma = 0.52$ are empirical factors of proportionality,

$$N = \left(\frac{gd\theta}{\theta dz} \right)^{0.5},$$

$$T_L = \frac{l}{\sigma_w},$$

l : the length scale of turbulence

H : the mixing height

z_0 : roughness length

l_n : the length scale of turbulence for neutral atmospheric temperature stratification

l_s : the length scale for stable temperature stratification

N : the local value of the Brunt-Väisälä frequency at height z

Information on dispersion conditions based on the formula for plume development is used to determine hourly values of vertical exchange of pollution by turbulence (Equation 3.6). Sodar measurements of vertical fluctuations in the wind field (σ_w) at the levels separating the model layers (20, 50 and 200 m) were used in addition to observed values of the temperature variation with height at station A (Hovin) as a typical value for the definition of the Brunt-Väisälä frequency.

In the finite difference model the concentration within each layer is assumed to be constant with respect to height within each grid square.

In order to estimate turbulent mixing of pollution consistent with the subgrid plume models, it is assumed that the pollution in the layer between two levels in the grid model corresponds to a Gaussian plume with the same vertical extension. The following formulae is found for the first moment of a Gaussian pollution distribution (\bar{z}):

$$\bar{z} = \frac{\int_{Ho}^{\infty} z c_o \exp\left(\frac{z - Ho}{\sigma_z}\right) dz}{\int_{Ho}^{\infty} c_o \exp\left(\frac{z - Ho}{\sigma_z}\right) dz}$$

$$\bar{z} = \sqrt{\frac{2}{\pi}} \sigma_z \quad (3.9)$$

A reasonable value of the vertical extent of a subgrid plume when the further description of dispersion is carried out in the grid system would be:

$$\sigma_{z_{1-2}}(t_o) = \sqrt{\frac{\pi}{2}} \Delta z_{1-2}$$

It is assumed that the growth of Gaussian plumes on each side of the separation between the grid cells cause exchange pollution in accordance with the following formulae for the flux between the layers ($F_{1,2}$):

$$F_{1,2} = -\frac{d\bar{z}}{dt}(c_2 - c_1) \quad (3.10)$$

The exchange of pollution between layer 1 and layer 2 during the time step Δt is calculated by the following equation based on equations 3.10 and 3.9:

$$\frac{F_{1,2}\Delta t}{C_2 - C_1} = -\sqrt{\frac{2}{\pi}}(\sigma_{z_{1-2}}(t_o + \Delta t) - \sigma_{z_{1-2}}(t_o)) \quad (3.11)$$

It is assumed that the first moment of the vertical pollution distribution between the first and second levels grows with time, causing an exchange of pollution according to Equation (3.11). The exchange will be proportional to the difference in concentration between the levels. The third layer also exchanges pollution with the background air above the upper layer. The following fluxes are calculated:

$$F_0 : \text{dry deposition to the ground,} \quad (3.12)$$

$F_0 = 0$ in this study.

$$\begin{aligned}
F_{1,2} \cdot \Delta t &= -\sqrt{\frac{2}{\pi}}(\sigma_{z_{1-2}}(t_0 + \Delta t) - \sigma_{z_{1-2}}(t_0)) \cdot (C_2 - C_1) \\
F_{2,3} \cdot \Delta t &= -\sqrt{\frac{2}{\pi}}(\sigma_{z_{2-3}}(t_0 + \Delta t) - \sigma_{z_{2-3}}(t_0)) \cdot (C_3 - C_2) \\
F_{3,b} \cdot \Delta t &= -\sqrt{\frac{2}{\pi}}(\sigma_{z_{3-b}}(t_0 + \Delta t) - \sigma_{z_{3-b}}(t_0)) \cdot (C_b - C_3)
\end{aligned} \tag{3.13}$$

The equations 3.13 are used to calculate pollution exchange between the layers in the grid system. Using K-theory would be an alternative.

The pollution fluxes calculated by 3.13 are consistent with the local subgrid models. The variation of the fluxes with grid distance and with meteorological conditions are automatically accounted for (eq. 3.6-3.13).

Measurements of vertical wind fluctuations (σ_w) and temperature at two levels are used as input data for calculating pollution exchange between the layers. Hourly averaged sodar measurements were used for vertical wind fluctuations (σ_w) and for measurements of temperature and temperature variation with respect to height (measurements from station A were used to determine temperature stratification). A further description of the vertical exchange including dry deposition is given by Grønskei and Gram (1984).

For the horizontal exchange process close to the source the method suggested by Irwin (1983) is applied using observed hourly values of horizontal wind fluctuations, σ_v , at each level (10, 35 and 150 m).

$$\sigma_y = \sigma_v f_y \tag{3.14}$$

where σ_y is standard deviation of the pollution distribution perpendicular to the wind direction, σ_v is standard deviation of the fluctuations in the horizontal crosswind component:

$$f_y = 1.0 / (1 + a(t / t_0)^{0.5})$$

$$a = 0.9$$

$$t_0 = 1000 \text{ s}$$

and t is advection time (s).

A procedure corresponding to Equation (3.13) could also be used for the horizontal exchange. The horizontal resolution (distance between grid points) in urban air pollution models is at least 10 times larger than the vertical resolution. The concentration variation in grid cells with time is not sensitive to turbulent exchange of pollution between grid cells in horizontal directions. In this study the horizontal fluxes were calculated by the K-theory in horizontal directions.

$$F_x = -K_h \left(\frac{\partial c}{\partial x} \right)$$

and in the y-direction (3.15)

$$F_y = -K_h \left(\frac{\partial c}{\partial y} \right)$$

$$K_h = 0.1 \sigma_v \Delta x$$

σ_v = standard deviation of horizontal wind fluctuations

Δx = horizontal grid distance.

Estimation of vertical exchange with the background atmosphere may cause errors underestimating concentrations in the lower layers of the model. This applies in particular to pollutants having the main sources in the third layer. The model could probably be improved by adding further layers of calculations above 200 m.

When a regional scale model is used to calculate background concentrations for the local scale model, the vertical fluxes in the large scale model may be used to specify the vertical exchange with the local scale model i.e. $F_{3,b}$

The horizontal advection scheme is based on using Bott's 4th degree positive definite scheme. Vertically the advection scheme is based on using a standard upwind finite difference approach. This combined scheme approximately preserves a constant pollution field and the mass of pollutants emitted into the system. A more detailed description of the finite difference approximation is given in Bott (1989).

The initial distributions of concentrations are specified by measurements or given the homogeneous value of zero, when distributions are not available.

Subgrid model

Close to point sources and close to roads with high traffic intensity, data on subgrid gradients are needed to describe pollution concentrations at measuring stations and for estimating exposure.

