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Urban Air Quality Assessment Model UAQAM

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ABSTRACT

The Urban Air Quality Assessment Model (UAQAM) calculates the city concentration caused by city emissions themselves, the so-called city background concentration. Three versions of the model for describing the dispersion were studied: Box, Gifford Hanna (GH) and a combined form of these two (the Box-GH model). Regional background emissions contributing to the city background concentration were accounted for using measurements and TREND model calculations. The UAQAM model versions were compared to measurements of SO_2 and NO_X concentrations. The Box-GH and GH models were found to be more appropriate in describing the city background concentration. The Box-GH model showing slightly better results compared to the GH model can be taken as a starting point for the assessment of urban air quality with UAQAM.

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SAMENVATTING

Europa is een sterk verstedelijkt continent. Meer dan 70% van de bevolking leeft in steden. De concentratie van menselijke activiteiten op een relatief klein oppervlak levert een grote druk op het stedelijk gebied op en heeft geleid tot talloze milieuproblemen zoals geluidshinder, afval en luchtverontreiniging. Door het Europees Milieu Agentschap wordt de stedelijke luchtverontreiniging beschouwd als één van de belangrijkste milieuproblemen in Europa (EEA, 1995). Op basis van een stedelijke luchtkwaliteitsstudie (Sluyter, 1995) werd geconcludeerd dat in alle Europese steden met meer dan 500.000 inwoners minstens één WHO-richtwaarde per jaar wordt overschreden. Deze overschrijdingen geven aan dat er gezondheidsrisico's aanwezig kunnen zijn voor de stedelijke bevolking.

In het RIVM project Luchtkwaliteit Europa, worden scenariostudies en brede stedelijke luchtkwaliteitsevaluaties uitgevoerd voor vele Europese steden. Om in staat te zijn de verschillen in de luchtkwaliteitssituatie tussen steden te identificeren en de beleidsimplicaties te evalueren, wordt in dit kader een (model)instrumentarium ontwikkeld dat een verband probeert te leggen tussen de stedelijke luchtkwaliteit en bepalende factoren zoals emissies, stadsomvang en meteorologie.

In dit rapport wordt een beschrijving gegeven van het Urban Air Quality Assessment Model (UAQAM). Dit model berekent de concentratie van luchtverontreiniging in stedelijk gebied veroorzaakt door emissies uit de stad zelf. In een werkversie van dit model werden 3 beschrijvingen van de verspreiding bestudeerd: een Box-model, het Gifford-Hanna (GH) model en een combinatie van de twee: het Box-GH-model. Deze modelversies zijn vergeleken met metingen van de concentratie van SO_2 en NO_X in steden. De regionale achtergrondsconcentratie (RBC) van de steden vormt een belangrijk deel van de concentratie in de stad. Daarom is de RBC aan de berekeningen toegevoegd die samengesteld is uit metingen en een geparametrizeerde uurlijkse variatie daarop.

De jaargemiddelde concentratie van SO_2 wordt redelijk goed beschreven door alle drie de modellen (correlatie coëfficiënt $\approx$ 0.7). De NO_X concentratie wordt het beste met het GH- en Box-GH-model beschreven (correlatie coëfficiënt $\approx$ 0.8). Het Box-model onderschat duidelijk de NO_X-concentraties. Dit wordt veroorzaakt doordat NO_X door lage bronnen wordt geëmiteerd. De dispersie vanuit deze bronnen wordt beter met GH-type modellen beschreven. Als de RBC toegevoegd wordt aan de berekende concentraties verbetert de vergelijking met de metingen.

De daggemiddelde concentratie wordt door de modellen niet goed beschreven (cc $\approx$ 0.3 en 0.5 voor SO_2 en NO_X). De verschillen tussen de modellen zijn klein. Echter voor NO_X is de fractie van de berekeningen die binnen een factor 2 van de metingen ligt een stuk groter voor de Box-GH- en GH-modellen dan voor het Box-model. De toevoeging van de RBC (op dagbasis) levert geen verbeteringen in de resultaten op.

De concentraties op het uur van de dag worden redelijk beschreven met de Box-GH- en GH-modellen zonder de RBC (cc. $\approx$ 0.7 en 0.6 voor SO_2 en NO_X). De correlatie tussen metingen en berekeningen met het Box-model zonder RBC is negatief. Een toevoeging van de RBC op uurbasis verslechtert de resultaten van alle modellen.

Het Box-model onderschat alle percentielen voor beide componenten. Het Box-GH- en GH-model beschrijven dit beter en de onderlinge verschillen zijn klein. Voor NO_X worden met deze modellen het 98 percentiel en het dagelijkse maximum onderschat, maar voor SO_2 zijn de resultaten wat beter.

Uit deze vergelijking met metingen komt duidelijk naar voren dat de variatie in de tijd op de RBC niet goed geparametrizeerd is. Met name voor SO_2 levert dit slechte resultaten op, op zowel dag- als uurbasis. Een betere beschrijving van de variatie in de RBC kan verkregen worden door een regionale achtergrond te gebruiken die wordt berekend door lange afstands-transportmodellen zoals EMEP of EUROS.

Verdere evaluatie van de modellen vergt dat de regionale achtergrondsconcentratie afdoende in de berekening wordt meegenomen. Daarnaast echter zijn ook de onzekerheden in de emissies en oppervlakte gegevens van de stad van belang, aangezien deze direct doorvertaald worden in de concentraties. Deze onzekerheden zijn zeer groot en niet eenvoudig in te schatten. Ook de onzekerheden in de metingen en de situering van de meetstations die als stadsachtergrond fungeren zijn factoren die een goede vergelijking met metingen bemoeilijken.

Desalniettemin kan geconcludeerd worden dat de Box-GH- en GH-modellen beter geschikt zijn dan het Box-model om de stadsachtergrond te beschrijven. De resultaten en de uitbreidingsmogelijkheden van het Box-GH-model zijn iets beter dan van het GH-model en kan daarom als uitgangspunt genomen worden voor het schatten van de stedelijke luchtkwaliteit met UAQAM.

SUMMARY

Europe is a highly urbanised continent. In 1990, more than 70% of the total population was found in cities. The concentration of human activities in a relatively small area puts enormous pressure on the urban system and has led to numerous environmental problems (e.g. noise, waste, air pollution). On the basis of a pan-European survey of the state of the environment (EEA, 1995), urban air pollution was regarded by the European Environmental Agency as one of the most important environmental problems in Europe. In the framework of RIVM project 722411 (European urban air quality) comparative air quality assessment and scenario studies are to be conducted for large sets of European cities. To be able to identify (dis)similarities in air quality conditions between cities and to assess the impact of policy options, information on, and tools to evaluate, environmental conditions determining urban air quality are essential.

In this report a description is given of the Urban Air Quality Assessment Model (UAQAM). With this model the concentration in the city caused by city emissions themselves, the so-called city background concentration is calculated. In the preliminary version of UAQAM three versions of the model for describing the dispersion were studied: Box, Gifford Hanna (GH) and a combined form of these two models (Box-GH model). These versions were compared to measurements of the concentrations of SO_2 and NO_X. The regional background concentration (RBC) forms an important part of the city's concentration. Therefore the annual RBC from measurements or model calculations using the TREND model (Van Jaarsveld, 1995) and a parametrised hourly variation around the calculated mean, were added to the model's calculations.

From the comparison with measurements it was clear that the variation in the regional background concentration had not been parametrised correctly. Particularly the fumigation of pollutants into the atmospheric boundary layer is an important process which contributes significantly to the city background concentration. Especially for SO_2, this RBC forms a large contribution to this concentration and the variations therein. A better description of the RBC on an hourly basis would require more information on the advection of the air entering the city. This can be accomplished using the results of Long Range Transport models, calculating the concentration on an hourly basis, as the RBC for the city.

The main source of uncertainty in the calculated concentrations is caused by the emission from and the estimate of the built-up area of the cities. The fairly large uncertainties are translated directly into the calculated concentrations. These uncertainties and the inappropriate parametrisation of the regional background concentration hamper a sound evaluation when comparing calculated concentrations with the concentration measurements. Besides, the measurement data used in the comparison on a daily and hourly basis are from individual stations which are considered as being representative of the city background. Because these stations are still influenced by local factors, this also introduces an uncertainty factor in the comparison.

Despite all the above uncertainties and shortcomings in the comparison, it was concluded that the Box-GH and GH models are more appropriate in describing the city background concentration than the Box model. The Box-GH model is slightly better than the GH model and can be taken as a starting point for the assessment of urban air quality with UAQAM.

1. INTRODUCTION

Europe is a highly urbanised continent. In 1990, more than 70% of the total population was found in cities. The concentration of human activities in a relatively small area causes enormous pressure on the urban system and has led to numerous environmental problems (e.g. noise, waste, air pollution).

On the basis of a pan-European survey of the state of the environment (EEA, 1995), urban air pollution was regarded by the European Environmental Agency as one of the most important environmental problems in Europe. From the underlying urban air quality study (Sluyter, 1995) it was concluded that at least one Air Quality Guideline as proposed by the World Health Organisation (WHO-AQGs) will be exceeded in all cities in a typical year. These exceedances indicate possible health risks citizens are exposed to.

In the framework of RIVM project 722411 (European urban air quality) comparative air quality assessment and scenario studies are to be conducted for large sets of European cities. To be able to identify (dis)similarities in air quality conditions between cities and assess the impact of policy options, information on, and tools to evaluate environmental conditions determining urban air quality are essential.

When making comparative air quality assessments for a large selection of cities, it is impracticable to make a very detailed assessment of the situation per city. Therefore, a methodological framework has been developed in which the urban air quality situation is assessed using *Pressure*, *State* and *Impact* modules (PSI chain). The modules consist of, and are linked through, simple indices which can be calculated from the most common and basic data (Figure 1.1). The *pressure* module describes the natural and anthropogenic environmental conditions. In the *state* module air pollutant concentrations are evaluated against WHO Air Quality Guidelines (WHO-AQGs). The *impact* module estimates exposure and (possible) health effects on citizens. Two complementary tools describing the PSI chain are currently being developed at RIVM for the assessment of city background concentration levels. These tols are:

- A set of urban environmental indices to be empirically linked to air pollutant concentrations;
- A simple urban air quality model which is able to calculate (annual) average city background concentrations and the number of exceedances of air quality guidelines for a broad selection of cities on the basis of relatively simple input data (city area, regional background concentrations and meteorological observations).

City background concentration refers to the concentration of pollutants at sites within cities not directly influenced by sources. This city background concentration can serve as input to models e.g. CAR, describing air pollution at street level (Eerens et al.,1993).

This report describes the first phase of the development of the urban air quality assessment model. Information on the development of the urban environmental indices can be found in Sluyter & den Tonkelaar (1995).

1.1 Goal

The report describes a simple urban air quality model which in an initial stage is able to:

> ***calculate (annual) average city background concentrations and the number of AQG exceedances on an hourly and daily basis for a broad selection[1] of cities using relatively simple and generally available input data.***

Since the model is needed for the assessment and scenario analysis of air quality in a broad selection of cities (e.g. all European cities with more than 50,000 inhabitants), it was concluded that the computing time per city should be small.

Available urban environmental data, both at the moment and in the near future, will be limited, especially when considering smaller cities. To be able to run the model for as many cities as possible with a minimal run time, the input required for the model should be limited to the most basic data available for most cities, or data which can be generated from national census data. Input data were concluded to be limited to urban emissions, city area, regional background concentrations and meteorological observations only. The structure of the model should be transparent i.e. simple parametrisations simulating the most important phenomena.

1.2 Background on urban air quality models

A literature survey of existing urban air quality models was made to identify the existence of a model satisfying the restrictions set out in Section 1.1. This survey is summarised in Appendix A. Roughly all models were used to simulate the air pollution situation for a specific city and usually typical for short time periods e.g. smog episodes. Generally, the models can be subdivided in complex (Eulerian 3D), analytical (Gaussian plume), statistical and box models. A large disadvantage of the 3D models is their large computing time and detailed input required to run the models. Statistical models, on the contrary, have a small computing time so can be used for longer simulation periods. However, the statistical relationships used in the models have to be updated each time emission or receptor characteristics changes and have to be adjusted for each city. With statistical models it is also difficult to calculate percentiles and establish exceedences. Analytical and box models do not have the above shortcomings. However, they represent a strong simplification of the dispersion process in a city. A large advantage is that the structure is very transparant and rather easy to model. Taking into account the large uncertainties in the input data of the cities (i.e. emissions, built-up area), it was concluded that an analytical or box description would meet the model requirements. The main modelling efforts lay in the preparation of the input data for the models, such as emission, meteorological and background concentration data. Therefore it was also concluded to set up the city background model at the RIVM's Air Research Laboratory called: Urban Air Quality Assessment Model (UAQAM). It was also concluded that UAQAM would be used in a brute force mode i.e. where the concentrations were calculated every hour to establish concentration percentiles, maxima and exceedences.

[1] In a first stage, the model will be used for all European cities selected within the framework of the Europe's Environment programme (see section 1.1). In a later stage the model will also be used for the assessment of air quality in smaller cities.

1.3 Outline of the report

Chapter 2 describes the UAQAM model, while Chapter 3 presents the model input and the selection of the information on European cities used in the evaluation of UAQAM. Modelled results are described in Chapter 4. In Chapter 5 conclusions are drawn and some recommendations for further development of the model are given.

2. MODEL DESCRIPTION

With UAQAM the concentration in a city resulting from emissions by sources in the city itself is calculated i.e. city background concentration. The calculated concentration is representative for the entire city and should not be influenced by local sources. The concentration is calculated on an hourly basis. UAQAM consists of three modules in which emissions, meteorological parameters and dispersion are modelled. A fourth module was constructed in which the hourly and seasonal variations in the regional background concentration of the cities is parametrised. In the following sections the modules will be subsequently addressed. Up to now chemical reactions and deposition are not taken into account. This means that UAQAM can only be used for components for which chemical reaction time scales are much larger than the time scale of the atmospheric transport and diffusion in the city.

2.1 Emissions

In general detailed information on emissions from cities are not available and are often based on total emission estimates of the countries. The yearly emission per city is divided in three source categories each having its own diurnal variation in source strength:
a) traffic,
b) domestic or space heating,
c) industry.

The diurnal variation in the emission for each source type was adapted from Van Jaarsveld (1990) and is depicted in Figure 2.1.

