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A modelling system for predicting urban air pollution: comparison of model predictions with the data of an urban measurement network in Helsinki

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Abstract

We have developed a modelling system for predicting the traffic volumes, emissions from stationary and vehicular sources, and atmospheric dispersion of pollution in an urban area. A companion paper addresses model development and its applications. This paper describes a comparison of the predicted NO_x and NO_2 concentrations with the results of an urban air quality monitoring network. We performed a statistical analysis concerning the agreement of the predicted and measured hourly time series of concentrations, at four monitoring stations in the Helsinki metropolitan area in 1993. The predicted and measured NO_2 concentrations agreed well at all the stations considered. The agreement of model predictions and measurements for NO_x and NO_2 was better for the two suburban monitoring stations, compared with the two urban stations, located in downtown Helsinki.

Keywords: Urban air quality; Testing; Modelling system; Monitoring network

1. Introduction

A companion paper presented an integrated urban pollution modelling system, and discussed some applications. The individual models in this system have been validated against results from experimental field campaigns (for instance, Walden et al., 1995). This modelling system is an important regulatory assessment tool for the national environmental authorities; it has been applied, for instance, in the environmental impact assessment of the different transportation system scenarios in the Helsinki Metropolitan Area (Hämekoski and Sihto, 1996).

It is therefore essential that the model performance is tested against experimental data in urban conditions. This paper discusses the comparison of model predictions and the results of the air quality monitoring network in the Helsinki metropolitan area in 1993. Some selected results have been published previously by Karppinen et al. (1997, 1998a, b). We have utilized the hourly NO and NO_2 concentration data from two urban, two suburban and one rural measurement station.

There are no empirical factors in the applied modelling system, except for the chemical transformation coefficients in the model UDM-FMI, for which we have applied the values reported by Janssen et al. (1998). We have utilised the original modelling system, without any adjustments or calibration based on the data considered here.

Häggkvist (1997) has performed a similar evaluation of dispersion models in an urban environment in Stockholm, Sweden. He compared the predictions of a standard Gaussian model with the NO_x concentrations obtained from three stations in central parts of the city. This study does not include an evaluation of NO_2 concentrations. He considered two hourly time-series, a summer week and a winter week, and two seasonal periods, including summer and winter seasonal averages and

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extreme concentrations. The mean differences between the measured and simulated concentrations averaged over the time periods considered varied from a few per cent to 60%.

Grønskei et al. (1993) compared the predictions of a time-dependent finite-difference model (combined with a puff model in order to allow for subgrid effects) with SO_2 and NO_x data from five measurement stations, on micro- and mesoscale. The concentrations of NO_2 were not addressed. They utilised data from two periods, lasting about two and a half and one month. They concluded that predicted hourly data were usually poorly correlated with observations, while the NO_x concentration variations representing larger integration times were reproduced much better.

2. Urban air quality monitoring network

Fig. 1 shows the location of the air quality monitoring stations in the Helsinki metropolitan area and the pollutants monitored in 1997 (Aarnio et al., 1995; Hämekoski and Koskentalo, 1998). Most of these stations have been located with the purpose of monitoring 'hot spots' near the busiest traffic environments, or major local energy production sources. The network contains five permanent multicomponent stations, these are located at Luukki, Leppävaara, Töölö, Tikkurila and Vallila (Table 1). Mobile stations are re-located each calender year; in 1997 these were at Laaksolahti, Runeberginkatu and Hakunila. There is also a particulate measurement station at Kaisaniemi and a meteorological station at Kallio.

We have selected the data from the permanent multicomponent stations to this study. These represent urban traffic (Töölö and Vallila), suburban traffic (Leppävaara and Tikkurila) and regional background conditions (Luukki).

Two urban monitoring stations, Töölö and Vallila, are located in the Helsinki downtown area. The station of Töölö is situated in a small square in a busy crossing area, surrounded by several buildings. The station of Vallila is situated in a small park, at the distance of about 20 m from a busy street.

The two suburban stations are located in the cities of Espoo and Vantaa. The station of Leppävaara in Espoo is situated in a shopping and residential area; the distance of the station to two major roads is approximately 200 m. The station of Tikkurila in Vantaa is located in a residential area, about 200 m from the nearest busy street. The