A highway model, corresponding to HIWAY (Petersen, 1980) is used to estimate concentrations close to a set of roads with high traffic intensity within the square km² (ΔC^l). A puff trajectory-model is used to calculate the influence of point sources (ΔC^p). The emission intensity of local area sources are reduced accordingly.

4. Evaluation of the NO_x model

The dispersion model has been applied to calculate hourly NO_x-concentrations, based upon data for NO_x-emission (Gram, 1994), and meteorological measurements (Hagen et al., 1993).

Table 3 shows the NO_x-model evaluation parameters for the winter period and the summer period. The model evaluation parameters are described in Appendix A. Time series of observed and calculated NO_x-concentrations are available on request.

Table 3: Evaluation of the NO_x -model for the winter period 1.11.91-29.2.92 and the summer period 1.5.-30.6.1992.

Station	\bar{C}_o (σ_o)	\bar{C}_c (σ_c)	M_o	M_c	r	rmse	$(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$	IA	N
	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$		$\mu\text{g}/\text{m}^3$	%		
Winter									
Valle Hovin	296 (421)	303 (398)	2 694	3 012	0.79	269	40	0.88	2 499
Skøyen	195 (239)	177 (189)	1 264	1 026	0.80	146	38	0.88	1 355
Holmlia	94 (98)	146 (150)	541	909	0.48	144	40	0.62	842
Nordahl Bruns gt.	166 (196)	237 (277)	1 434	1 600	0.73	203	35	0.80	2 876
Pilestredet	476 (425)	427 (424)	2 319	2 410	0.76	299	39	0.87	1 264
Strømsveien	714 (629)	808 (1 079)	3 637	7 535	0.75	748	52	0.79	1 217
Etterstadsletta	216 (298)	333 (394)	1 865	2 776	0.64	328	23	0.75	1 239
Fyrstikkalleen	381 (467)	429 (544)	3 058	3 831	0.78	348	99	0.87	1 019
Summer									
Valle Hovin	53 (71)	119 (123)	732	1 038	0.48	127	53	0.56	1 340
Skøyen	30 (30)	62 (44)	223	292	0.63	48	67	0.63	353
Nordahl Bruns gt.	39 (31)	79 (66)	347	520	0.49	71	57	0.49	1 338

\bar{C}_o = Average observed concentration
 \bar{C}_c = Average model calculated conc.
 M_o = Maximum observed concentration
 M_c = Maximum calculated concentration
 $(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$ = Percentage systematic rmse
 N = Number of observations

σ_o = St. dev. observed concentration
 σ_c = St.dev. model calculated conc.
 r = Correlation coefficient
 rmse = Root mean square error
 IA = Index of agreement

In the winter period the model works well to explain the values at the stations Valle Hovin, Skøyen and Pilestredet and reasonably well at the stations Strømsveien and Fyrstikkalleen. The indices of agreement at the three best stations are close to 0.9. The indices of agreement at Strømsveien and Fyrstikkalleen are 0.79 and 0.87 respectively. Good agreements at these stations as well as at Etterstadsletta are disturbed by an overestimation of the influence from neighbouring roads as a result of the subgrid model in low wind conditions. In particular the influence from Strømsveien is seriously overestimated in episodes i.e. the maximum observed concentration is only 50% of the calculated maximum value and standard deviations of the calculated values close to Strømsveien is 71% higher than the standard deviation of the observed values (see table 4).

*Table 4: Statistical parameters describing differences between observed and calculated time series of concentrations.
Unit: per cent.*

	$\frac{\Delta\bar{C}}{\bar{C}_o}$	$\frac{\Delta\sigma}{\sigma_o}$	$\frac{\Delta C_m}{C_{mo}}$
Winter			
Valle Hovin	2	-5	12
Skøyen	-9	-21	-19
Holmlia	55	53	40
Nordahl Bruns gt.	43	41	12
Pilestredet	-10	0	4
Strømsveien	13	71	107
Etterstad	54	32	49
Fyrstikkalleen	13	20	25
Summer			
Valle Hovin	124	73	41
Skøyen	106	47	31
Nordahl Bruns gt.	103	113	50

$\Delta\bar{C} = \bar{C}_c - \bar{C}_o$: The difference between calculated and observed average values.

$\Delta\sigma = \sigma_c - \sigma_o$: The difference between the standard deviations in calculated and observed time series.

$\Delta C_m = C_{mc} - C_{mo}$: The difference between maximum calculated and maximum observed concentration values.

In the summer period the observed values are seriously overestimated at the stations Valle Hovin, Skøyen and Nordahl Bruns gt. The discrepancies may be reduced in the following way:

- Improved subgrid model including suggested modification of procedures for dispersion calculations close to open roads and streets (Hertel and Berkowicz, 1989).
- Improvements in the procedure for calculating dispersion parameters during summer period.
- Improved description of wind and dispersion conditions in particularly in the suburbs (Holmlia).

The area source model as well as the line source model should be modified.

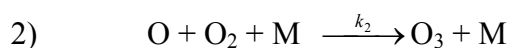
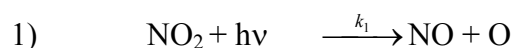
5. Deviation from photochemical balance on an urban scale in Norway

The concentrations of NO, NO₂ and O₃ varies as a result of

- emission and dilution,
- reaction between NO and O₃,
- photodissociation of NO₂,
- other chemical reactions.
- deposition

Within the framework of the project it has not been possible to describe in detail the complex interaction between emission, dispersion and deposition of nitrogen oxides and ozone and chemical reactions in the atmosphere over urban areas.

The basic photochemical cycle in an urban atmosphere are described by the following three reactions:



The reaction number 2 is fast and very low concentrations of atomic oxygen is found in the atmosphere. Ozone can be considered to be a result of reaction number 1.

In an urban area several scales of pollution are present explaining the spatial distribution of pollution components (see Figure 3). The descriptions of spatial distributions include non linear terms in areas where chemical reactions are important.

When the atmosphere is not well mixed, the effect of spatial fluctuations has to be accounted for estimating the reaction between NO and O₃ i.e.

$$\begin{aligned}
 R_{NO,O_3} &= k_3 [NO][O_3] \\
 &= k_3 [\overline{NO}][\overline{O_3}] + k_3 [\overline{NO}'][\overline{O_3}'],
 \end{aligned}$$

where $[NO]'$ and $[O_3]'$ are the deviations from the spatial average concentrations $[\overline{NO}]$ and $[\overline{O_3}]$.