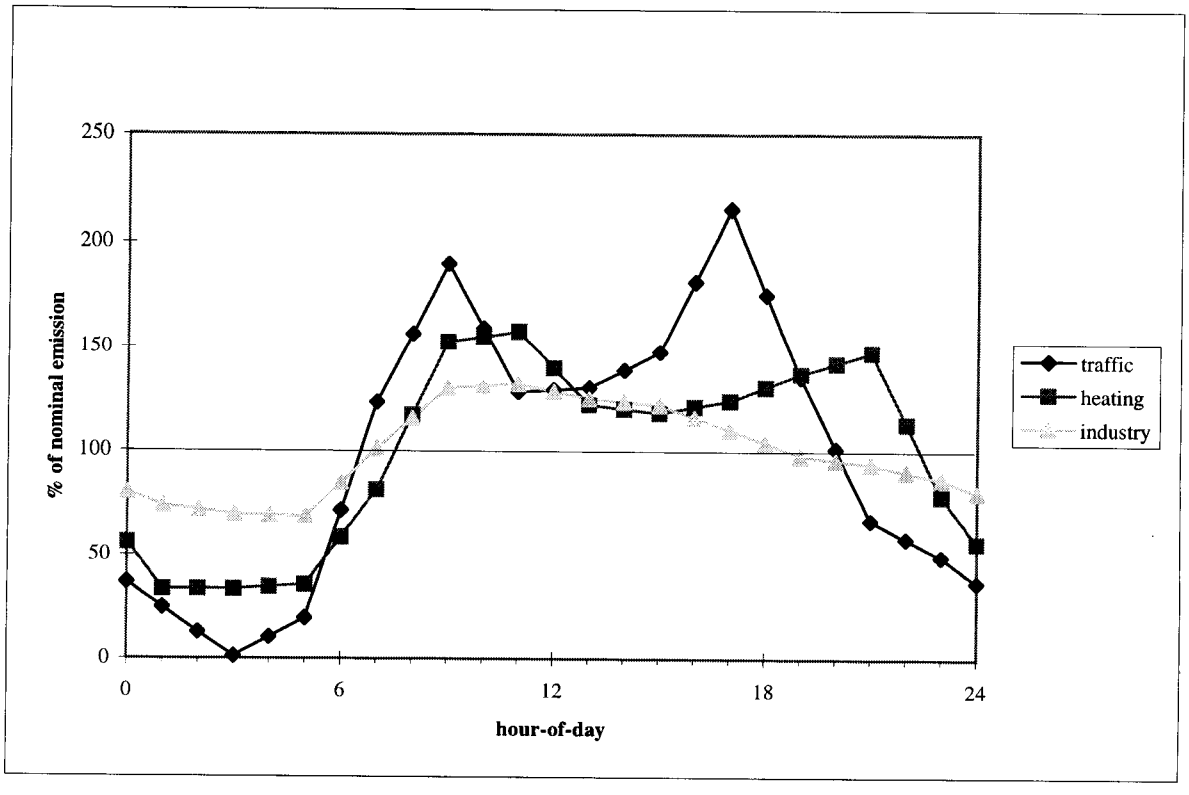

Figure 2.1: Diurnal variation in emission rates for three source types: traffic, domestic/space heating and industry.

The variation in the emissions of SO_2 from domestic and space heating throughout the year was parametrised, depending on daily mean temperature (t_{day} in °C) and wind velocity (u_{day} in m/s), at a height of 10 m. If the daily mean temperature is higher than 12 °C then the emission caused by heating is assumed to be zero; if the temperature is below 12 °C the relative emission (Qh_{rel}) is defined by (Van Jaarsveld, 1995):

$$Qh_{rel} = (19 - t_{day})\sqrt{\frac{u_{day}}{3.2}} \tag{2.1}$$

The emissions caused by heating at day n is then given by:

$$Qh_{day}(n) = \frac{Qh_{rel}(n)}{\sum_{i=1}^{365} Qh_{rel}(i)} Qh_{year} \tag{2.2}$$

where: $Qh_{day}(n)$ = heating emission at day n (kton km^{-2} day^{-1})
$Qh_{rel}(n)$ = relative heating emission at day n
Qh_{year} = annual heating emission (kton km^{-2} a^{-1})

Industrial emissions were equally distributed between a low and high boundary, $heff_{low}$ and $heff_{high}$. These boundaries were calculated with (De Leeuw et al., 1987):

$$heff_{low} = (1 + 3*u_{50}^{-1/3})*50 \tag{2.3}$$
$$heff_{high} = (1 + 3*u_{50}^{-1/3})*200 \tag{2.4}$$

where u_{50} is wind velocity at 50 m (see Section 2.2).

2.2 Meteorological parameters

In the dispersion formulation of UAQAM meteorological parameters, like advection velocity, atmospheric stability and the boundary layer height, are needed. In the following sections the calculation methods for these parameters is presented. They are calculated from synoptic data (wind velocity, temperature, cloud cover) from the nearest WMO station (Section 3.3).

2.2.1 Advection and atmospheric stability

The fluxes of sensible and latent heat are calculated using a software library by Beljaars and Holtslag (1990). Input to the library routines are surface roughness and synoptic data. Output is, among other parameters, friction velocity (u_*) sensible heat flux (h_s) and Obukhov length (L). The surface wind velocity at 10 m at the WMO station is translated to 50 m, using so-called flux profile relationships (e.g. Dyer and Hicks, 1970) using surface properties at the WMO site i.e. grassland (Table 2.1). At this height the local influences of surface roughness on the wind velocity are diminished. This wind velocity at 50 m above the city is used. With the wind at 50 m, the temperature and the cloud cover, and the fluxes at the urban surface are calculated employing the above meteorological routines. In these calculations the surface properties are adjusted for urban area (Table 2.1).

Table 2.1: Surface properties for grass and urban area used in the Beljaars and Holtslag (1990) routines;
z_0: surface roughness (m), α: Priestly Taylor parameter, A_g: soil heat transfer coefficient (W m^{-2} K^{-1})

property	WMO site (grassland)	urban area
z_0	0.03	3
albedo	0.23	0.18
α	1.0	0.1
A_g	5.0	8.0

The α= 0.1 is used to simulate a rather dry surface, i.e. a surface with a low water availability. This means that the energy in the radiation balance available for sensible and latent heat fluxes is predominantly used for the sensible heat flux i.e. thermal convection. The A_g = 8.0 is a value typical for concrete and results in a relatively large input heat flux at the urban surface.

The wind speed at 50 m is used as the typical advection velocity and is used in the dispersion formulations. In fact, the wind speed above a city will be influenced by the city roughness elements to a greater height than 50 m. Therefore a greater height well above the characteristic building height would have been more appropriate. However, the above routines are limited to the atmospheric surface layer and especially under stable conditions this is generally smaller than 50 m. Therefore an arbitrary value of 50 m was chosen as a reference height as a compromise between the above factors.

2.2.2 Urban boundary-layer height UBL

The height, H, of the urban boundary layer (UBL) is calculated with parameterization schemes for the atmospheric boundary layer height using the above meteorological data and surface properties for urban area. The height of the UBL under neutral and stable atmospheric conditions is estimated with:

$$\frac{H}{L} = \frac{c_1 u_* / fL}{1 + c_2 H / L} \tag{2.5}$$

based on Nieuwstadt (1981) and numerical values given by Holtslag and Westrhenen (1989): $c_1 = 0.15$, $c_2 = 0.31$ and Coriolis parameter, f, is 0.0001 s^{-1}.
The growth of the UBL in unstable atmospheric conditions is estimated with (Tennekes, 1973):

$$\frac{\partial H}{\partial t} = \frac{h_s}{\gamma H} \tag{2.6}$$

where h_s is the sensible heat flux (mK s^{-1}) and γ the thermal stability of the layer above the UBL; here taking 0.004 K m^{-1} as a climatological value (Van Pul et al., 1994). The UBL of the previous time step is taken as an initial value for the UBL growth. A value of 100 m was used as a(n) (arbitrary) minimum value for the UBL height.

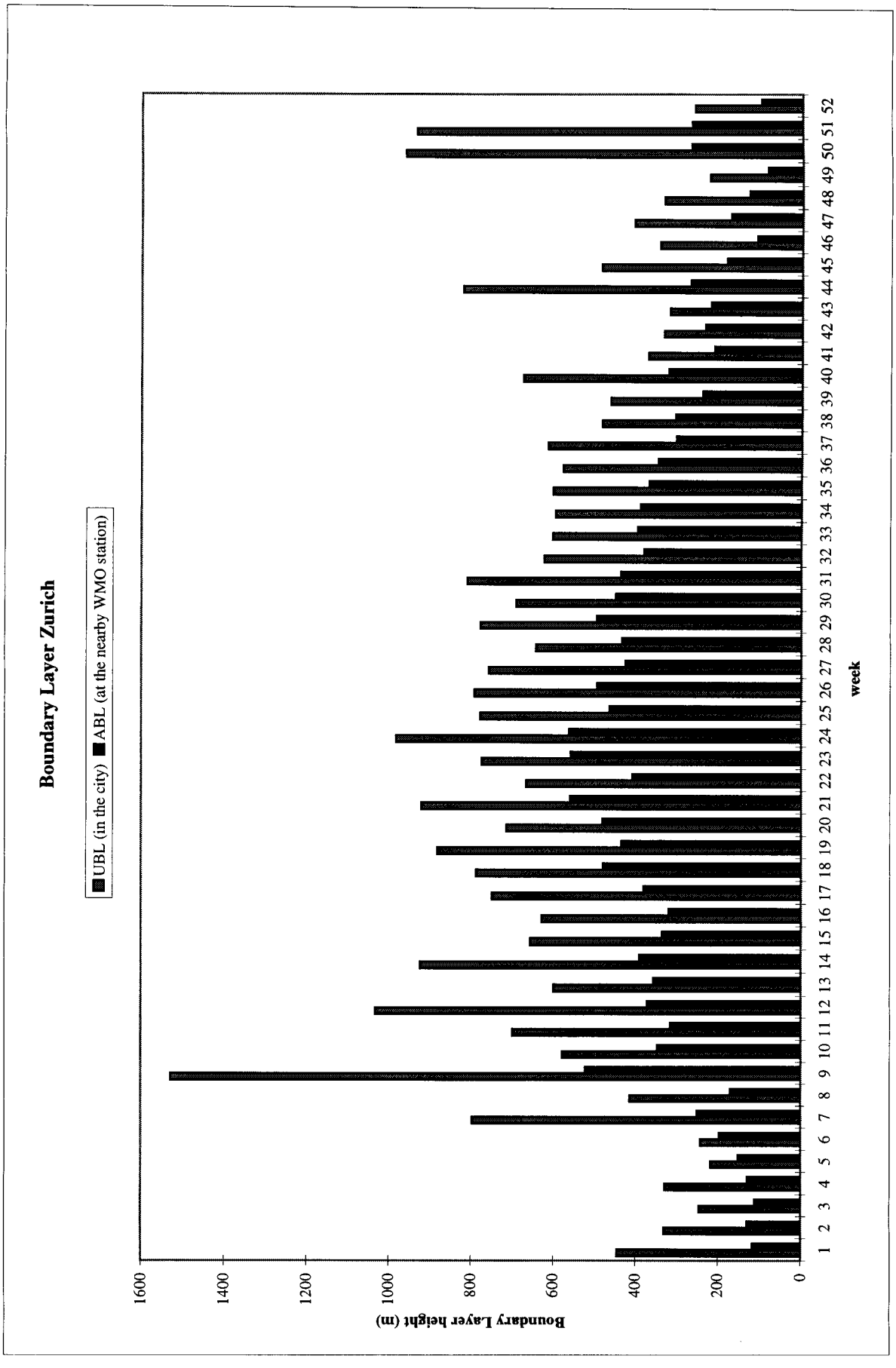

Figure 2.2: Modelled boundary layer height at Zurich and at the nearest WMO station.

An example of a yearly course for the UBL for Zurich and the atmospheric boundary layer height (ABL) for the reference WMO station are depicted in Figure 2.2. Clearly, the UBL is much larger than the ABL. This is caused by the more vigorous turbulence induced by a rougher surface and a larger sensible heat flux compared to the WMO site.

2.3 Dispersion

The dispersion of air pollutants in the city is modelled using two approaches: a box model, and the Gifford and Hanna model. These models and the combined Box-GH model will be described in the following sections. In these descriptions regional background concentration is not taken into account. In Section 3.4 an approximation of the contribution of the background concentration to the city background is presented.

2.3.1 Box model

In the box model it is assumed that emissions are instantaneously mixed up to the urban boundary layer height (i.e. no vertical concentration gradient). The latter is allowed to vary in time, depending on the meteorological situation (see Section 2.2.2). All emissions, Q, are equally distributed over the city area, A. The distribution of the elevated sources (industry) with height is as follows: if $H < heff_{low}$, no emission; if $H > heff_{high}$, all emissions; if $heff_{low} < H < heff_{high}$, the fraction $H - heff_{low}/heff_{high} - heff_{low}$ of the emissions is used.

The concentration, C, at a certain location, x, in the box is the result of all downwind emissions between the city edge and the location (Pasquill and Smith, 1983):

$$C = \frac{Qx}{uH}$$

where: Q = source strength ($\mu g\ s^{-1}\ m^{-2}$)
u = wind velocity at 50 m ($m\ s^{-1}$)
H = urban boundary layer height (UBL) (m)
x = distance from the city edge (m)

The concentration at the downwind edge of the box is found for $x=L_u$, where L_u is a typical linear scale of the built-up area, here calculated with $L_u = A^{1/2}$ (m). The spatial averaged concentration in the box is half the concentration at the downwind edge:

$$C = \frac{QL_u}{2uH} \qquad (2.7)$$

The concentration in Equation 2.7 can be seen as the concentration occuring in the centre of the urban area. In fact, the concentration range which can be calculated by the Box model amounts to 0 (at the upwind edge) up to twice this concentration (at the downwind edge).

2.3.2 Gifford and Hanna model (GH model)

Gifford and Hanna (1973) presented a simple description of the city background concentration for area sources based on the Gaussian Plume model. The contribution of sources located upwind between the locations x_1 and x_2 to the surface concentration at a certain point can be written with:

$$C(x) = \sqrt{\frac{2}{\pi}} \frac{Q}{u} \int_{x_1}^{x_2} \frac{dx}{\sigma_z} \tag{2.8}$$

The vertical dispersion depth $\sigma_z = a\, x^{\,b}$ where a and b are dispersion parameters given by Hanna (1972). The values of a=0.40 and b=0.91 for unstable and a=0.15 and b=0.75 for neutral and stable atmospheric stratification are used. In taking the neutral dispersion values in stable cases we are following the findings of Rao et al. (1989), who concluded this to result in a more realistic fit to data for urban area. So the urban atmosphere is in fact never stable as far as dispersion is concerned.

The concentration at a point, X, influenced by sources from the edge of the city , x = 0 to x = X, is found with:

$$C_X = \sqrt{\frac{2}{\pi}} \frac{Q}{u} \frac{X^{1-b}}{a(1-b)} \tag{2.9}$$

A concentration distribution over the city is obtained with Equation 2.9. The value of *b* is about 0.75 so the power in Equation 2.9 is 0.25, which indicates a weak dependency of the concentration for distance X. This reflects the fact that mainly nearby sources determine the ground concentration at a point.

The GH model can be viewed as a box model of which the lid is formed by the vertical diffusion depth σ_z and which increases with transport time from the city edge. To obtain a concentration, C_{Lu}, for the city as a whole, Equation 2.9 has to be integrated over L_u:

$$C_{L_u} = \sqrt{\frac{2}{\pi}} \frac{Q}{u} \frac{L_u^{1-b}}{a(1-b)(2-b)} \tag{2.10}$$

Emissions from elevated sources (industry) were handled as follows:
if $\sigma_z < heff_{low}$, no emission, if $\sigma_z > heff_{high}$, all emissions; if $heff_{low} < \sigma_z < heff_{high}$, the fraction $\sigma_z - heff_{low} / heff_{high} - heff_{low}$ of the emissions was used. Here the σ_z at $x=L_u$ is used.