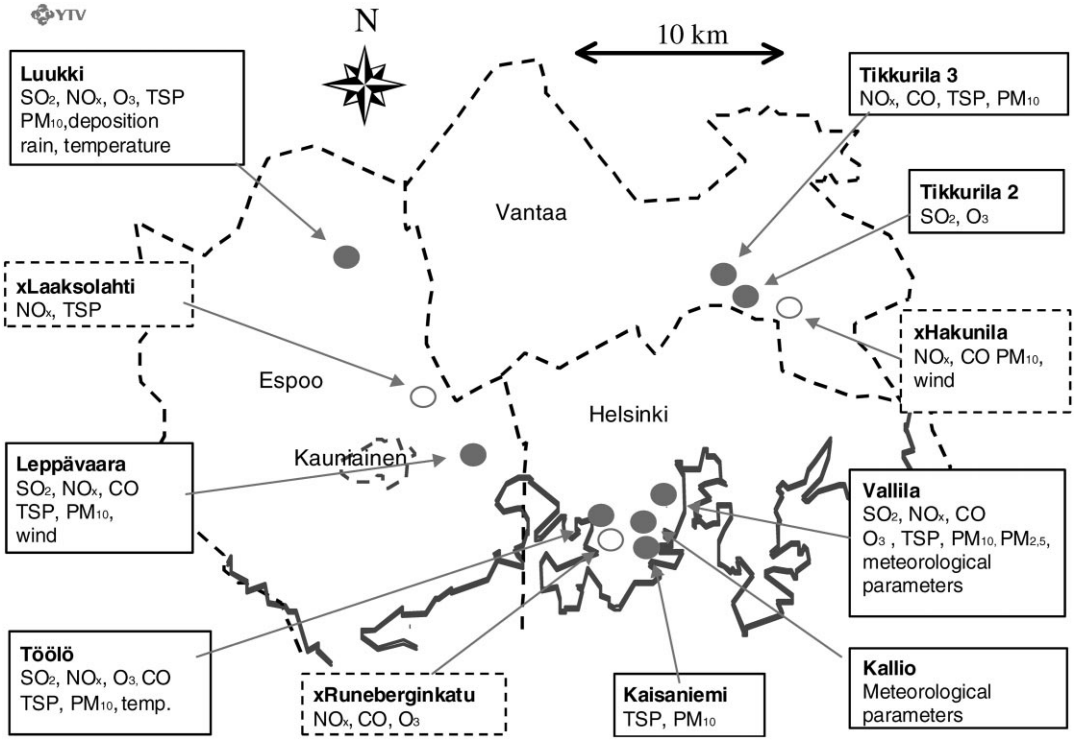

Fig. 1. The urban air quality monitoring network in Helsinki metropolitan area in 1997. The legends show the name of the station and the pollutants, which are measured continuously. The open circles correspond to the so-called "mobile" stations, which are re-located each calender year. The other stations are permanently located.

Table 1
The pollutants measured continuously at the five stationary air quality monitoring stations in the Helsinki metropolitan area in 1993. Notation: TSP = total suspended particulate matter and PM_{10} = thoracic particles

Name of the station	NO	NO_2	O_3	CO	SO_2	TSP	PM_{10}
1. Töölö (urban)	×	×	×	×	×	×	×
2. Vallila (urban)	×	×	—	×	×	×	×
3. Leppävaara (suburban)	×	×	—	×	×	×	×
4. Tikkurila (suburban)	×	×	×	—	×	×	×
5. Luukki (rural)	×	×	×	—	×	×	×

monitoring height is 4.0 m at the stations of Töölö, Vallila and Leppävaara, and 6.0 m at the station of Tikkurila. Regional background concentrations were monitored in a rural environment in Luukki, approximately 20 km to the northwest of downtown Helsinki.

3. Results and discussion

We consider first the variation in time of the measured and predicted monthly average concentrations. We then compare annual average concentrations, and predicted and measured statistical parameters corresponding to the national health-based air quality guidelines. Finally, we address the agreement of model predictions with measurements, utilizing statistical analysis of the hourly concentration data.

3.1. The seasonal variation of measured and predicted concentrations

Kukkonen et al. (1999, 2000) have discussed the seasonal variation of measured concentrations and meteorological conditions in Northern European conditions. Most unfavourable meteorological conditions for the efficient mixing of pollution include stable atmospheric stratification, low wind speed or calm, and the presence of a strong ground-based inversion. The meteorological conditions in Northern Europe are most unfavourable for the efficient mixing of pollution during the winter half-year, and particularly in winter.

Figs. 2a–d show the seasonal variation of the predicted and measured monthly averages of the NO_x concentrations at the four monitoring stations considered in 1993. The measured NO_x concentrations are highest at the urban station of Töölö and lowest at the suburban station of Tikkurila.

The modelling system clearly underpredicts the measured NO_x concentrations at the station of Töölö in all seasons (by a factor of 2–3). At the other three stations, the predicted NO_x concentrations agree fairly well with the measured data, although the model slightly underpredicts the concentrations in most cases. The variation in time of the predicted NO_x concentrations is similar with the observed variation at all four stations considered.