$[NO]'$ and $[O_3]'$ show negative correlation close to the source regions in an urban area, and the fluctuation term suppress the development of NO_2 from the reaction between NO_2 and O_3 .

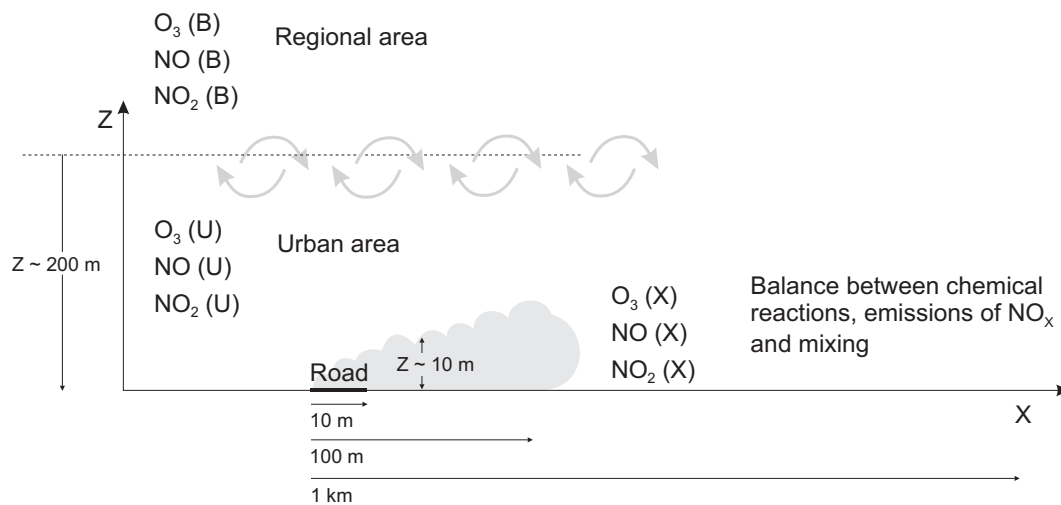


Figure 3: A simplified NO_2 -model for exhaust emissions from a road in an urban area.

(X): distance from road

(U): urban scale concentrations

(B): regional (background) concentrations

In an air parcel the following equations for the individual derivatives with respect to time as a result of chemical reactions reads:

$$\frac{d_h [\overline{NO}]}{dt} = k_1 [\overline{NO_2}] - k_3 [\overline{O_3}][\overline{NO}] - k_3 [\overline{O_3}'][\overline{NO}'] - \overline{w}' [\overline{NO}]' + Q_{NO} \quad (5.1)$$

$$\frac{d_h [\overline{NO_2}]}{dt} = -k_1 [\overline{NO_2}] + k_3 [\overline{O_3}][\overline{NO}] + k_3 [\overline{O_3}'][\overline{NO}'] - \overline{w}' [\overline{NO_2}]' + Q_{NO_2} \quad (5.2)$$

$$\frac{d_h [\overline{O_3}]}{dt} = k_1 [\overline{NO_2}] - k_3 [\overline{O_3}][\overline{NO}] - k_3 [\overline{O_3}'][\overline{NO}'] - \overline{w}' [\overline{O_3}]', \quad (5.3)$$

where w is a measure for the vertical turbulent diffusion.

The marked concentration values show deviations from the spatial average value of the concentration within the air parcel (see chapter 3 and equation 3.1). The O_3 - and NO -concentrations in the atmosphere show negative correlations, and the nonhomogeneous mixing delays the reaction.

The sum of equations (5.1) and (5.2) and the sum of equations (5.2) and (5.3) show that the sum of nitrogen compounds $[NO_x] = [NO] + [NO_2]$ and of oxidant compounds $[O_x] = [O_3] + [NO_2]$ are not influenced by nonlinear chemical reaction terms.

$$\frac{d_h}{dt} ([\overline{NO}] + [\overline{NO_2}]) = -\overline{w}' [\overline{NO}]' - \overline{w}' [\overline{NO_2}]' + Q_{NO_x} \quad (5.4)$$

$$\frac{d_h}{dt} ([\overline{NO_2}] + [\overline{O_3}]) = -\overline{w}' [\overline{NO_2}]' - \overline{w}' [\overline{O_3}]' + Q_{NO_2} \quad (5.5)$$

Further it is seen that

$$\frac{d_h}{dt} ([\overline{NO}] - [\overline{O_3}]) = \overline{w}' [\overline{O_3}]' - \overline{w}' [\overline{NO}]' + Q_{NO} \quad (5.6)$$

To study the relative importance of chemical and dispersion processes in the formation of NO_2 the following equation is given

$$\frac{1}{[\overline{NO_2}]} \frac{d[\overline{NO_2}]}{dt} = \frac{\overline{w}' [\overline{NO_2}]'}{[\overline{NO_2}]} + k_3 [\overline{O_3}] [\overline{NO}] + k_3 [\overline{O_3}]' [\overline{NO}]' - k_1 + \frac{Q_{NO_2}}{NO_2} \quad (5.7)$$

$$[\overline{NO_2}] = [\overline{NO_2}] + [\overline{NO_2}]'$$

:

concentrations

$$[\overline{O_3}] = [\overline{O_3}] + [\overline{O_3}]'$$

k_3 : reaction coefficient for production of NO_2 as a result of reaction between NO and O_3 . The plume containing NO from car traffic, mixes with ambient air containing O_3

k_1 : the photodissociation coefficient for NO_2 by absorption of short wave solar radiation

$$k_1 = 0.01 * (1 - 0.5 * N / 8) * (\exp(-0.39 / \sin(\tau))) \quad [s^{-1}] \quad (5.8)$$

$$k_3 = \left(2.56 / T\right) \exp(-1430 / T) \quad [s \cdot ppb]^{-1}$$

where

N : the cloudiness given in octals ($N = 0$: clear sky; $N = 8$: overcast)

τ : height of the sun above the horizon. Unit: degree

T : temperature. Unit: °K

The cloudiness parameter N is taken from measurements every 6 hour at the meteorological station at Fornebu Airport. τ is calculated for each hour depending on time of the day and day of the year.

To evaluate the importance of the different terms in Eq. 5.7 in the process of improving models, typical values and range of variation in cities are estimated. To study their relative importance the conditions are described as a function of advection time from a line source.

Figure 4 shows the specific rate of concentrations reduction for NO_2 as a function of advection time from the road. Close to the road i.e. when the advection time is less than about 30-50 seconds, the dispersion of the plume is the most important term explaining the rate of concentration reduction for NO_2 . When NO_2 is diluted O_3 is transferred from the background atmosphere and the reaction between NO and O_3 is important as long as NO is observed in the atmosphere, i.e. close to the sources or when the dissociation of NO_2 is important.