2.3.3 Box-GH model

In the Box model all emissions are mixed instantaneously to the box height i.e. the UBL height. This description is more appropriate for high-elevated sources since the emissions from these sources are mixed rather quickly in the UBL. Since a large part of the emissions are from

surface sources, the concentration calculated with the Box model underestimates the city background concentration and has to be interpreted as a minimum value.

In the GH model only ground level area sources are modelled. If the model is used to calculate the city background concentrations originating from the total urban emissions, this concentration will be an overestimation and can be considered as a maximum concentration. Therefore a hybrid model version, denoted Box-GH model, was constructed in which the dispersion from elevated sources (industry) is modelled with the Box model and the ground and low-level emissions (traffic and domestic heating) are modelled with the GH model.

2.4 Background concentration

With the dispersion formulations in the previous section the contribution of the city emissions to the city concentration is modelled. To make comparisons with measurements on a monthly, daily or hourly basis, the regional background concentration (RBC) has to be added to this concentration. The RBC provided represents an annual average and a distribution in time has to be made. A relative RBC (RBC_{rel}) was calculated using the boundary layer height, H_{wmo}, and the wind speed at a height of 10 m (u_{10} in m/s) at the selected WMO station closest to the city with:

$$RBC_{rel} = \frac{1}{u_{10} \cdot H_{wmo}} \tag{2.11}$$

The influence of the wind speed and boundary layer height on the (vertical) dispersion of pollutants is simulated with Equation 2.11 and is similar to the description used in the Box model (Equation 2.7). The boundary layer is set at an arbitrary minimum of 50 m to avoid extremely high concentrations.

The RBC at hour n is then given by:

$$RBC_{hour}(n) = \frac{RBC_{rel}(n)}{\sum_{i=1}^{8760} RBC_{rel}(i)} \; 8760 \; RBC_{year} \tag{2.12}$$

where: $RBC_{hour}(n)$ = RBC at hour n ($\mu g/m^3$)
$RBC_{rel}(n)$ = relative RBC at hour n
RBC_{year} = annual average RBC ($\mu g/m^3$)
8760 is the number of hours in one year.

3. MODEL INPUT AND SELECTION OF INFORMATION ON EUROPEAN CITIES

Table 3.1 lists the input required to run the model. Latitude, longitude, area and emission from the city were taken from the so-called City Report Forms[2] (CRFs; van Zantvoort et al., 1995) which were made in the framework of the Europe's Environment programme (Section 3.1 and 3.2). Temperature, wind velocity and cloud cover were taken from a WMO station located nearby the city (Potma, 1993; Section 3.3). As discussed in Section 2.4, the regional background concentration has to be added to the UAQAM calculations. The concentrations for this regional background are given in Section 3.4. Information on the measured city background concentrations used in the validation of the model results are presented in Section 3.5.

Table 3.1: Input parameters for UAQAM

	input variables	unit
city	latitude longitude area emission	decimal degrees decimal degrees km^2 kton per year
WMO station	temperature wind velocity cloud cover	°C m/s octa
region	regional background concentration RBC	$\mu g/m^3$

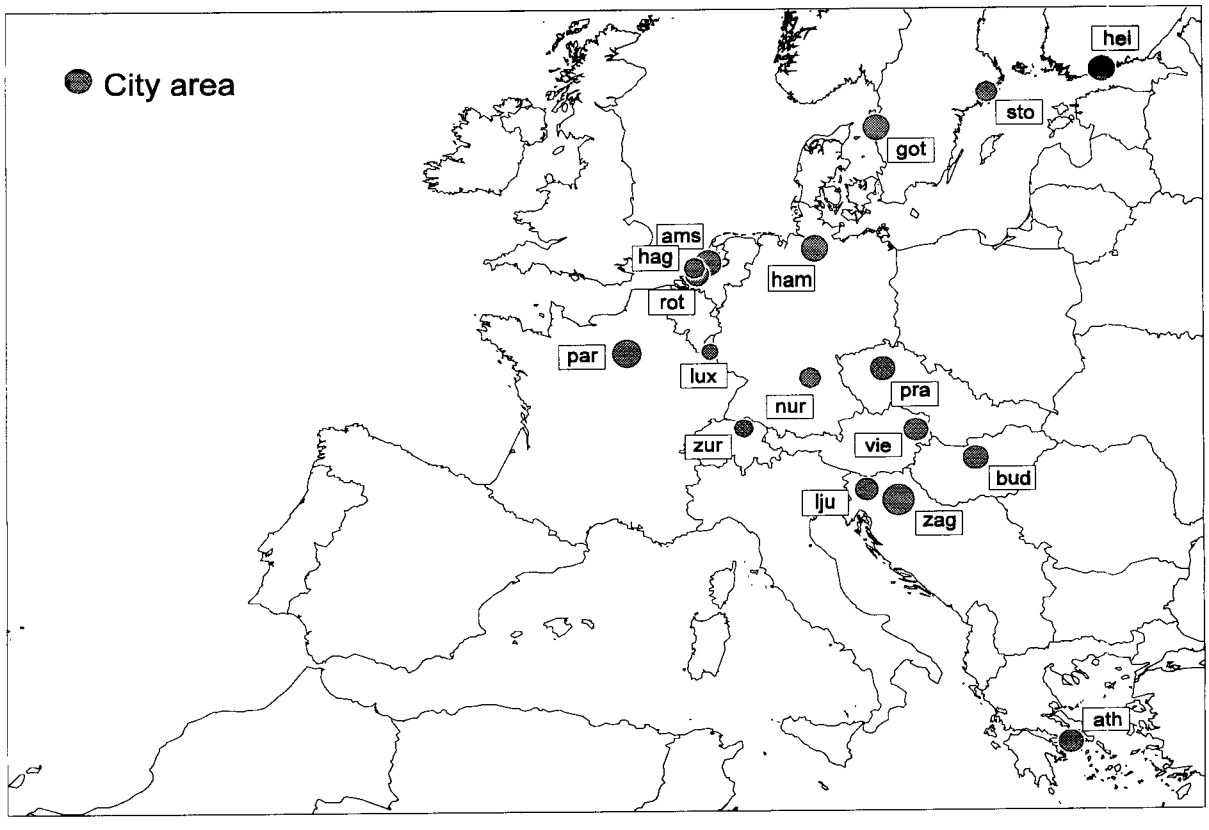

Figure 3.1: Selected cities.

[2] Air quality data is summarised per city for 105 cities in so-called City Report Forms (CRFs).

3.1 Selection of cities and general information

Cities for which the following data were available were selected:

- SO_2 emissions for one year between 1989 and 1992,
- annual average city background SO_2 concentrations for one year between 1989 and 1992,
- total or built-up area for the city or the conurbation.

The above requirements were met by 17 cities (Figure 3.1). General information on these cities is presented in Table 3.2.

Table 3.2: General information on selected cities (Van Zantvoort et al., 1995)

city	country	siting	total area (km^2)		built-up area (km^2)		inhabitants (*1000)	
			city	con-urbation	city	con-urbation	city	con-urbation
Amsterdam	Netherlands	plain	162	583	--	--	702	1 077
Athens	Greece	coastal valley	427	--	350	--	886	3 100
Budapest	Hungary	river basin	370	525	200	--	2 109	4 434
Gothenburg	Sweden	coastal	--	654	--	132	--	734
The Hague	Netherlands	coastal plain	65	151	--	--	430	654
Hamburg	Germany	plain	755	--	--	--	1 626	--
Helsinki	Finland	coastal plain	184	743	105	242	491	929
Ljubljana	Slovenia	valley	290	--	43	--	273	--
Luxembourg	Luxembourg	valley	--	55	--	22	--	78
Nuremberg	Germany	river basin	186	--	95	--	500	--
Paris	France	plain	105	1200	--	--	2 189	8 510
Prague	Czech Republic	river basin	495	--	210	--	1 216	--
Rotterdam	Netherlands	coastal plain	201	307	--	183	582	1 089
Stockholm	Sweden	coastal-plain	188	--	--	--	667	--
Vienna	Austria	valley-river basin	415	--	190	--	1 564	--
Zagreb	Croatia	river basin	--	1932	--	80	707	954
Zurich	Switzerland	valley	92	92	24	24	356	356

Conurbation: Core municipality together with its morphologically integrated neighbouring cities/towns, or a city and its suburbs, excluding secondary towns or suburbs separated by more than 2.5 km from the prime city. [3]

City: The core municipality of the named conurbation/city.

Total area: Total administrative area.

Built-up area: Area with permanent man-made structures (e.g. houses, buildings, infrastructure).

3.2 Emissions

For the Dutch cities, emissions from the Emission Registration Office (Emissieregistratie, pers. comm., 1989) were used. This concerns emissions for areas of 5 by 5 kilometres (Table 3.3). For the other 14 cities the emissions reported in the CRFs were used (Table 3.4). It is not clear what area these emissions refer to. If provided, the area of the conurbation is used as input for the model runs and otherwise that of the city. If available, the total (administrative) area was used, otherwise the built-up area. The distribution of emission over sources of

[3] The choice of 2.5 km was guided by atmospheric transport calculations. Model runs using the OPS model (Van Jaarsveld, 1990) for an inert emission source distributed evenly over the city area showed that the contribution to the resulting annual average concentration field of that component under average meteorological conditions had decreased to 10% of its maximum at 2.5 km from the source area.

traffic, domestic/space heating and industry (Van Zantvoort et al., 1995) is shown in Figure 3.2 and Figure 3.3 for SO_2 and NO_X, respectively.

The uncertainties in the area and emission data is fairly large. However, an assessment of these uncertainties could not be made because the inventory methods differ from city to city (Sluyter, 1995).

Table 3.3: Emission data for selected Dutch cities

city	area (km^2)	Q_{SO2} (kton)	Q_{SO2} / area (ton/km^2)	Q_{NOx} (kton)	Q_{NOx} / area (ton/km^2)
Amsterdam	225	2.4	11	14.5	64
The Hague	150	0.8	5	7.8	52
Rotterdam	300	47.6	155	38.5	125

Table 3.4: Emission data for selected cities (except Dutch cities)

city	total area (km^2)	built-up area (km^2)	Q_{SO2} (kton)	Q_{SO2} / total area (ton/km^2)	Q_{SO2} / built-up area (ton/km^2)	Q_{NOx} (kton)	Q_{NOx} / total area (ton/km^2)	Q_{NOx} / built-up area (ton/km^2)
Athens	427	350	17.8	42	51	36.2	85	103
Budapest	525	525	37.6	72	72	27.0	51	51
Gothenburg	654	132	2.1	3	16	16.9	26	128
Hamburg	755	755	21.0	28	28	35.3	47	47
Helsinki	743	242	21.9	29	90	35.7	48	148
Ljubljana	290	43	20.0	69	465			
Luxembourg	55	22	0.6	11	27	1.8	33	82
Nuremberg	186	95	4.1	22	43	11.2	60	118
Paris	1200	1200	100.0	83	83			
Prague	495	210	45.8	93	218	22.0	44	105
Stockholm	188	188	2.4	13	13	10.8	57	57
Vienna	415	190	13.9	33	73	31.6	76	166
Zagreb	1932	80	9.6	5	120			
Zurich	92	24	3.8	41	158	5.3	58	221

3.3 Meteorology

Temperature, wind velocity and cloud cover were extracted from a global observational database compiled by ECMWF (for implementation at RIVM, see Potma, 1993). These data are given on a six-hourly basis, i.e. 00, 06, 12 and 18 UT. The six-hourly data were linearly interpolated to hourly values. A WMO station nearby (Table 3.5) was selected for all the cities. Generally, these stations are situated well outside the built-up area of the cities. The wind velocity measured at 10 m is translated to a wind velocity at 50 m (see Section 2.3). When one of the parameters was missing the previous value was used. However, when this happened twice in a time-series, the concentration was not calculated at this point of time and was left out by the calculation of the daily and annual average.

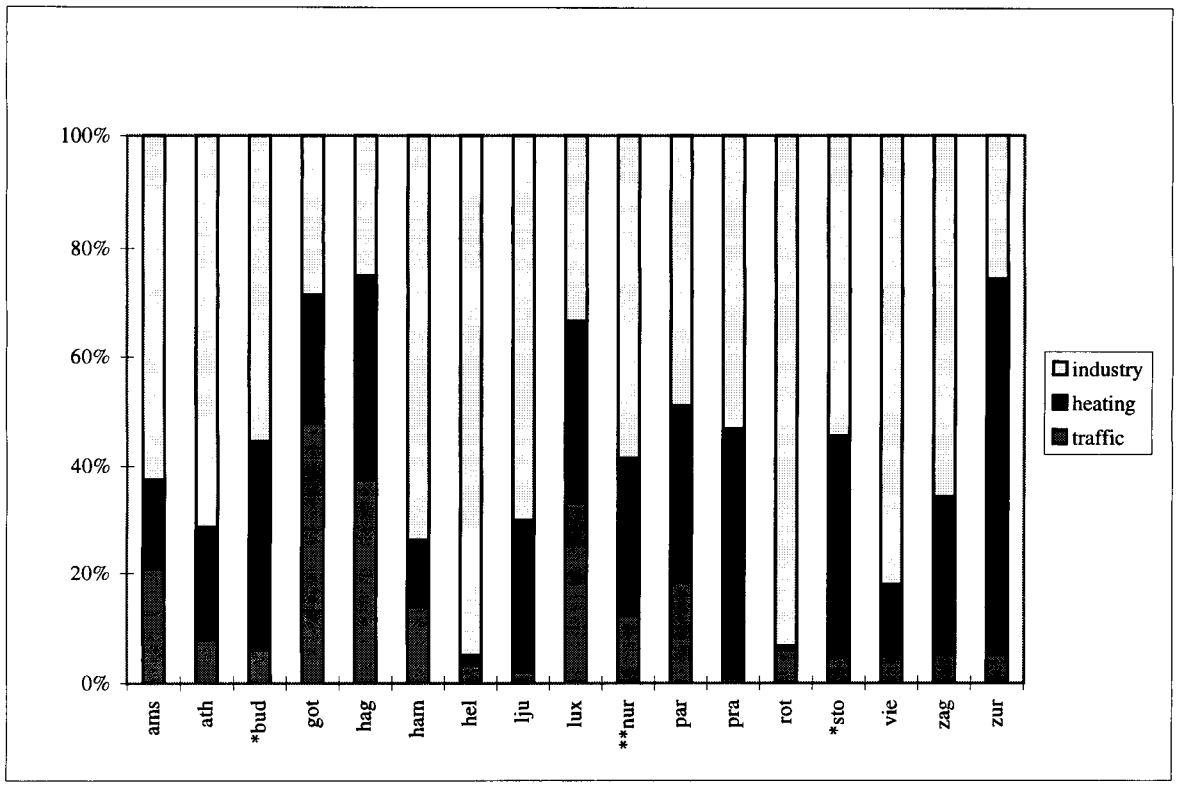

Figure 3.2: Distribution of SO_2 emission over three sources: traffic, domestic/space heating and industry per city.