As the development of NO_2 is suppressed, a chemical balance is not expected to be found in urban areas unless the O_3 - or NO_2 -concentration is very small.

When the advection time last longer than 100-200 seconds the photodissociation of NO_2 becomes important when the solar radiation is strong. At night and in winter the photodissociation of NO_2 is negligible.

The scale analyses of the different terms in equation (5.6) indicate that chemical reactions as well as effects of small scale mixing have to be taken into account when NO_2 -concentrations are going to be described in an urban area. The time scale of small scale mixing is larger than the Lagrangian time scale (se eq. 3.6-eq. 3.8).

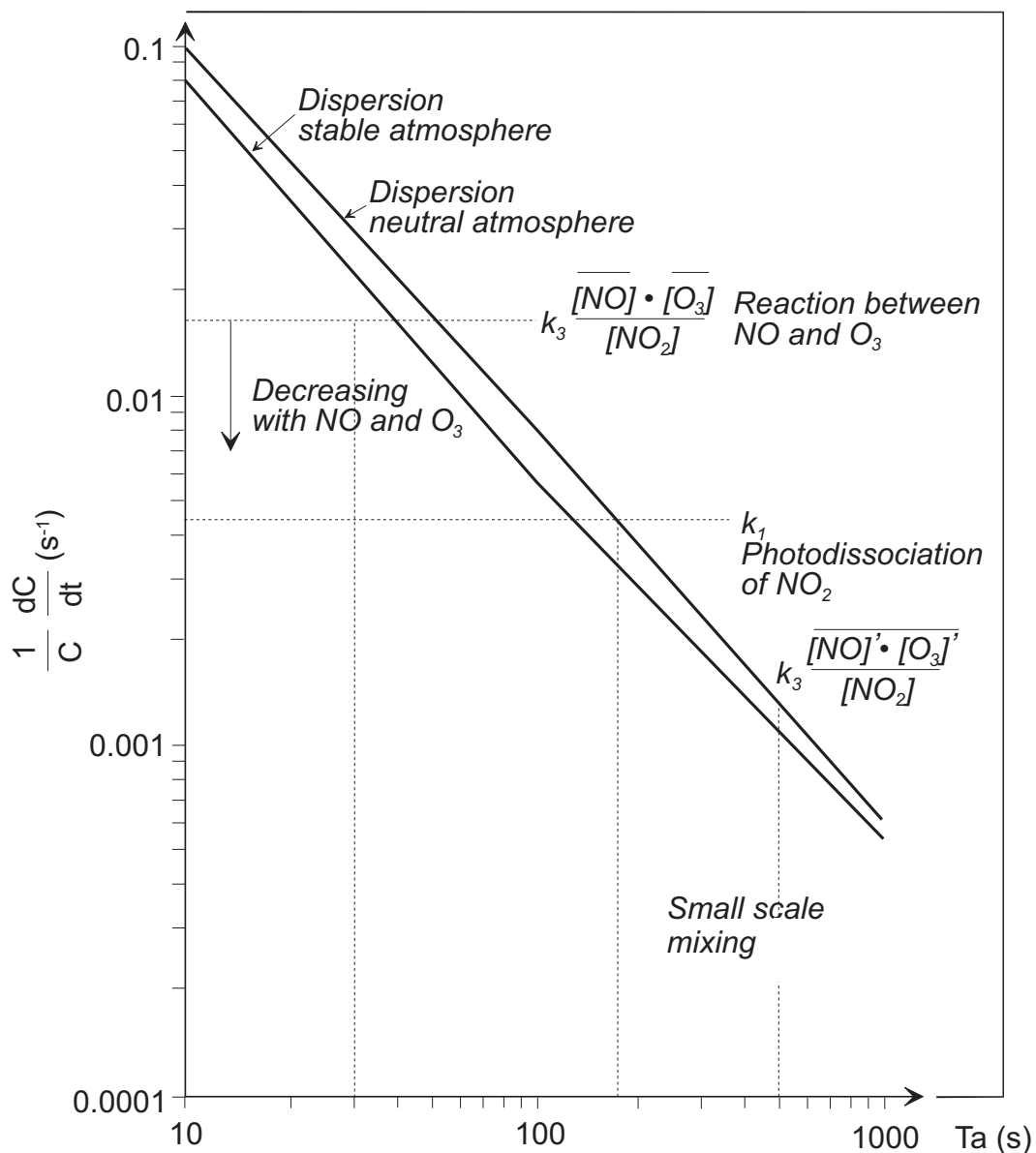


Figure 4: The relative importance of the processes affecting the NO_2 -concentrations in an urban area as a function of advection time from a road with high traffic.

6. Evaluation of the chemical balance conditions at the different stations

As the plume moves from the road the contribution from dispersion becomes less important. Further away the reaction between NO and O₃ and the photo dissociation of NO₂ may form a chemical balance far from local sources, i.e. when the advection time is larger than 1000s. The three chemical components were measured as hourly mean values on several stations, and deviation from a chemical balance at the different stations was studied.

$$\frac{d[NO_2]}{[NO_2]dt} \sim \frac{k_3[NO][O_3]}{[NO_2]} - k_1 \sim 0 \quad (6.1)$$

Eq. 5.8 indicates that during the night and during the winter months the photodissociation of NO₂ is slow compared to the other processes. In these situations either [NO] or [O₃] values should be very small.

By substituting [NO] = [NO_x] - [NO₂] and [NO₂] = [O_x] - [O₃] in equation (6.1) this gives a second degree equation in O₃ to be solved

$$[O_3] = (b - \sqrt{b^2 - 4ac}) / 2a \quad (6.2)$$

where $a = -k_1$, $b = k_1([O_x] - [NO_x]) - k_2$ and $c = k_2[O_x]$.

Finally NO₂ concentrations are calculated by

$$[NO_2] = [O_x] - [O_3] \quad (6.3)$$

According to Janssen et al., 1990 a chemical equilibrium exists locally in the plume when the advection time is larger than about 10 min. Close to sources (advection time less 10 min) the molecular diffusion affects the distribution of concentration fluctuations, and the rate of chemical reactions slows down as a result of incomplete mixing on molecular basis (eq. 5.1, 5.2 and 5.3).

Air quality guidelines are given for time average concentrations equal or larger than one hour, and description of short term fluctuations may not be required. One hour time average concentrations smooth out plumes with various scales in the urban area.

To study the deviation from chemical balance scatterplots of observed and calculated NO₂-concentrations are considered. The calculated NO₂ concentrations are based on equation (6.1) using observed values of NO and O₃ at the same station as observed NO₂-concentrations.

Figure 5 shows plots for Valle Hovin for May and December. A typical advection time from a road with high traffic to the station is about 100 s. For hourly average concentration values these results are typical for the other stations too.

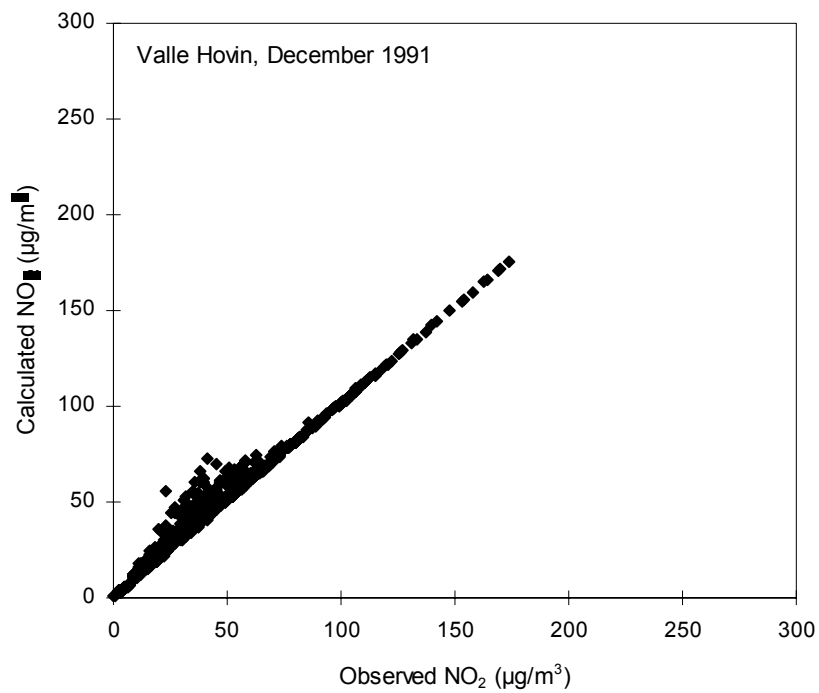
Very good correspondance is found for high and low NO₂-concentrations in December. The NO₂-concentrations based on observed NO and O₃-concentrations in the chemical balance equation render slightly higher values than observed values in December. In May the scatterplot show larger deviations from the chemical balance condition. Further in May as well as in December observed concentrations around 40 µg NO₂/m³ tend to be overestimated by the chemical model. The overestimation is probably a result of segregation between between NO and O₃ in the atmosphere.

Figure 6 shows plots for stations located close to streets characterized by high traffic intensity.

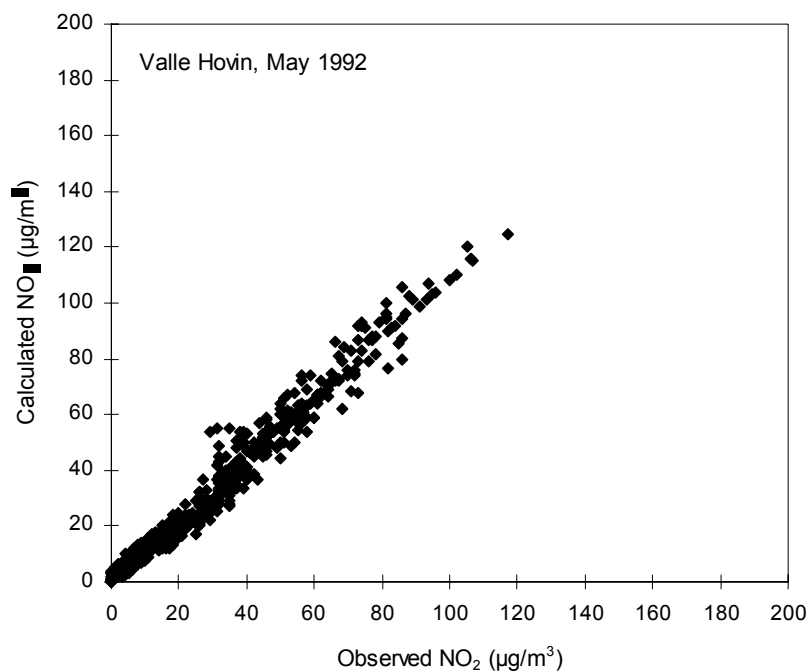
The high NO₂-concentrations occur when the ozone values are close to zero. In these situations the calculated NO₂ becomes equal to the observed values.

When ozone values are observed at the stations, the calculation procedure based on assumption of chemical balance overestimates the observed values. In Oslo the overestimation occurs when the concentrations are lower than about 100 µg/m³.

Chemical balance tends to overestimate the NO₂-concentrations and underestimate the O₃-concentrations at all stations within the Oslo-area. These observations may also be expected when the NO₂-model suggested by Yamartino and Wiegand in 1986 is used. Further it is seen that the difference from a local balance is small on all stations for high NO₂-values.

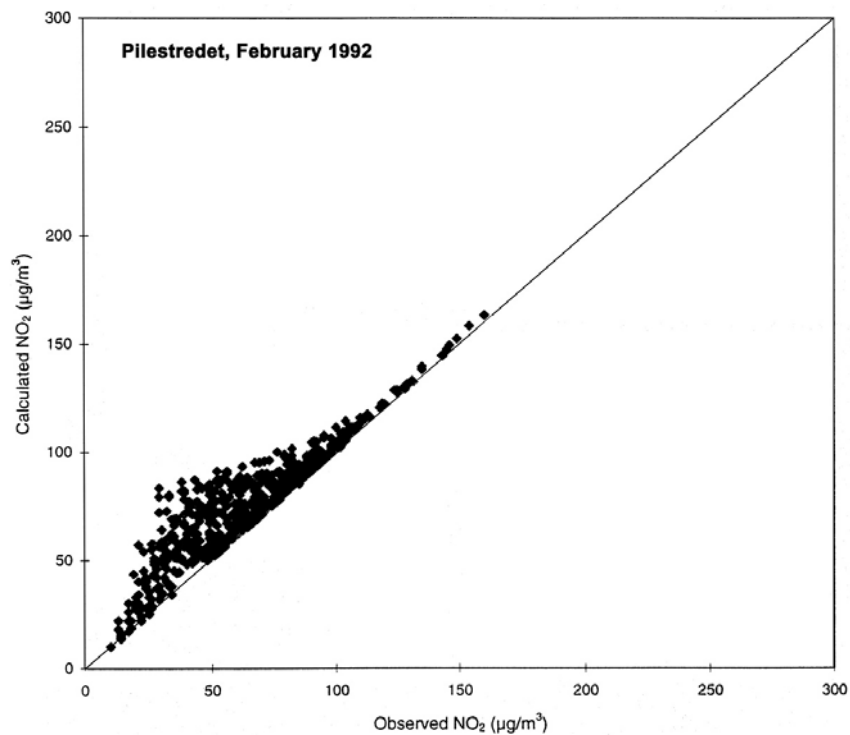


a) December 1991.