*) Ratio between heating and industry is calculated.

**) Ratio is calculated.

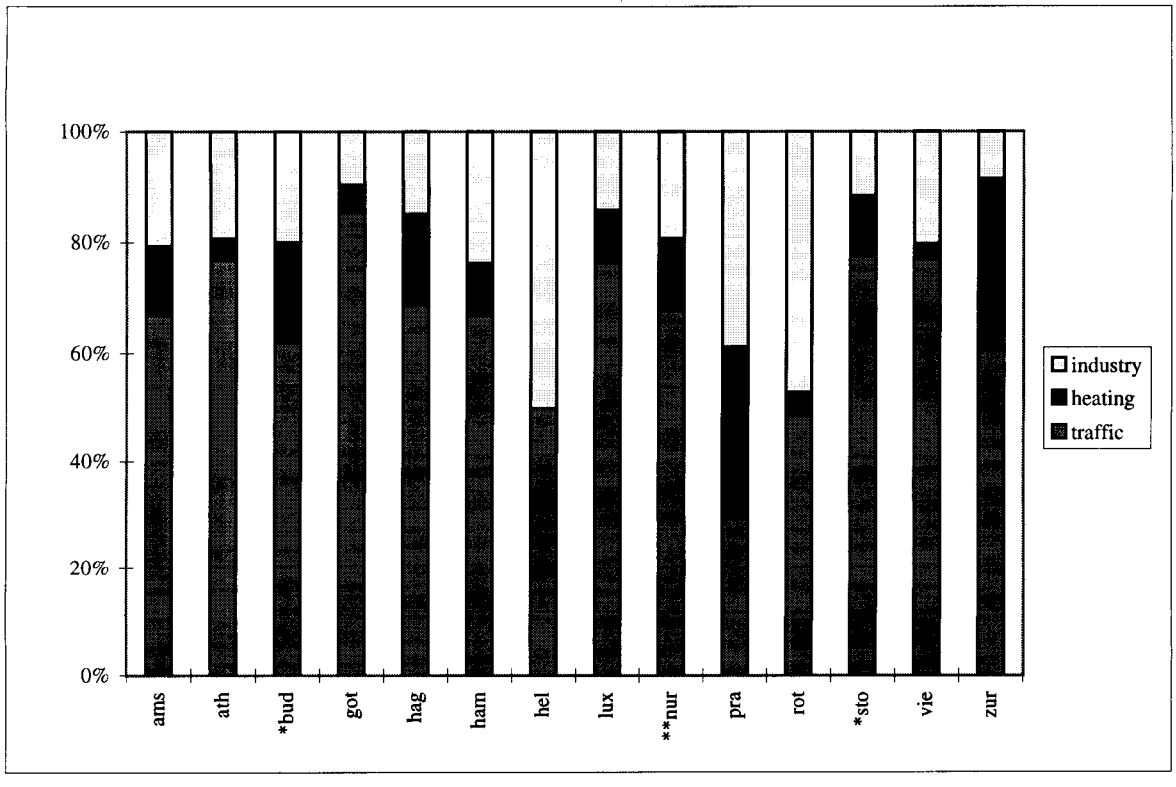

Figure 3.3: Distribution of NO_X emission over three sources: traffic, domestic/space heating and industry per city.

*) Ratio between heating and industry is calculated.

**) Ratio is calculated.

In the model the shift between local time and UT is not accounted for. This means that there will be a shift between the emission calculated with Equation 2.1 and the meteorological parameters. For the cities in Table 3.3 and Table 3.4 this is 1 hour in wintertime and 2 hours in summertime, except for Helsinki and Athens which are situated in a time zone which is two hours ahead of UT in wintertime.

Table 3.5: Distance between city coordinates (Times, 1990) and the meteorological station

city	distance (km)	city	distance (km)	city	distance (km)
Amsterdam	13	Helsinki	8	Rotterdam	5
Athens	11	Ljubljana	21	Stockholm	15
Budapest	28	Luxembourg	10	Vienna	6
Gothenburg	12	Nuremberg	6	Zagreb	15
The Hague	20	Paris	17	Zurich	2
Hamburg	9	Prague	18		

3.4 Regional background concentrations

To compare modelled results with measurements, regional background concentrations (RBC) had to be added to the modelled concentrations. For seven cities annual average SO_2 concentrations from regional background stations were available in the CRFs (see Table 3.6). Regional annual average SO_2 concentrations for the other cities as well as all regional NO_X concentrations were calculated with the TREND model (Van Jaarsveld, 1990). A variation on a daily and hourly basis on this annual mean was parametrised according to Section 2.4.

3.5 City background concentrations

Annual averaged concentrations were taken from the CRFs representing one or more city background stations. Hourly concentration data for at least one city background station for the year 1990 were obtained via a questionnaire among the contact persons in the selected 17 cities. These data were also used to construct daily and monthly averaged concentrations. Annual average concentrations for these stations are sometimes different than the mean values in the CRFs because the concentration values taken from the CRFs are averages from more than one station and because they are from different years (1989-1992).

Table 3.6 shows the availability of SO_2 and NO_X concentrations (with at least 75% of data available) of the 17 selected cities. These data were used to evaluate the modelled results (Section 4.1).

Table 3.6: Available SO_2 and NO_X concentrations

city	CRF annual average SO_2 concentrations		SO_2 time-series		NO_X time-series	
	city background	regional background	# of stations	time scale	# of stations	time scale
Amsterdam	x	x	1	hour	1	hour
Athens	x	x	-	-	-	-
Budapest	x	x	-	-	-	-
Gothenburg	x	-	2	hour	-	-
The Hague	x	x	1	hour	1	hour
Hamburg	x	-	1	month	-	-
Helsinki	x	x	2	hour	2	hour
Ljubljana	x	-	-	-	-	-
Luxembourg	x	-	-	-	-	-
Nuremberg	x	-	1	hour	1	hour
Paris	x	-	-	-	-	-
Prague	x	-	-	-	-	-
Rotterdam	x	-	1	hour	1	hour
Stockholm	x	x	-	-	-	-
Vienna	x	x	2	hour	-	-
Zagreb	x	-	2	day	-	-
Zurich	x	-	1	hour	1	hour

4. RESULTS AND DISCUSSION

In Section 4.1 the results from the Box model, the Box-GH model and the GH model as described in Section 2.3.1-2.3.3 are compared with measurements on an annual, daily and hour-of-day basis. Section 4.2 describes the model sensitivity of the Box-GH model.

4.1 Comparison with measurements

Comparison of results from the three models with measurements is shown in Section 4.1.1-4.1.3 by the linear regression line between measured and modelled data and the fraction of prediction within a factor of 2 (FOP2). In Section 4.1.4 modelled percentiles and peak values are compared with measurements at individual monitoring stations.

Annual average SO_2 concentrations of the selected cities predicted by the three models have been compared with city background concentrations from the CRFs (Section 4.1.1). Because these concentrations are means of more than one station, they are considered to represent the city background concentration better than data from only one station. Because the CRFs do not provide NO_X concentrations, the modelled annual average NO_X concentrations are compared with data from individual measuring stations.

Evaluation of modelled concentrations on a daily basis (Section 4.1.2) and hour-of-day basis (Section 4.1.3) took place by comparison with data from individual measuring stations. To check the parametrisation of the RBC (Section 2.4), the correlation between measured data and modelled concentrations *with* and *without* RBC was calculated.

4.1.1 Annual average city background concentrations

Modelled annual average SO_2 concentrations calculated by the three models compared to measured concentrations are presented in Figure 4.1 and Table 4.1. The correlation between measured and modelled concentrations is higher for the Box model compared to the other two models. The slope of the regression line is closer to 1 for the other two models, but the intercept is also higher for the latter.

Table 4.1: Fraction of predictions within a factor of 2, correlation and regression for annual average SO_2 concentrations

without RBC:

SO_2 (17 cities)	Box model	Box-GH model	GH model
FOP2	0.41	0.35	0.18
correlation	0.65 *	0.53 *	0.56 *
intercept ($\mu g/m^3$)	4	10	10
slope	0.7	0.8	1.0

with RBC:

SO_2 (17 cities)	Box model	Box-GH model	GH model
FOP2	0.65	0.59	0.47
correlation	0.77 *	0.69 *	0.70 *
intercept ($\mu g/m^3$)	5	8	8
slope	0.8	1.0	1.0

*: Correlation is significant at a confidence level of 0.95.

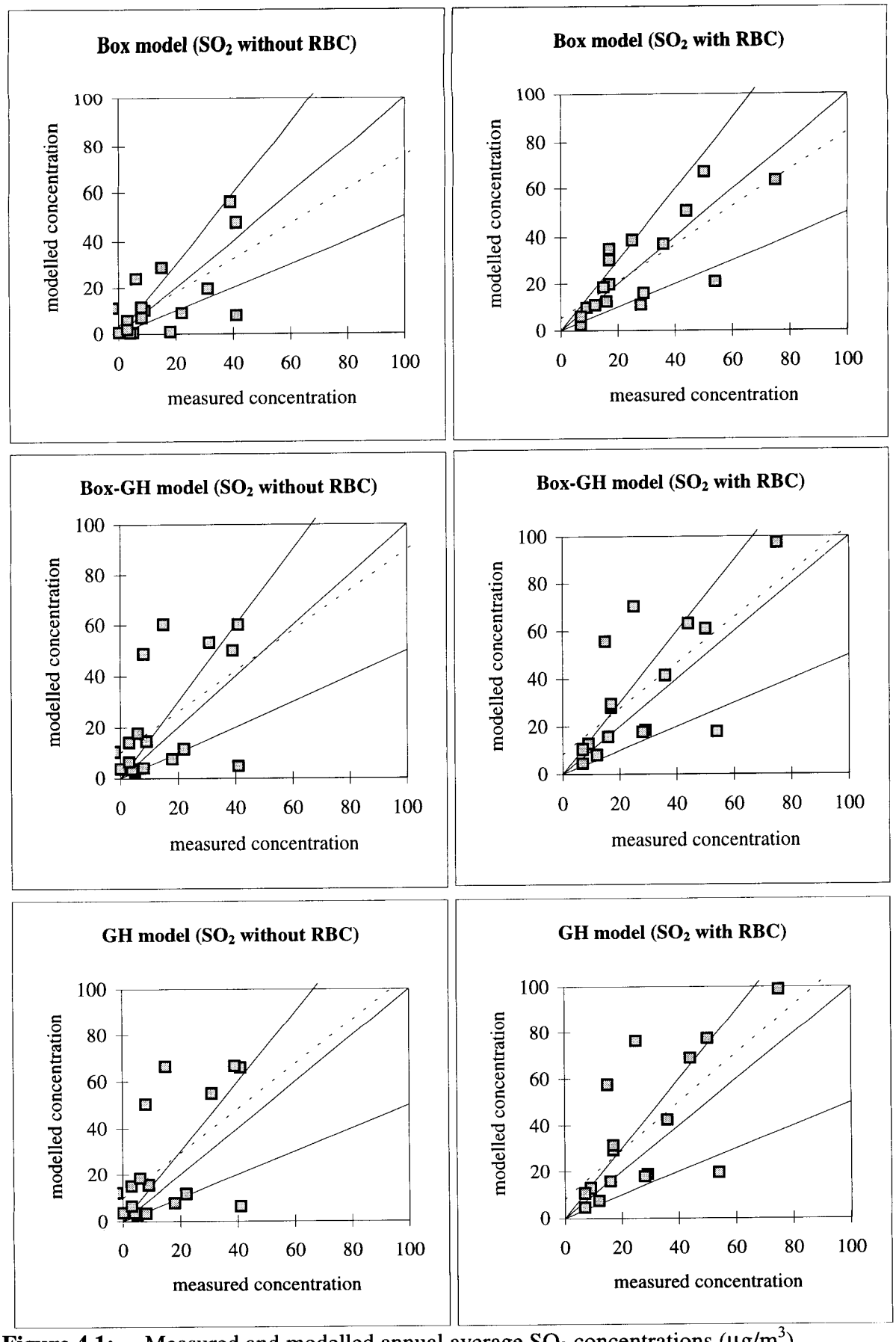

Figure 4.1: Measured and modelled annual average SO_2 concentrations ($\mu g/m^3$) with and without RBC. Box model, Box-GH model and GH model. Included: 1-on-1 line, factor of 2 lines and regression line (= dotted line).

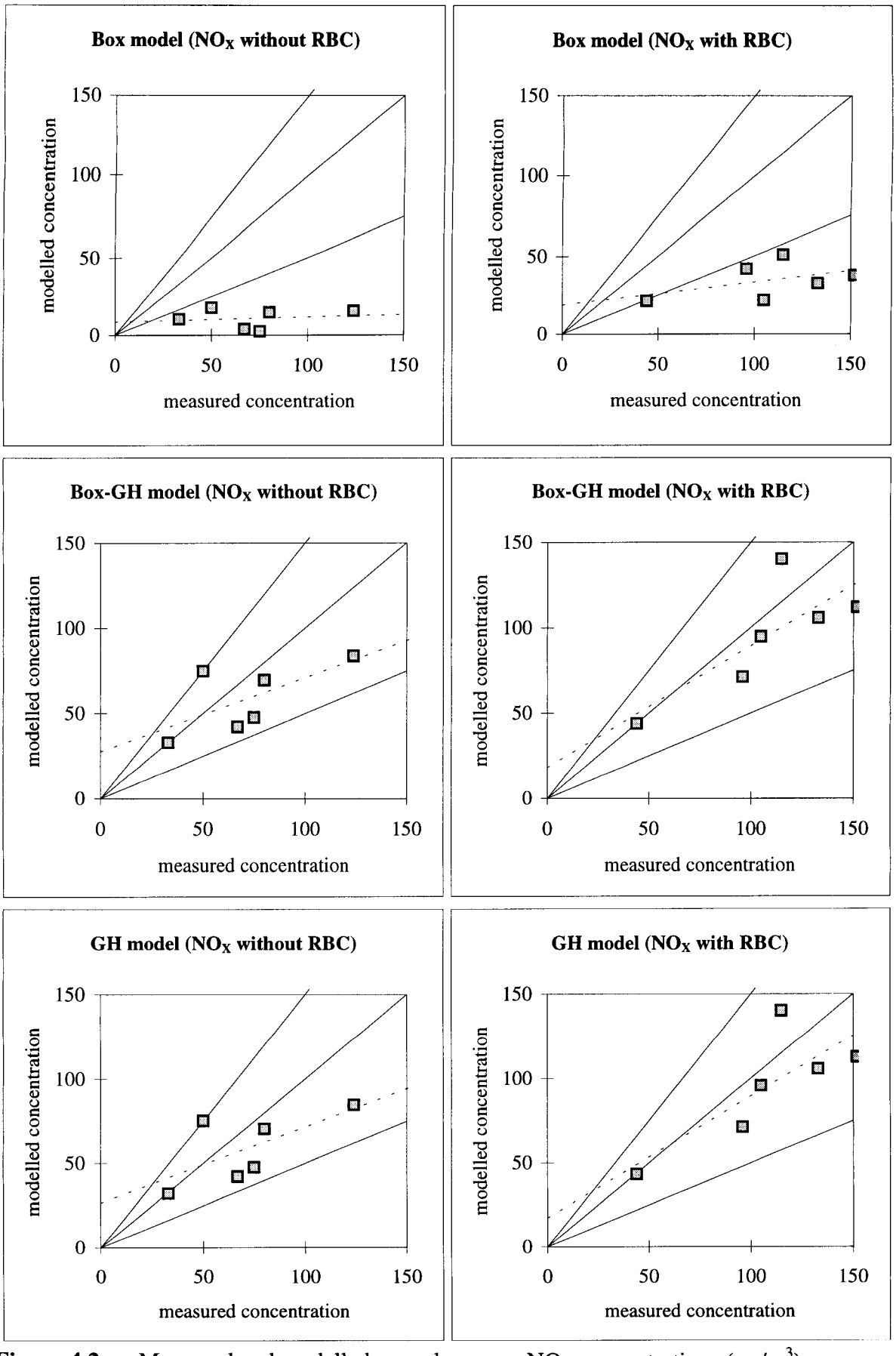

Figure 4.2: Measured and modelled annual average NO_X concentrations ($\mu g/m^3$) with and without RBC. Box model, Box-GH model and GH model. Included: 1-on-1 line, factor 2 lines and regression line (= dotted line).