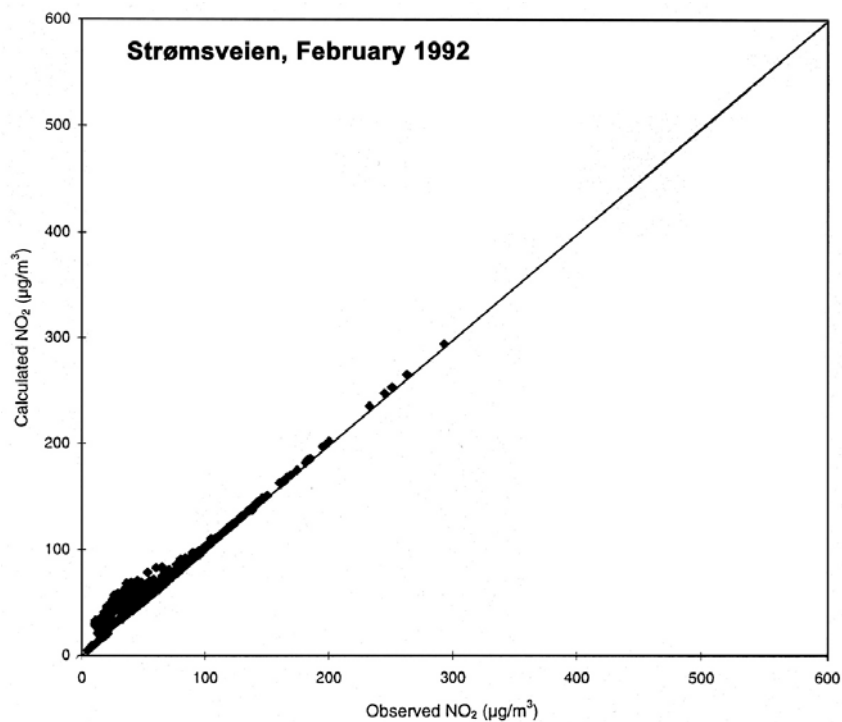


b) May 1992.

Figure 5: Observed and calculated hourly NO₂-concentrations at Valle Hovin. The calculated NO₂-concentrations are based on the chemical balance equations 6.2 and 6.3.



a) Pilestredet



b) Strømsveien

Figure 6: Observed and calculated hourly NO₂-concentrations at Pilestredet (a) and at Strømsveien (b) in February 1992.

7. Description of the NO₂-model

The calculation procedure for NO₂ was proposed by Yamartino and Wiegand in 1986, when O_x and NO_x are individually conserved in an urban area (see equation (5.4) and equation (5.5)).

The model calculations of $[NO_x]$ at a given station is given by

$$[NO_x] = [NO_x]_{ij} + W \cdot [NO_x]_k + [\beta_{NO_x}] \quad (7.1)$$

where $[NO_x]_{ij}$ is the km² grid concentration at the given station as calculated by the finite difference model, and $[NO_x]_k$ is the subgrid contribution from individual roads as calculated by the subgrid model.

The background concentration $[\beta_{NO_x}]$ is set equal to the measured value of $[NO_x]$ at station Jeløya for each hour. Jeløya is located approximately 50 km south of Oslo. In the case of lacking data from the Jeløya station, the background value of $[NO_x]$ is set equal to the respective average values of $[NO_x]$ at Jeløya station in the two periods, which are 15 µg/m³ in the winter period (1 Nov 1991-28 Feb 1992), and 10 µg/m³ in the summer period (1 May-30 June 1992).

The calculation procedure for $[O_x]$ at a given station is similarly given by

$$[O_x] = [O_x]_{ij} + W \cdot [O_x]_k + [\beta_{O_x}] \quad (7.2)$$

where $[O_x]_{ij}$ is the contribution of $[O_x]$ as a result of emissions within km²-squares at the given station as calculated by the finite difference model, and where $[O_x]_k$ is the corresponding O_x contributions from individual roads as calculated by the subgrid model.

The background concentration $[\beta_{O_x}]$ is set equal to the measured value of O_x at Jeløya for each hour. In the case of lacking data at Jeløya the background value of $[O_x]$ is set equal to average values of $[O_x]$ at Jeløya in the two periods which are 55 µg/m³ for the winter period (1 Nov 1991-28 Feb 1992), and 95 µg/m³ for the summer period (1 May-30 June 1992).

In Oslo the emission of ozone is very small, and the emission of O_x is equal to the primary emission of NO_2 from the combustion processes, i.e. from car traffic and from home heating. The equation (7.2) reads

$$[O_x] = [NO_2]_{ij} + [NO_2]_k + [\beta O_x] \quad (7.3)$$

$[NO_2]$ and $[O_3]$ is then calculated based on the same balance equation as given in Eq. 6.2 and 6.3.

This gives hourly values of NO_2 and O_3 from the calculated hourly values of $[NO_x]$ and $[O_x]$ at each station in the area. Since O_3 is not emitted from the cars

$$[O_x]_k = [NO_2]_k$$

According to chapter 6 it is indicated that the relation between hourly values of NO , NO_2 and O_3 concentrations is described by reactions between NO and O_3 , photodissociation of NO_2 as well as small scale mixing in the atmosphere.

8. Evaluation of the NO_2 - and O_3 -models

The results of the evaluations of the NO_2 - and the O_3 - models described in chapter 7 are shown in the tables 5 and 6.

Dispersion calculations of NO_x and specification of background values for O_3 remain the most important sources of discrepancies between calculated and observed concentrations.

Close to streets with high traffic the highest discrepancies are observed. There are several systematic deviations to consider when the model is going to be improved.

- The deviation between observed and calculated concentrations close to line sources are particularly high in situations characterized by low wind and poor dispersion conditions.
- It is a tendency to calculate higher NO_2 and lower O_3 concentrations than observed. The development of NO_2 as a result of chemical reactions between emissions of NO and the background concentrations of O_3 in the urban atmosphere is delayed (10 min) as a result of small scale segregation of NO and O_3 .

When a combination of dispersion calculations and chemical reactions are accounted for in detailed calculations it is seen that small gradients in the NO_2 concentrations may be found close to the roads in episodes with high background O_3 -concentration and poor exchange of air. The observations close to Fyrstikkalleen indicate similar results. The maximum NO_2 -value 50 m from Strømsveien reads only 3% lower values than the maximum NO_2 concentrations at the edge of the road.

Table 5: Evaluation of the NO₂ model for the winter and summer periods.

Station	\overline{C}_o (σ_o)	\overline{C}_c (σ_c)	M_o	M_c	r	rmse	$(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$	IA	N
	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	$\mu\text{g}/\text{m}^3$	%		
Winter									
Valle Hovin	49 (33)	69 (37)	283	261	0.74	33	65	0.78	2 498
Skøyen	39 (21)	57 (27)	136	180	0.73	26	70	0.74	1 355
Holmlia	31 (18)	53 (26)	111	178	0.48	32	70	0.55	842
Nordahl Bruns gt.	44 (24)	66 (29)	194	178	0.64	32	72	0.68	2 876
Pilestredet	66 (29)	83 (33)	210	244	0.76	28	63	0.80	1 264
Strømsveien	76 (42)	109 (77)	324	554	0.62	69	48	0.64	1 217
Etterstadsletta	45 (32)	73 (34)	246	258	0.66	39	76	0.68	1 239
Fyrstikkalleen	57 (35)	82 (43)	313	328	0.68	41	63	0.73	1 019
Summer									
Valle Hovin	29 (22)	68 (35)	117	197	0.43	51	62	0.47	1 340
Skøyen	19 (14)	50 (26)	63	117	0.63	37	84	0.48	353
Nordahl Bruns gt.	30 (19)	56 (30)	137	182	0.55	37	73	0.55	1 338

\overline{C}_o = Average observed concentration

\overline{C}_c = Average model calculated conc.

M_o = Maximum observed concentration

M_c = Maximum calculated concentration

$(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$ = Percentage systematic rmse

N = Number of observations

σ_o = St. dev. observed concentration

σ_c = St. dev. model calculated conc.

r = Correlation coefficient

rmse = Root mean square error

IA = Index of agreement

Table 6: Evaluation of the O_3 model for the winter and summer periods.

Station	\overline{C}_o (σ_o) $\mu\text{g}/\text{m}^3$	\overline{C}_c (σ_c) $\mu\text{g}/\text{m}^3$	M_o $\mu\text{g}/\text{m}^3$	M_c $\mu\text{g}/\text{m}^3$	r	rmse $\mu\text{g}/\text{m}^3$	$(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$ %	IA	N
Winter									
Valle Hovin	15 (17)	9 (17)	62	71	0.81	12	57	0.88	1 602
Skøyen	19 (23)	11 (18)	102	75	0.79	16	75	0.84	1 451
Holmlia	20 (26)	13 (20)	83	70	0.68	25	81	0.75	1 243
Nordahl Bruns gt.	10 (11)	8 (15)	59	70	0.77	10	24	0.85	1 453
Pilestredet	13 (17)	2 (6)	74	35	0.54	18	96	0.56	1 271
Strømsveien	7 (15)	2 (6)	52	36	0.46	10	87	0.61	1 243
Etterstadsletta	9 (8)	5 (10)	39	38	0.54	10	53	0.71	1 151
Fyrstikkalleen	12 (17)	3 (8)	80	36	0.50	18	92	0.59	1 019
Summer									
Valle Hovin	29 (13)	35 (27)	80	122	0.53	24	30	0.62	1 335
Skøyen	30 (16)	53 (30)	98	126	0.67	32	72	0.60	1 163
Nordahl Bruns gt.	36 (14)	45 (27)	97	119	0.58	24	39	0.64	1 338

\overline{C}_o = Average observed concentration

\overline{C}_c = Average model calculated conc.

M_o = Maximum observed concentration

M_c = Maximum calculated concentration

$(\overline{\Delta C_s^2} / \overline{\Delta C^2})^{0.5}$ = Percentage systematic rmse

N = Number of observations

σ_o = St. dev. observed concentration

σ_c = St.dev. model calculated conc.

r = Correlation coefficient

rmse = Root mean square error

IA = Index of agreement

9. References

- Bott, A. (1989) A positive finite advection scheme obtained by no-liar renormalization of the advective fluxes. *Monthly Weather Review*, 117, 1006-1015.
- Csanady, G.T. (1993) Turbulent diffusion in the environment. Dordrecht, G, Reidel.
- Eidsvik, K.J. (1982) Wind diagnoses in winter flow over Oslo based on a few measurement stations. *Atmos. Environ.*, 16, 2383-2390.
- Environmental Protection Agency (1984) Interim procedures for evaluating air quality models (revised). Triangle Park, NC, Office of Air Quality Planning and Standards (EPA-450/4-84-023).
- Fox, D.G. (1981) Judging air quality model performance - review of the Woods Hole workshop. *Am. Met. Soc. Bull.*, 62, 599-609.
- Fox, D.G. (1984) Uncertainty in air quality modelling. *Am. Met. Soc. Bull.*, 65, 27-36.
- Gram, F. (1994) Emissions of NO_x and NMVOC in Oslo in 1991. Lillestrøm (NILU OR 79/94) (in Norwegian).
- Grønskei, K.E. and Gram, F. (1984) A dispersion model for regional air pollution problems. In: *Air Pollution Forecasting*. Papers presented at the WMO RA VI International Meeting, Leningrad, November 1980.
- Grønskei, K.E., Walker, S.-E. and Gram, F. (1990) Short term cohort study of the relationship between health and air pollution in Grenland, Norway. Calculation of spatial concentration distribution based on measurements. The data for evaluation of exposure. Lillestrøm (NILU OR 65/90).
- Grønskei, K.E., Walker, S.-E., and Gram, F. (1993) Evaluation of a model for hourly spatial concentration distribution. *Atmos. Environ.*, 27B, 105-120.
- Grønskei, K.E. (1994) Description of dispersion and formation of NO₂. Lillestrøm (NILU OR 13/94).
- Hagen, L.O. (1992) Air quality monitoring in Norway. Result for the period April 1991-March 1992. Lillestrøm (NILU OR 66/92).
- Hagen, L.O., Haugsbakk, I. and Larssen, S. (1993) Nitrogen oxides and oxidants in Norwegian cities; formation and effects. Measurements of air quality and meteorological conditions in Oslo, October 1991-June 1992. Lillestrøm (NILU OR 32/93).