Modelled annual average NO_X concentrations calculated by the three models compared to measured concentrations are presented in Figure 4.2 and Table 4.2. For all cities, annual average NO_X concentrations calculated by the Box model are at least a factor of 2 lower than measurements. The slope of the regression line is almost zero and the correlation is low.

Table 4.2: Fraction of predictions within a factor of 2, correlation and regression for annual average NO_X concentrations

without RBC:

NO_X (6 cities)	Box model	Box-GH model	GH model
FOP2	0.00	0.83	0.83
correlation	0.15	0.66	0.67
intercept ($\mu g/m^3$)	9	28	27
slope	0.0	0.4	0.4

with RBC:

NO_X (6 cities)	Box model	Box-GH model	GH model
FOP2	0.00	1.00	1.00
correlation	0.46	0.79 *	0.79 *
intercept ($\mu g/m^3$)	19	18	17
slope	0.1	0.7	0.7

*: Correlation is significant at a confidence level of 0.95.

4.1.2 Daily average concentrations

Measurements of 13 monitoring stations were used for a comparison with modelled SO_2 concentrations on a daily basis (Table 4.3 and Table 4.4). Cities with two monitoring stations are indicated with city name 1 and 2. Note that these data are different from the annual measurements i.e. the daily concentrations summed to an annual value different from the annual value of Section 4.1.1. Both the FOP2 and the correlation of SO_2 are on the average the highest for the Box-GH model. However, the difference between the three models is small. The slope of the regression line is for all models and all stations below 0.6 (except for Zurich, Table 4.5). The results of all models are not improved if the RBC is added.

All the stations at which the correlation for the Box model is highest (Nuremberg and Zurich for SO_2 and NO_X; Helsinki-1 and -2 for NO_X) are exactly the same stations for which the correlation of measurements with modelled concentrations *with* RBC are higher than *without* RBC for all three models. The RBC is calculated in the same way as the city's contribution calculated by the Box model (see Section 2.4). However, for more than half of the stations, correlation of SO_2 concentrations are higher without RBC.

Table 4.3: Fraction of prediction within a factor of 2 for daily average SO_2 concentrations modelled with RBC

SO_2	Box model	Box-GH model	GH model
Amsterdam	0.29	0.34	0.34
Gothenburg 1	0.10	0.27	0.27
Gothenburg 2	0.23	0.42	0.42
The Hague	0.33	0.38	0.38
Helsinki 1	0.31	0.41	0.36
Helsinki 2	0.31	0.43	0.39
Nuremberg	0.56	0.50	0.50
Rotterdam	0.21	0.40	0.30
Vienna 1	0.44	0.61	0.55
Vienna 2	0.32	0.38	0.35
Zagreb 1	0.07	0.04	0.05
Zagreb 2	0.36	0.38	0.38
Zurich	0.63	0.41	0.39
average	*0.32*	*0.38*	*0.36*

Table 4.4: Correlation between daily average modelled and measured SO_2 concentrations

correlation modelled (*without RBC*) and measured						
SO_2	Box model		Box-GH model		GH model	
Amsterdam	0.02		0.32	*	0.29	*
Gothenburg 1	0.38	*	0.34	*	0.34	*
Gothenburg 2	0.17	*	0.18	*	0.18	*
The Hague	0.24	*	0.40	*	0.40	*
Helsinki 1	0.09		0.21	*	-0.01	
Helsinki 2	0.11	*	0.32	*	0.04	
Nuremberg	0.39	*	0.24	*	0.27	*
Rotterdam	0.13	*	0.18	*	0.11	*
Vienna 1	0.46	*	0.67	*	0.63	*
Vienna 2	0.47	*	0.63	*	0.59	*
Zagreb 1	0.66	*	0.75	*	0.74	*
Zagreb 2	0.49	*	0.52	*	0.52	*
Zurich	0.75	*	0.67	*	0.68	*
average	*0.34*		*0.42*		*0.37*	

correlation modelled (*with* RBC) and measured						
SO_2	Box model		Box-GH model		GH model	
Amsterdam	0.04		0.09		0.08	
Gothenburg 1	0.34	*	0.35	*	0.34	*
Gothenburg 2	0.13	*	0.14	*	0.14	*
The Hague	0.22	*	0.26	*	0.26	*
Helsinki 1	0.11	*	0.17	*	0.07	
Helsinki 2	0.14	*	0.24	*	0.12	*
Nuremberg	0.39	*	0.35	*	0.36	*
Rotterdam	0.14	*	0.17	*	0.14	*
Vienna 1	0.44	*	0.59	*	0.53	*
Vienna 2	0.44	*	0.57	*	0.51	*
Zagreb 1	0.62	*	0.69	*	0.68	*
Zagreb 2	0.44	*	0.49	*	0.49	*
Zurich	0.76	*	0.69	*	0.70	*
average	*0.32*		*0.37*		*0.34*	

*: Correlation is significant at a confidence level of 0.95.

Table 4.5: Intercept and slope of regression line of daily average SO_2 concentrations modelled with RBC

SO_2	Box model		Box-GH model		GH model	
	intercept ($\mu g/m^3$)	slope	intercept ($\mu g/m^3$)	slope	intercept ($\mu g/m^3$)	slope
Amsterdam	9	0.0	12	0.1	12	0.1
Gothenburg-1	1	0.1	3	0.1	3	0.1
Gothenburg-2	2	0.0	4	0.1	4	0.1
The Hague	9	0.2	12	0.3	12	0.3
Helsinki-1	18	0.1	7	0.1	7	0.0
Helsinki-2	9	0.1	7	0.1	7	0.1
Nuremberg	12	0.4	20	0.4	20	0.4
Rotterdam	26	0.4	24	0.2	24	0.3
Vienna-1	17	0.5	16	0.5	18	0.5
Vienna-2	19	0.6	18	0.6	20	0.5
Zagreb-1	7	0.1	6	0.1	8	0.1
Zagreb-2	16	0.1	14	0.1	16	0.1
Zurich	3	0.6	11	1.7	12	1.7

Modelled daily average NO_X concentrations are compared with measurement data from seven stations (Table 4.6 and Table 4.7). The correlation between measured and modelled NO_X concentrations is almost the same for all three models. The average FOP2 is, however, much higher for the Box-GH and the GH model than for the Box model.

Table 4.6: Fraction of prediction within a factor of 2 for daily average NO_X concentrations modelled with RBC

NO_X	Box model	Box-GH model	GH model
Amsterdam	0.30	0.39	0.39
The Hague	0.25	0.66	0.66
Helsinki 1	0.44	0.39	0.40
Helsinki 2	0.40	0.58	0.54
Nuremberg	0.27	0.74	0.73
Rotterdam	0.37	0.56	0.55
Zurich	0.03	0.67	0.67
average	*0.30*	*0.57*	*0.56*

Table 4.7: Correlation between daily average modelled and measured NO_X concentrations

correlation modelled (*without RBC*) and measured			
NO_X	Box model	Box-GH model	GH model
Amsterdam	0.37 *	0.49 *	0.48 *
The Hague	0.64 *	0.66 *	0.66 *
Helsinki 1	0.50 *	0.45 *	0.44 *
Helsinki 2	0.42 *	0.34 *	0.33 *
Nuremberg	0.58 *	0.42 *	0.44 *
Rotterdam	0.48 *	0.56 *	0.55 *
Zurich	0.67 *	0.56 *	0.57 *
average	*0.52*	*0.50*	*0.50*

correlation modelled (*with* RBC) and measured			
NO_X	Box model	Box-GH model	GH model
Amsterdam	0.34 *	0.38 *	0.38 *
The Hague	0.59 *	0.64 *	0.64 *
Helsinki 1	0.53 *	0.52 *	0.51 *
Helsinki 2	0.47 *	0.44 *	0.43 *
Nuremberg	0.59 *	0.50 *	0.51 *
Rotterdam	0.51 *	0.55 *	0.54 *
Zurich	0.70 *	0.63 *	0.63 *
average	*0.53*	*0.52*	*0.52*

*: Correlation is significant at a confidence level of 0.95.

The slope of the regression line varies from 0.2 to 0.5 for the Box model and from 0.2 to 0.6 for the other two models (Table 4.8). The intercept of the regression line calculated by the Box-GH and the GH model are 2 to 5 times higher than calculated by the Box model. The results of the models do not improve significantly if the RBC is added.

Table 4.8: Intercept and slope of regression line of daily average NO_X concentrations modelled with RBC

NO_X	Box model		Box-GH model		GH model	
	intercept ($\mu g/m^3$)	slope	intercept ($\mu g/m^3$)	slope	intercept ($\mu g/m^3$)	slope
Amsterdam	38	0.2	75	0.2	75	0.2
The Hague	12	0.2	43	0.3	43	0.3
Helsinki-1	10	0.4	34	0.3	33	0.3
Helsinki-2	11	0.2	35	0.2	34	0.2
Nuremberg	14	0.2	65	0.3	65	0.3
Rotterdam	22	0.5	73	0.6	73	0.6
Zurich	13	0.2	56	0.3	57	0.3

4.1.3 Concentrations at the hour-of-day

Modelled SO_2 concentrations are compared to measurement data from 11 monitoring stations, see Figure 4.3. (Note that the modelled concentrations in Figure 4.3 consist of the modelled city contribution plus an *annual* RBC). The average FOP2 of 11 stations is higher for the Box-GH and GH model than for the Box model. However, for some stations the FOP2 of the Box model is higher (Table 4.9). Correlation between measurements and modelled concentrations without RBC for all stations is negative for the Box model and positive for the Box-GH and the GH models. The average correlation is negative for all models when the modelled RBC is included (Table 4.10).

Table 4.9: Fraction of prediction within a factor of 2 for average SO_2 concentrations at hour-of-day modelled with RBC

SO_2	Box model	Box-GH model	GH model
Amsterdam	0.54	0.67	0.71
Gothenburg 1	0.00	0.00	0.00
Gothenburg 2	0.04	0.42	0.42
The Hague	0.33	0.50	0.50
Helsinki 1	0.54	0.83	0.79
Helsinki 2	0.54	0.88	0.83
Nuremberg	0.42	0.50	0.50
Rotterdam	0.46	0.79	0.79
Vienna 1	0.13	0.33	0.58
Vienna 2	0.21	0.46	0.42
Zurich	0.63	0.29	0.25
average	*0.35*	*0.52*	*0.53*

Table 4.10: Correlation between modelled and measured average SO_2 concentrations at hour-of-day

correlation modelled (*without RBC*) and measured			
SO_2	Box model	Box-GH model	GH model
Amsterdam	-0.57	0.81 *	0.83 *
Gothenburg 1	0.04	0.81 *	0.81 *
Gothenburg 2	-0.11	0.11	0.13
The Hague	-0.43	0.70 *	0.71 *
Helsinki 1	-0.60	0.90 *	0.74 *
Helsinki 2	-0.49	0.89 *	0.87 *
Nuremberg	-0.62	0.54 *	0.67 *
Rotterdam	-0.73	0.76 *	0.87 *
Vienna 1	-0.77	0.75 *	0.90 *
Vienna 2	-0.49	0.80 *	0.92 *
Zurich	0.50 *	0.50 *	0.52 *
average	*-0.39*	*0.69*	*0.72*

correlation modelled (*with* RBC) and measured			
SO_2	Box model	Box-GH model	GH model
Amsterdam	-0.90	-0.88	-0.88
Gothenburg 1	-0.63	0.21	0.21
Gothenburg 2	-0.41	-0.42	-0.39
The Hague	-0.84	-0.84	-0.84
Helsinki 1	-0.68	-0.27	-0.28
Helsinki 2	-0.62	-0.29	-0.08
Nuremberg	-0.83	-0.61	-0.52
Rotterdam	-0.80	0.08	0.71 *
Vienna 1	-0.88	-0.83	-0.76
Vienna 2	-0.73	-0.66	-0.54
Zurich	0.15	0.47 *	0.51 *
average	*-0.65*	*-0.37*	*-0.26*

*: Correlation is significant at a confidence level of 0.95.

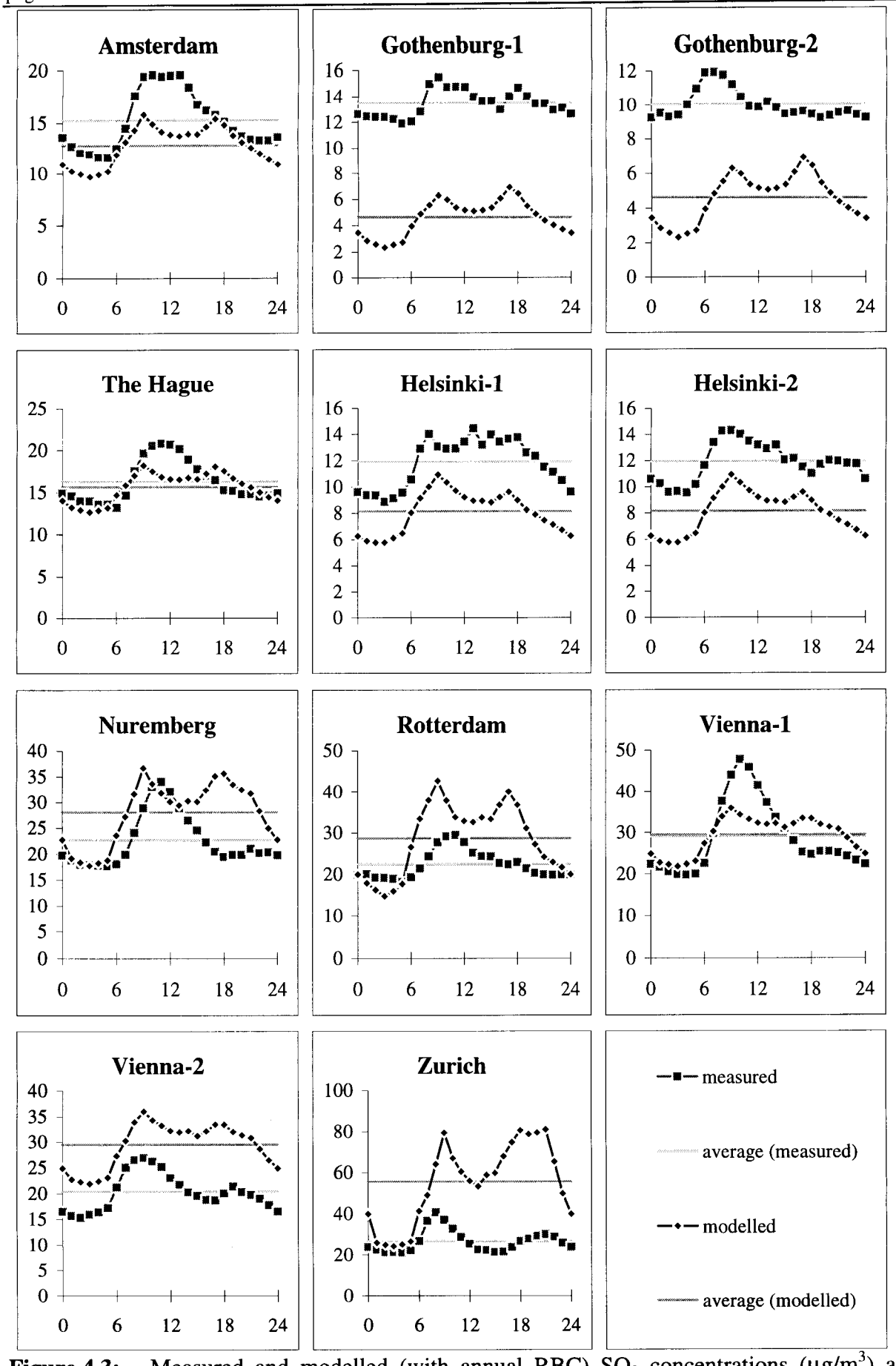

Figure 4.3: Measured and modelled (with annual RBC) SO_2 concentrations ($\mu g/m^3$) at hour-of-day; Box-GH model.

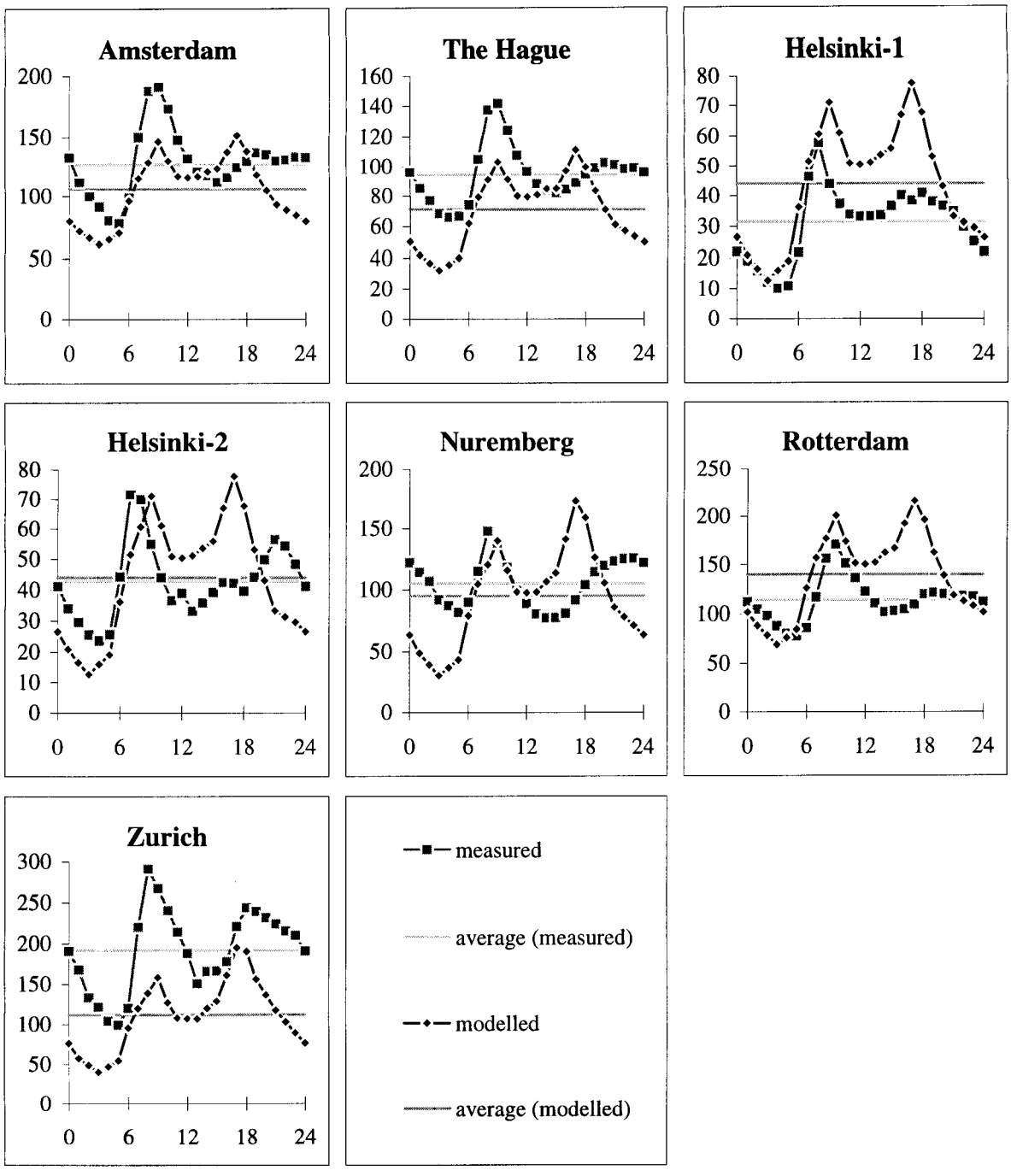

Figure 4.4: Measured and modelled (with annual RBC) NO_X concentrations ($\mu g/m^3$) at hour-of-day; Box-GH model.

Measurement data from seven stations are used to compare with modelled NO_X concentrations, see Figure 4.4. (Note that the modelled concentrations in Figure 4.4 consist of the modelled city contribution plus an *annual* RBC). At all stations the FOP2 is much higher for the Box-GH and GH model than for the Box model (Table 4.11). The correlation between the measurements and modelled concentrations without RBC is also much higher. On average these correlations are reduced when the modelled RBC is added and becomes negative for the Box model (Table 4.12).

Table 4.11: Fraction of prediction within a factor of 2 for average NO_X concentrations at hour-of-day

NO_X	Box model	Box-GH model	GH model
Amsterdam	0.46	0.96	0.96
The Hague	0.33	1.00	1.00
Helsinki 1	0.29	0.58	0.67
Helsinki 2	0.42	0.92	0.92
Nuremberg	0.08	0.88	0.88
Rotterdam	0.00	0.79	0.83
Zurich	0.04	0.75	0.71
average	*0.23*	*0.84*	*0.85*

Table 4.12: Correlation between modelled and measured average NO_X concentrations at hour-of-day

correlation modelled (*without RBC*) and measured			
NO_X	Box model	Box-GH model	GH model
Amsterdam	-0.22	0.63 *	0.64 *
The Hague	-0.04	0.57 *	0.58 *
Helsinki 1	-0.32	0.86 *	0.86 *
Helsinki 2	0.11	0.43 *	0.44 *
Nuremberg	0.53 *	0.08	0.08
Rotterdam	-0.29	0.59 *	0.61 *
Zurich	0.68 *	0.72 *	0.72 *
average	*0.06*	*0.56*	*0.56*

correlation modelled (*with* RBC) and measured			
NO_X	Box model	Box-GH model	GH model
Amsterdam	-0.49	-0.11	-0.10
The Hague	-0.42	0.38	0.39
Helsinki 1	-0.48	0.83 *	0.84 *
Helsinki 2	-0.07	0.47 *	0.49 *
Nuremberg	0.26	0.21	0.20
Rotterdam	-0.34	0.18	0.23
Zurich	-0.10	0.68 *	0.69 *
average	*-0.23*	*0.38*	*0.39*

*: Correlation is significant at a confidence level of 0.95.

4.1.4 Percentiles and peak values

Figure 4.5 and Figure 4.6 show daily average 50 and 98 percentile and maximum values at the individual measuring stations for SO_2 and NO_X, respectively, along with the modelled data. In general, the Box model underestimates all percentiles for both components. The differences between the calculated percentiles by the Box-GH and GH model are small. The 50 percentile is modelled reasonably well by the Box-GH and GH models for both components. However, the 98 percentile and maximum values for NO_X are underestimated by these models. For SO_2, the 98 percentiles and maximum are somewhat better predicted. Especially for the Dutch cities is the comparison good, probably because the emission data is more detailed.

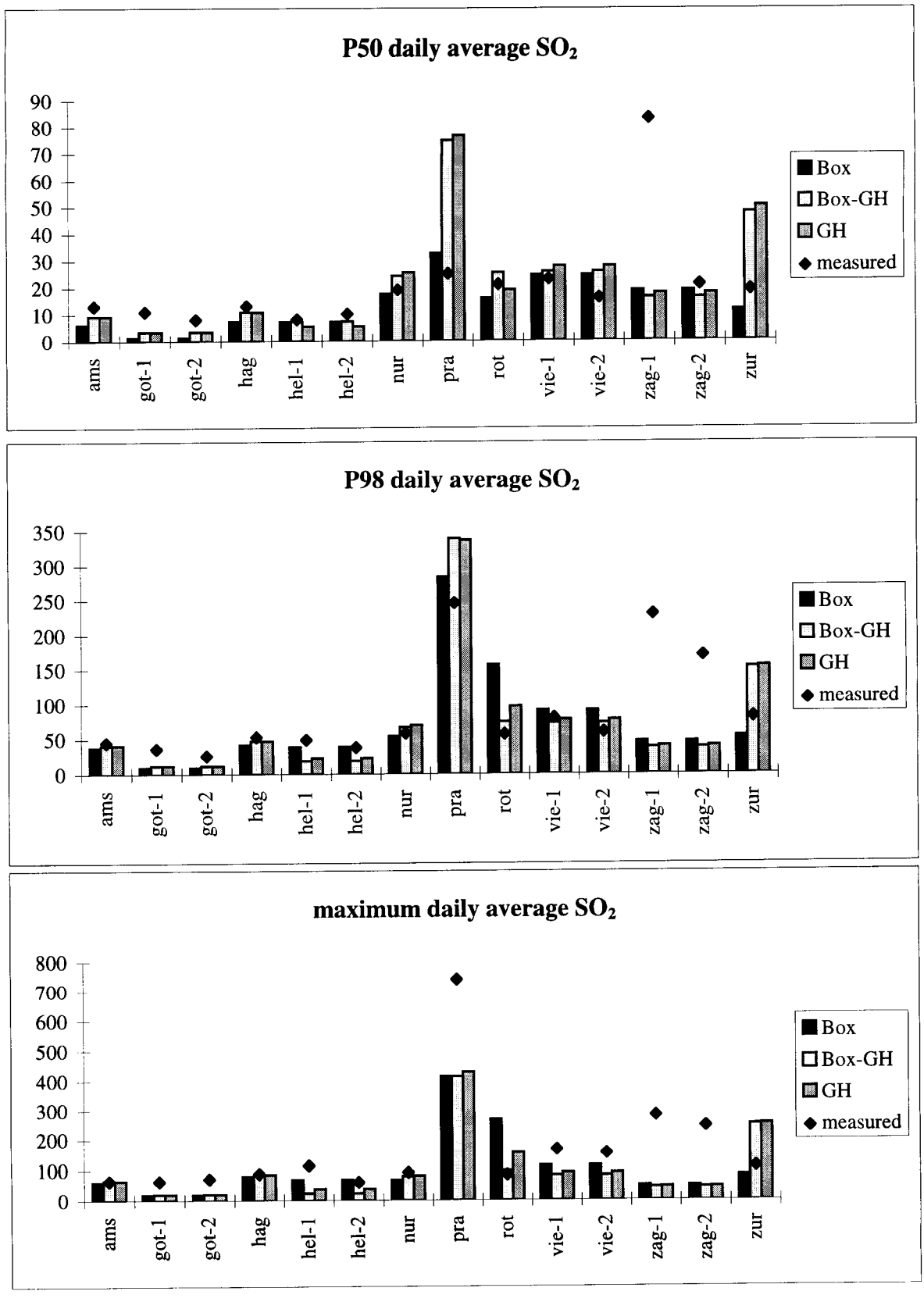

Figure 4.5: Measured and modelled daily average 50 and 98 percentiles and maxima for SO_2 ($\mu g/m^3$) in 1989.

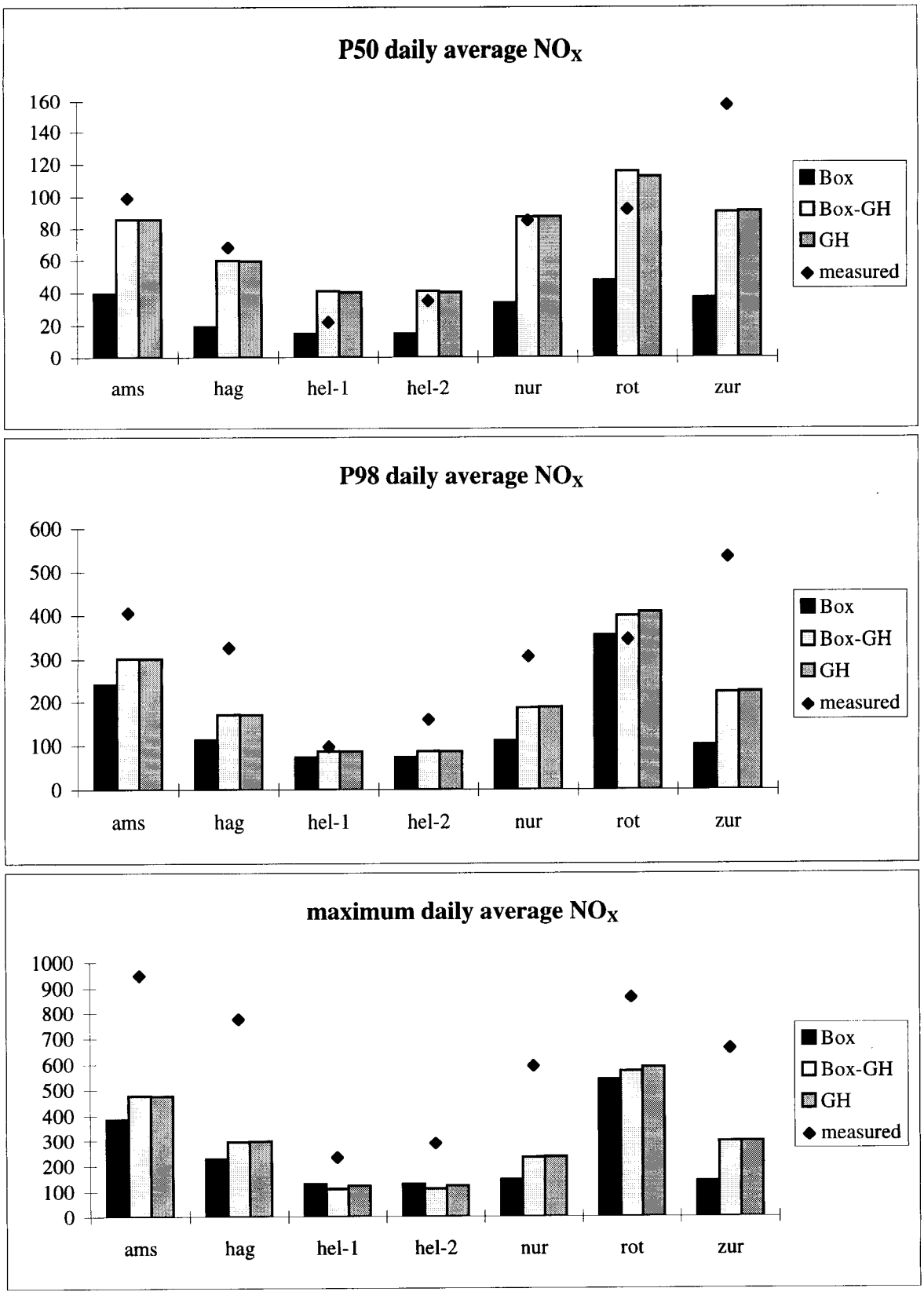

Figure 4.6: Measured and modelled daily average 50 and 98 percentiles and maxima for NO_X ($\mu g/m^3$) in 1989.