- Hertel, O. and Berkowicz, R. (1989) Modelling pollution from traffic in a street canyon. Evaluation of data and model development. Roskilde, Danmarks Miljøundersøgelser (DMU Luft-A131).
- Irwin, J.S. (1983) Estimating plume dispersion - a comparison of several sigma schemes. *J. Clim. appl. Met.*, 22, 92-114.
- Janssen, L.H.J.M., Nieuwstadt, F.T.M. and Donze, M. (1990) Time scales of physical and chemical processes in chemically reactive plumes. *Atmos. Environ.*, 24A, 2861-2874.
- Kendall, M., Stuart, A. and Ord, J.K. (1983) Design and Analysis, and Time Series, 4th edn. London, Charles Griffin (*The Advanced Theory of Statistics, vol. 2.*).
- Larssen, S. and Røstad, A. (1993) Monitoring of automotive pollutant concentrations in Oslo for the period 1989-92. Lillestrøm (NILU OR 7/93).
- Larssen, S., Tønnesen, D.A. and Johnsrud, M. (1990) Calculation of air pollution levels in Vålerenga/Gamlebyen, an area in Oslo with a large traffic burden. Lillestrøm (NILU OR 19/90).
- Petersen, W.B. (1980) User's Guide for HIWAY-2: a highway air pollution model. Research Triangle Park, NC., U.S. Environmental Protection Agency (EPA-600/8-80-018).
- Torp, C. and Larssen, S. (1993) ROADAIR 2.0. User's manual. Lillestrøm (NILU TR 14/92).
- Venkatram, A., Strimatis, D. and Dicristofaro, D. (1984) A semiempirical model to estimate vertical dispersion of elevated releases in the stable boundary layer. *Atmos. Environ.*, 18, 923-928.
- Willmott, C.J. (1982) Some comments on the evaluation of model performance. *Am. Met. Soc. Bull.*, 63, 1309-1313.
- Yamartino, R.J. and Wiegand, G. (1986) Development and evaluation of simple models for the flow turbulence and pollutant concentration fields within an urban street canyon. *Atmos. Environ.*, 20, 2137-2156.

Appendix A

Description of model evaluation parameters

Introduction

US EPA has given guidelines on procedures to be followed in evaluating air quality models (EPA, 1984), and a list of recommended model evaluation performance parameters. In this study statistical parameters have been selected in accordance with these recommendations (Fox, 1981, 1984). Selecting the parameters, results of Willmott (1982) were also taken into consideration.

Description of model evaluation performance parameters

Let T denote the number of data, and let O_t and P_t denote the observed and calculated (predicted) values at time t , $t = 1, \dots, T$. For each station the following model evaluation parameters are defined:

\bar{O}	: Mean value of observations
\bar{P}	: Mean value of predictions
σ_o	: Standard deviation of observations
σ_p	: Standard deviation of predictions
NMD	: Normalized mean difference
RMSE	: Root mean square error
RMSE _S	: Systematic RMSE
RMSE _U	: Unsystematic RMSE
a, b	: Intercept and slope of regression line
r	: Correlation coefficient
IA	: Index of agreement

The parameters are defined through the following set of equations:

Mean values:

$$\bar{O} = \frac{1}{T} \sum_{t=1}^T O_t \quad (\text{A.1})$$

$$\bar{P} = \frac{1}{T} \sum_{t=1}^T P_t \quad (\text{A.2})$$

These denote the usual arithmetical average values of the time series O_t and P_t .

Standard deviations:

$$\sigma_o = \left(\frac{1}{T-1} \sum_{t=1}^T (O_t - \bar{O})^2 \right)^{0.5} \quad (\text{A.3})$$

$$\sigma_p = \left(\frac{1}{T-1} \sum_{t=1}^T (P_t - \bar{P})^2 \right)^{0.5} \quad (\text{A.4})$$

These denote the usual standard deviations of the time series O_t and P_t .

Normalized mean difference:

$$NMD = (\bar{O} - \bar{P}) / \bar{O} \quad (\text{A.5})$$

This dimensionless parameter is a measure of the bias of P versus O. Ideally it should be zero, or close to zero.

Root mean square error:

$$RMSE = \left(\frac{1}{T} \sum_{t=1}^T (O_t - P_t)^2 \right)^{0.5} \quad (\text{A.6})$$

The RMSE is another measure of the size of the error produced by the model.

Systematic and unsystematic RMSE:

$$RMSE_s = \left(\frac{1}{T} \sum_{t=1}^T (O_t - \hat{P})^2 \right)^{0.5} \quad (\text{A.7})$$

$$RMSE_u = \left(\frac{1}{T} \sum_{t=1}^T (\hat{P} - P_t)^2 \right)^{0.5} \quad (\text{A.8})$$

where

$$\hat{P}_t = a + bO_t \quad (\text{A.9})$$

with a and b being the intercept and slope of the regression line:

$$a = \bar{P} - b\bar{O} \quad (\text{A.10})$$

$$b = \left[\sum_{t=1}^T (O_t - \bar{O})(P_t - \bar{P}) \right] / \left[\sum_{t=1}^T (O_t - \bar{O})^2 \right] \quad (\text{A.11})$$

Here $RMSE^2 = RMSE_s^2 + RMSE_u^2$.

Willmott (1982) argues that systematic and unsystematic root mean square error gives valuable information on the possibility of model improvement.

For a good model the unsystematic portion of the RMSE is much larger than the systematic, while a large systematic RMSE indicates a poor model. For a more thorough discussion, see Willmott (1982).

Correlation coefficient:

$$r = \frac{1}{T} \sum_{t=1}^T (O_t - \bar{O})(P_t - \bar{P}) / (\sigma_o \cdot \sigma_p) \quad (\text{A.12})$$

This is the ordinary product-moment correlation coefficient.

Index of agreement:

$$IA = 1 - \frac{\sum_{t=1}^T (P_t' - O_t')^2}{\sum_{t=1}^T (|P_t'| + |O_t'|)^2} \quad (\text{A.13})$$

where

$$P_t' = P_t - \bar{O} \quad \text{and} \quad O_t' = O_t - \bar{O} \quad (\text{A.14})$$

The index of agreement has been recommended by Willmott (1982), as a better parameter to describe the “agreement” between the two time series O_t and P_t .

The index IA is a number between 0 and 1, with 0 indicating worst agreement, and 1 indicating best agreement.

When impact of new sources is considered, concentration has to be predicted. To evaluate the accuracy of the peak concentration prediction, the following parameters are considered:

$$R_m = P_m / O_m \quad (\text{A.15})$$

$$\Delta = \Delta t_m \quad (\text{A.16})$$

where

$$\Delta t_m = \text{Difference of timing of occurrence of situation peak.}$$

The ratio of predicted and observed concentrations should also be calculated for some percentiles to characterize the models behaviour for different pollution situations.