4.2 Uncertainty and sensitivity analysis of the Box-GH model

The concentration in the Box-GH model is calculated with Equations 2.7 and 2.10. In Equation 2.7 the concentration is linearly dependent on emission, Q, wind velocity, u, urban boundary layer (UBL) height, H and city length scale, L_u. In Equation 2.10 this is similar for Q and u but the concentration is independent of H and its dependency on L_u is with a power 0.25 (1-b, b=0.75). This means that for the Box-GH model variations or uncertainties in Q and u are translated directly in the concentration. Variations or uncertainties in H and L_u are reduced due to the limited dependency in the GH model description. The uncertainty in the concentration caused by the meteorological parametrisation is presented in Section 4.2.1. The influence of climatology, and area and emission as a whole, on the concentration is given in Sections 4.2.2 and 4.2.3, respectively.

4.2.1 Meteorological parametrisation

The dependency of the concentration on meteorological variables other that the wind velocity, u, is only present in the Box model via the UBL height, H. H is parametrised as a function of u_* and h_s . This is different for each stability range: neutral: H~ u_*, stable: H ~$u_*^{3/2}$, unstable: H~ $h_s^{1/2}$. The estimates of u_* and h_s are parametrised as a function of the variables denoted in Table 2.1. In this table typical values for cities were taken. Here we will illustrate the variation in the concentration due to a variation in z_0 and α.

Surface roughness length z_0
Runs with the Box-GH model showed that changing the surface roughness length from 3 to 2 m reduces annual average SO_2 concentrations for all except one station. The maximum reduction is 6.2% for the city's contribution. A reduction from 3 to 2 m leads to a reduction of 12% in u_* under neutral conditions. This reduction is translated directly in the H and subsequently in the concentration modelled with the Box model. This reduction is approximately halved in the Box-GH model, since the GH-model is not dependent on H, which is used in roughly half of the SO_2 emissions of the cities.

Priestley-Taylor constant
When the Priestley-Taylor constant is raised from 0.1 to 1, annual average SO_2 concentrations (without RBC) are raised maximally 7.5%. Varying the α to 1 implies that more evaporation is possible despite the available sensible heat, h_s. Typically the h_s is reduced then by a factor of 2 and the UBL height under unstable conditions by 1.4. Under neutral and stable conditions this effect is negligible. Assuming that the unstable conditions do occur in approximately half the modelled time, the concentration is increased by about 20%. In the Box-GH model again this increase is reduced and amounts to about 10%.

4.2.2 Climatology

The influence of a different climate on the concentration was observed by running the model for each city with an emission, Q and city length scale L_u which was averaged over all cities. Results of the Box-GH model for SO_2 are shown in Figure 4.7. Besides the influence of the climatology and also the siting of the city is in fact included. However, some effects of the siting on the concentration are also present in the cities' climates. From the figure it can be

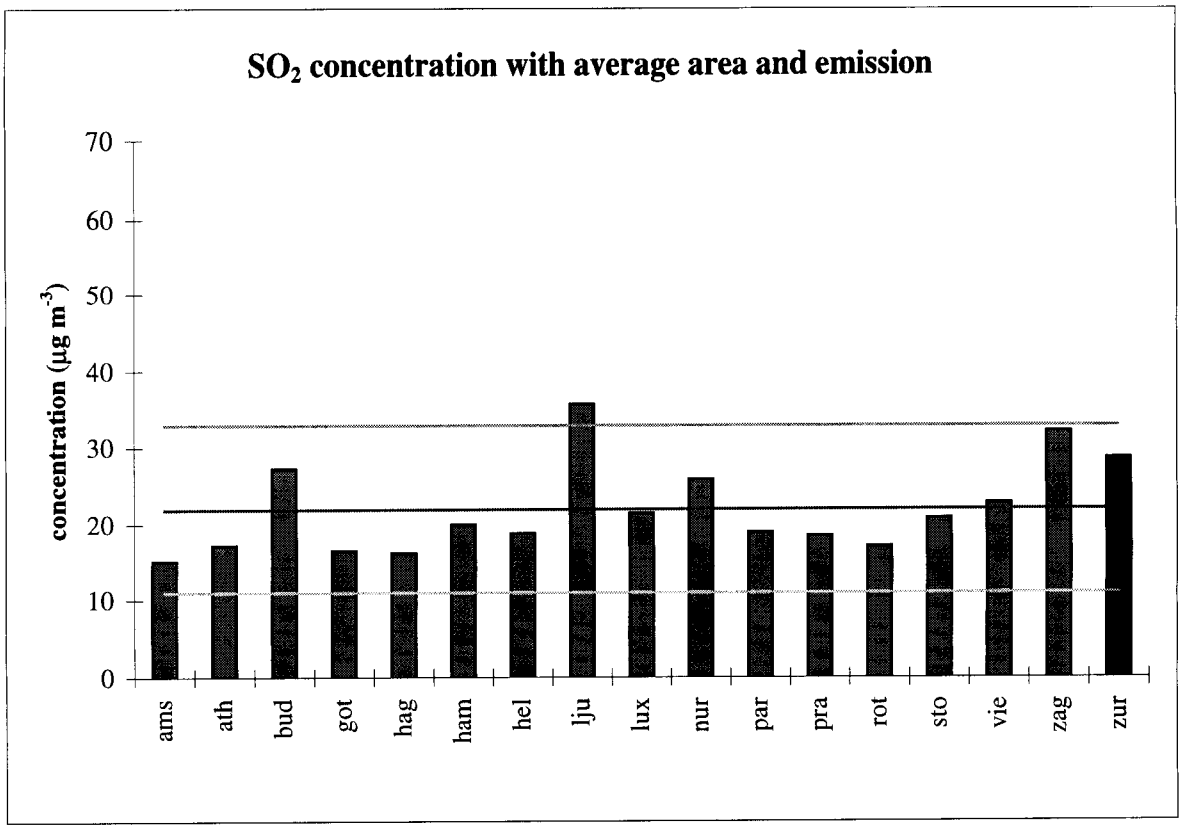

Figure 4.7: Modelled variation of annual average SO_2 concentrations due to location.

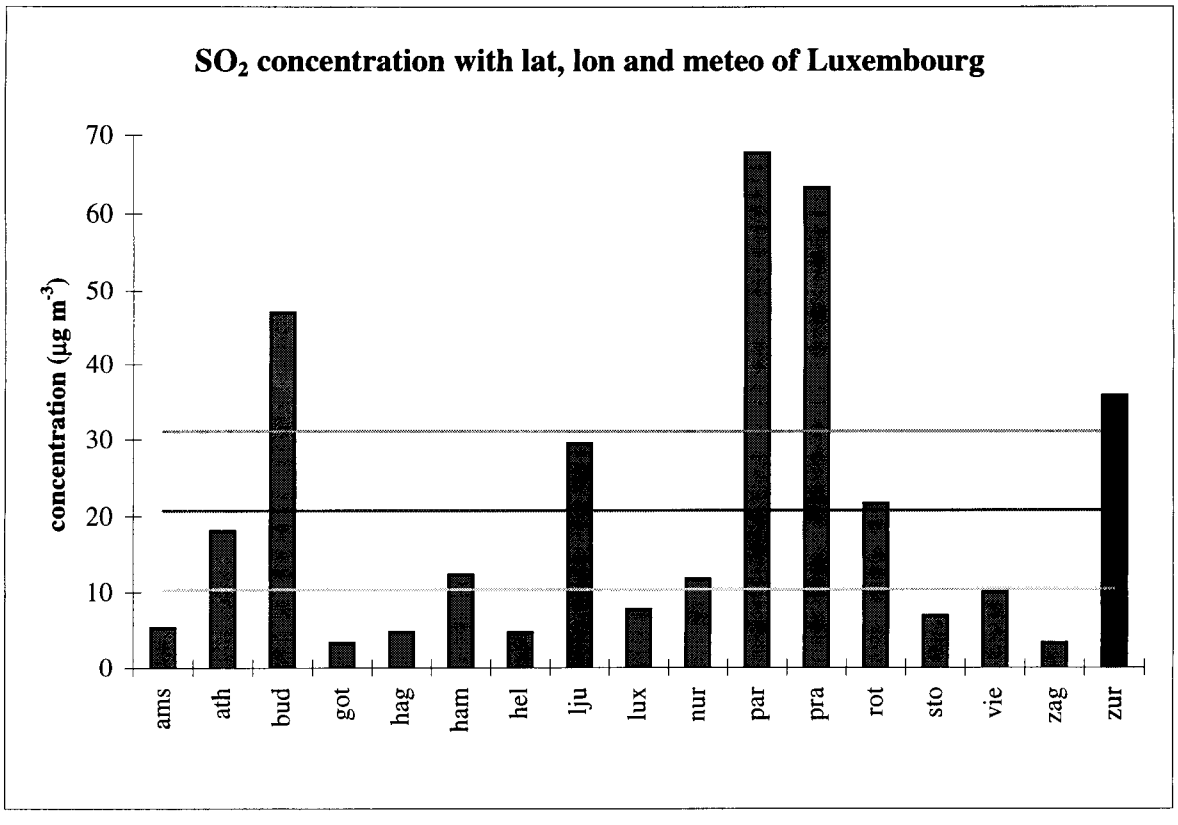

Figure 4.8: Modelled variation of annual average SO_2 concentrations due to emission.

inferred that the influence of a different climate and siting can induce a -25% to +50% variation on the annual mean concentration for all cities. Cities above this mean are sited in a river basin or valley. Differences between cities categorised as plain or coastal are small i.e. less than 10%.

4.2.3 Area and emission

The average temperature, wind velocity and cloud cover of all 17 cities is closest to the data of Luxembourg. With the latitude, longitude and meteorological parameters of Luxembourg the Box-GH model is run to determine the variation in the concentration induced by a variation in the area and emission without the climatological variations. Results for the SO_2 concentration are depicted in Figure 4.8. The differences between cities are very large and can amount easily to a factor of 10. This indicates that the emissions and area are the crucial factors in determining the concentration. The uncertainty in the calculated concentration will mainly be caused by the uncertainty in the emissions and area.

4.3 Discussion

The Box model simulates the annual SO_2 concentrations without RBC somewhat better than the Box-GH and GH model. This supports the idea that the Box model is more suited for air pollutants emitted from elevated sources. The results of the models improve if the RBC is included. However, the differences between the modelled results are small because the city background concentration is formed to a large extent by the RBC. In general, the background for all cities forms about 50% of the measured SO_2 concentration.

The Box-GH and GH models simulate the annual NO_X concentrations fairly well and much better than the Box model. The differences between the results of the Box-GH and GH models are very small. The GH-type models are more appropriate for modelling the NO_X concentrations because a large part of the NO_X emissions is emitted at the surface level. Adding the RBC to the calculated concentrations improved the correlation with the measurements. In general, the background for all cities forms about 30% of the measured NO_X concentration.

The differences between the models for both components on a daily basis are small. However, the daily NO_X concentrations are modelled somewhat better than the SO_2 concentrations (cc $\approx$ 0.50 and cc $\approx$ 0.35 for NO_x and SO_2). Also, the FOP2 of the NO_X concentrations calculated by the Box-GH and GH models is higher than calculated by the Box model. In general, the results of the Box-GH model for both components are slightly better than results of the other two models. Adding the RBC to the concentrations did not generally improve the results of the models for either component. This suggests that the variation in the RBC on a daily basis (Equation 2.11) is not parametrised correctly.

The hour-of-day concentrations for both components are reasonably well described with the Box-GH and GH models, calculated without RBC. The correlation on the basis of concentrations *with* RBC for both components is reduced compared to those *without* RBC. This means that the variation of RBC on an hourly basis is also not parametrised correctly, as seen in Equation 2.11. The dispersion process influenced by the wind velocity and the atmospheric boundary layer are simulated with this equation. However, this process is

particularly important for the variation in the RBC for pollutants emitted in the boundary layer. However, the fumigation process in which pollutants from above this boundary layer are mixed into this layer is not taken into account. This is difficult to parametrise since this would require information on the concentration up to typically 1000 m. Including a concentration dependency in Equation 2.11 would result in a diurnal variation which is opposite to the existing one. Ignoring this process, especially for SO_2, results in erroneous diurnal courses and thus in negative correlations between modelled and measured concentrations. The fumigation process is clearly present in the measurements (Figure 4.3) Since this diurnal variation in the Box model is described in a similar way this leads to negative correlations with modelled values without RBC as well. Indeed, NO_X fumigation is less important and the influence of the RBC parametrisation is less pronounced (Table 4.12). Note that an important part in the concentration variation is caused by the emission patterns (Figure 2.1).

The comparison of the percentiles and peaks of daily concentrations reflects the above findings, i.e. the Box model underestimates the concentrations of SO_2 and NO_X on a daily basis.

The main source of uncertainty in the calculated concentrations is caused by the emission and built-up area concentrations of the cities. These fairly large uncertainties are translated directly into the calculated concentrations. An assessment of these uncertainties could not be made because the inventory methods differ from city to city (Sluyter, 1995). These uncertainties and the inappropriate parametrisation of the regional background concentration hampers a sound evaluation with the concentration measurements. Besides, the measurement data used in the comparison on a daily and hour-of-day basis are from individual stations which are considered as representing the city background. Because these stations are still influenced by local factors, which also introduces an uncertainty factor in the comparison. From the differences between the modelling results for two measurement sites in a city, it can be seen that the spatial variability of the concentrations in the city can be fairly large (Tables 4.3-4.8).

5. CONCLUSIONS AND RECOMMENDATION

In this report a description is given of the Urban Air Quality Assessment Model (UAQAM). This model describes the concentration in the city caused by emissions from the city itself, the so-called city background concentration. In the preliminary version of UAQAM three versions of models for the dispersion description were studied; the Box, Gifford Hanna (GH) and a combined form of these two models (Box-GH model). These versions were compared to measurements of the SO_2 and NO_X concentrations. The regional background concentration (RBC) forms an important part of the city's concentration. This was the reason for adding the annual RBC from measurements or model calculations with TREND (Van Jaarsveld, 1995) and a parametrised hourly variation around this mean to the model calculations.

The annual SO_2 concentration is described reasonably well -correlation coefficient (cc.)=0.7- for all three models. The Box model showed slightly better results. The results of the models improved if the RBC was included. Consequently, the differences between the modelled results are reduced the city background concentration is formed to a large extend by the RBC. The annual NO_X concentration is best described with the GH and Box-GH models (cc.=0.8). The Box model clearly underestimates the NO_X concentrations. This is because NO_X in cities are emitted to a large extent by surface-level sources. The dispersion from these low sources is better described by GH-type models.

Generally, for all three models the SO_2 and NO_X concentrations on a daily basis are not described very well (cc. $\approx$ 0.3 and 0.5, respectively). The differences between the models are small. However, for NO_X the fraction of prediction -factor 2 (FOP2)- of the Box-GH and GH models is much larger than for the Box model. In general, the results of the Box-GH model for both components are slightly better than for the other two models. Adding the RBC to the concentrations did not generally improve the results of the models for both components.

The concentrations of SO_2 and NO_X on an hour-of-day basis are reasonably well described with the Box-GH and GH models without the regional background (cc. $\approx$ 0.7 and 0.6, respectively). The differences between the Box-GH and GH models are small. The correlation between measured and calculated concentration by the Box model without RBC is negative. When adding the RBC, all models show a significant reduction in the correlation. For the Box model the correlation becomes more negative.

In general, the Box model underestimates all percentiles for both components. The differences between the percentiles calculated by the Box-GH and GH models are small. The 50 percentile is modelled reasonably well by the Box-GH and GH models for both components. However, the 98 percentile and maximum values for NO_X are underestimated by these models. The 98 percentiles and maximum are somewhat better predicted for SO_2 .

From the above findings it was concluded that the variation in the regional background concentration is not parametrised correctly. Particularly the fumigation of pollutants into the atmospheric boundary layer is an important process, which contributes significantly to the city background concentration. Especially for SO_2, this RBC largely contributes to this concentration and the variations within it. A better description of the RBC on an hourly basis would require more information on the advection of the air entering the city. This can be accomplished using the results of Long Range Transport models, calculating the

concentration on an hourly basis, as the RBC for the city (such as. EMEP (Barrett et al.,1995), EUROS (Van Rheineck Leyssius et al., 1990)).

The main source of uncertainty in the calculated concentrations is caused by the emission and built-up area concentrations of the cities. These fairly large uncertainties, which are translated directly into the calculated concentrations, hamper, along with the inappropriate parametrisation of the regional background concentration, a sound evaluation with the concentration measurements. Besides, the measurement data used in the comparison on a daily and hour-of-day basis are from individual stations considered as representive of the city background. Because these stations are still influenced by local factors, this also introduces an uncertainty factor in the comparison.

The influence of meteorology and siting of the city can induce a -25% up to +50% variation in the annual mean concentration. The uncertainty due to the uncertainties in meteorological factors and parameterizations is about 10-20%.

Despite the above uncertainties, it was concluded that the Box-GH and GH models are more appropriate in describing the city background concentration than the Box-model. The Box-GH model is slightly better than the GH model and can be taken as a starting point for the assessment of urban air quality with UAQAM.

UAQAM has been evaluated with SO_2 and NO_X data which are assumed to be chemically inert on the time scales considered here. In principle, UAQAM can be used for other inert components relevant in urban areas, i.e. Pb, benzene and CO. Since the computing time of UAQAM is short, it is possible to deal with some of the chemistry in the formation of ozone and particles. This would make UAQAM more suited for smog modelling as well.

With UAQAM only one value is calculated to serve as the city background concentration. However, the dispersion description is kept flexible in order to allow spatially more detailed calculations for the city or for specific city areas (residential, downtown and commercial). In a more differentiated or original form, UAQAM can serve as input to models describing air pollution at street level, such as CAR (Eerens et al., 1993).

In UAQAM, effects such as the heat island, land sea breeze or the specific siting of the city are not taken into account. In a following version simple parametrisations of these issues could be used to simulate these phenomena in a first-order approximation.

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Appendix A. Background on urban air quality modelling

This appendix presents a literature survey of existing urban air quality models. It is not intended to give a complete overview of urban air quality models but to provide some insight into the type of models used. Therefore the literature survey was restricted to the models published in *Atmospheric Environment.*

Table A.1: Overview of urban air quality models in the literature

name	type	application area	application scale	input	output	chemistry	miscellaneous	reference
no name	3D grid numerical model	St. Louis (USA)	30*40*7 stretched grid system covers an urban area of 40*60 km^2.	wind speed and direction, temperature and temperature differences, area and point source emissions for a typical winter and summer day, and mixing height	hourly SO_2 and 12-h average sulphate concentrations	first-order chemical transformation from SO_2 to particulate sulphate	model incorporates advection, turbulent diffusion, chemical reaction, surface deposition and emissions	Ku, Rao and Rao, 1987a Ku, Rao and Rao, 1987b (Rao, Ku and Rao, 1989)
UAM (Urban Airshed Model)	3D grid Eulerian numerical photochemical model	Denver (Colorado, USA)	3D array of grid cells (hor: 2*2 miles) situated over the urban area	hourly NO_x and reactive HC emissions, meteorological data, modelled mixed layer height, background concentrations	1-hour average O_3 concentrations	carbon bond mechanism	200 major point source plumes are modelled	Dennis and Downton, 1984 (Scheffe and Morris, 1993)
no name	3D grid Lagrangian numerical photochemical model	south coast air basin of California (USA)	hor: study area of 400*150 km. grid cells of 5*5 km vert: 1525 m. 5 cells with relative spacing of. 0.02, 0.04, 0.14, 0.30 and 0.5	emissions from 130 different source categories, wind speed, cloud cover, surface roughness	1-hour average O_3 and NO_2 concentrations	52 reactions (Fall and Seinfeld)	model includes surface removal and turbulent diffusion	McRae, Goodin and Seinfeld, 1982 McRae and Seinfeld, 1983
State-Space model	statistical adaptive state-space model coupled with Kalman filtering	semi-urban area of Madrid (Spain)	specific local area	one-day-lagged wind speed and persistence daily Fe and Pb concentrations (in this case over 4 years)	daily average Fe and Pb concentrations	none	comparison with Box-Jenkins modelling (transfer function and ARIMA)	Hernandez, Martin and Valero, 1992

name	type	application area	application scale	input	output	chemistry	miscellaneous	reference
no name	statistical stepwise cluster analysis method	Xiamen (China)	specific local area	5-year average pollutant concentrations and source values	annual average SO_2, NO_x and DF (dust fall) concentrations	none	The method has improved monovariate AID (Automatic Interaction Detection) Algorithm, and can effectively deal with continuous and discrete variables, as well as non-linear relations between the variables.	Huang, 1992
no name	numerical chemical plume model	St. Louis (USA)	urban plume	NO_x, HC, CO and SO_2 emissions	sulphate particles and O_3 concentrations at the hour-of-day	10 ozone and sulphate-generating reactions	-	Isaksen, Hesstvedt and Hov, 1978
no name	Lagrangian particle scheme that utilises wind and turbulent fields from a numerical mesoscale model	Perth (Australia)	urban airshed	wind speed, turbulence and emissions	magnitude and spread of the urban plume	none	stationary homogenous Gaussian solution to the Langevin equation	Pitts and Lyons, 1992
TEMPER	bivariate temperature and persistence based regression model	lower Fraser Valley of British Columbia (Canada)	urban area	8 years of data from May to September from two monitoring stations were analysed.	daily maximum 1h average O_3 concentrations	none		Robeson and Steyn, 1990
ARIMA (Autoregressive Integrated Moving Average)	univariate autoregressive integrated moving average model	lower Fraser Valley of British Columbia (Canada)	urban area	8 years of data from May to September from two monitoring stations were analysed.	daily maximum 1h average O_3 concentrations	none		Robeson and Steyn, 1990
no name	univariate deterministic/ stochastic model	lower Fraser Valley of British Columbia (Canada)	urban area	8 years of data from May to September from two monitoring stations were analysed.	daily maximum 1h average O_3 concentrations	none		Robeson and Steyn, 1990
no name	hybrid modelling approach which links the output of a deterministic Gaussian plume line source model with knowledge of a suitable parametric form of the probability distribution	Canberra (Australia)	urban area	vehicle patterns and emissions, basic meteorological measurements and historical concentrations	seasonal extremes of 1-hour average CO concentrations	none	goodness-of-fit tests and error performance criteria are applied to discriminate among candidate parametric forms	Jakeman, Bai and Miles, 1991

name	type	application area	application scale	input	output	chemistry	miscellaneous	reference
no name	hybrid model combining ATDL model with a two-parameter lognormal distribution	Brisbane (Queensland, Australia)	area of 64 km^2 divided into 256 cells of 4*4 km	daily average wind speed developed from 3-h values, wind direction reduced to 16 point wind rose, and emissions	daily average TSP concentrations	none	emissions from 106 point sources were allocated to 10 height classes	Simpson and Miles, 1990
no name	3D grid time-dependent finite difference model combined with a puff model	Skien-Porsgrunn (Norway)	3D array of grid cells situated over the urban area hor: 1*1km vert: 3 levels of 50, 50 and 100 m	hourly data on emission, wind and dispersion conditions and background concentrations	1-hour average SO_2, $PM_{2.5}$ and NO_x concentrations	none	includes horizontal and vertical advection and turbulent exchange, a puff model for large point source plumes and a road model along streets	Grønskei, Walker and Gram, 1993
RAMS-CALGRID model (RAMS= Regional Atmospheric Modelling System)	prognostic mesoscale model (RAMS) coupled with 3D grid Eulerian photochemical model (CALGRID)	Greater Athens area (Greece)	hor: 46*46 grid system cells of 4*4 km vert: 10 layers of variable thickness up to 2500 m totally	emission for a typical 24h period in Athens; all the necessary hourly meteorological data and other parameters required by CALGRID were produced by RAMS	hourly O_3 concentrations	SAPRC chemical mechanism		Pilinis, Kassomenos and Kallos, 1993
RAM	Gaussian plume model	St. Louis (USA)	urban area	wind speed, area emissions and effective height, daily maximum and minimum mixing height and hourly surface observations	hourly SO_2 concentrations	none		Ku, Rao and Rao, 1987b (Rao, Ku and Rao, 1989)
no name	a) box model b) vertical cell model	Central Europe	urban area	time-dependent traffic emission rates for THC, NO and NO_2	diurnal variation in O_3 concentration on a typical summer day	compact EM mechanism or detailed ALW reaction mechanism		Zellner and Moussiopoulos, 1986
no name	photochemical box model	Edmonton and Calgary (Canada)	box over urban area hor: city vert: mixing height	meteorological data, PBL height, emissions, measured NO_x concentrations and $NMHC/NO_x$ ratios	continuous O_3 and PAN concentrations	explicit chemistry for selected alkanes, alkenes and aromatics	-	Gladstone, Niki, Shepson, Bottenheim, Schiff and Sandhu, 1991
PBM (Photochemical Box Model)	photochemical box model	St. Louis (USA)	Box over urban area hor: city vert: mixing height	CO, NO_X and NMHC emissions resolved to hourly rates and distributed according to weekday/ weekend hourly traffic patterns. temperature, water vapour mixing ratio and wind speed	1-hour average CO, NO, NO_2 and O_3 concentrations	gas phase chemical kinetic mechanism used in RADM2 (by Stockwell) and an earlier version of PBM (by Demerjian)	A 1D high resolution boundary layer model (by Blackader) has been adapted to consider the effect of urban heat islands in the simulation of mixed layer height. A radiative transfer model (by Madronich) calculates actinic flux and photolytic rate constants.	Jin and Demerjian, 1993

name	type	application area	application scale	input	output	chemistry	miscellaneous	reference
no name	box model based on moving trajectory model of Hough and Derwent (1987)	Greater Athens area (Greece)	Box of 20 km * 15 km * mixing height	meteorological data (wind speed, temperature, solar radiation), NO_x, HCs and CO emissions and background concentration	continuous O_3, NO and NO_2 concentrations	about 170 chemical reactions	modelling during photochemical smog episodes and during average summer conditions	Roemer, 1989
ATDL model (ATDL = Atmospheric Turbulence and Diffusion Laboratories)	box model	c) St.Louis (USA) d) Brisbane (Queensland, Australia)	Box over urban area	area emissions, wind speed and stability parameters	hourly particles and SO_2 concentrations	none		a)Gifford and Hanna, 1973 b)Benarie,1978 c)Rao, Ku and Rao, 1989 d)Simpson and Miles, 1990
CPBM (Canyon Plume Box Model)	urban canyon dispersion box model	Bonner Strasse, Cologne (Germany)	urban street canyon with specific geometry	traffic and pollutant data, modelled flow and turbulence produced by sub-models, measured NO, NO_2, O_3 and CO concentrations	½ hour NO_x, NO_2 and CO concentrations	modified photostationary state approximation		Yamartino and Wiegand, 1986
CALINE (California Line Source Dispersion Model)	2D highway dispersion model based on Gaussian plume methodology	Michigan, Chicago, Los Angeles and Sacramento (USA)	highway	estimated meteorology and traffic parameters	½ or 1-hour average suspended particulates, CO and NO_2 concentrations	reactive plume chemistry simplified set of controlling reactions for NO_2	includes an algorithm to handle bluff and canyon situations and algorithms to account for vehicle-induced thermal turbulence and wind direction variability	Benson, 1992
CAR model (Calculation of Air pollution from Road traffic)	parametrised street dispersion model	several cities in the Netherlands	streets	background concentrations, traffic data, street type, average wind speed, city radius	annual average concentrations and percentiles of non-reactive air pollutants and NO_2	semi-empirical relation for NO_2	including street canyons	Eerens, Sliggers and van den Hout, 1993
OMG (=Osaka Municipal Government) VOLUME-SOURCE model	micro-scale dispersion model for motor vehicle exhaust gas	Osaka (Japan)	area extending 200 m from the side of the road in an urban area	emission height and rate, advection speed of plume, turbulence	exhaust gas concentration at certain time and place	none	analytical solution to the Fickian diffusion equation	Kono and Ito, 1990

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