There are several possible reasons for the underprediction of concentrations at the station of Töölö. The monitoring station is located in a busy traffic junction, and the evaluation of both traffic emissions and atmospheric dispersion is therefore difficult. The modelling system most likely underpredicts emissions near busy junctions (as discussed in the companion paper). It is also problematic to model appropriately traffic-induced turbulence within a complex junction. The measurement location is also surrounded by several major buildings and street canyons, which is not allowed for in the dispersion modelling. There are also uncertainties in the representativeness and pre-processing of meteorological data in urban conditions, and in evaluating both the urban and regional background concentrations.

As discussed in the companion paper, the regional background concentrations are based on data from the monitoring station of Luukki, situated in the northeastern part of the Helsinki metropolitan area. The predicted regional background NO_x concentration varies from a minimum of 3% in the urban area to a maximum of 34% in the suburban area, of the total measured concentration.

Figs. 3a–d present the seasonal variation of the predicted and measured monthly averages of NO_2. At all the stations, the predicted NO_2 concentrations agree well with the measured data. The variation in time of the predicted and observed NO_2 concentrations is similar, except for the station of Vallila.

At the station of Töölö, the predicted NO_2 concentrations agree clearly better with the measured values, compared with the corresponding results of NO_x. As discussed in the companion paper, we have applied a modelling system, which allows for the chemical interdependence of the NO_x concentrations originating from various sources and the O_3 concentrations. The predicted NO_2 concentrations therefore depend critically on the computed O_3 concentrations. The predicted NO_2

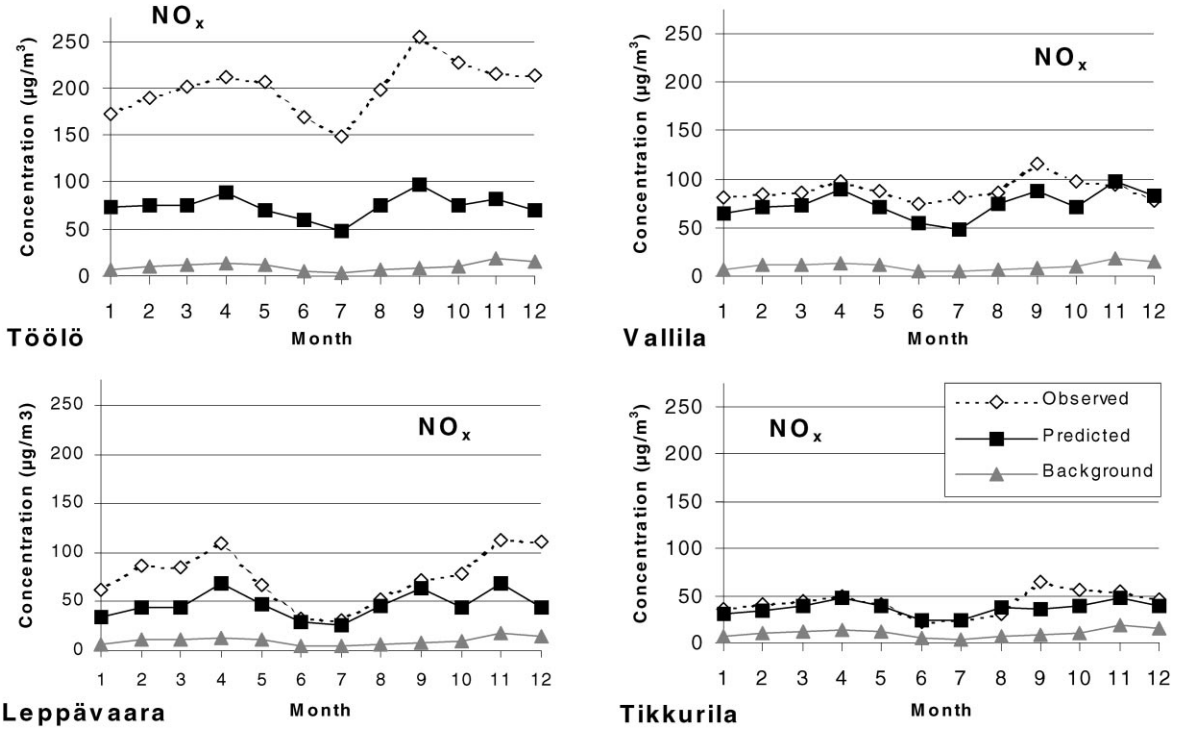

Fig. 2. a–d The predicted and measured monthly averages of the NO_x concentration ($\mu g\,m^{-3}$) at the four monitoring stations considered, together with the regional background concentrations in 1993.

concentrations can be realistic, if the urban background O_3 and NO_2 concentrations are predicted right, although the predicted NO_x concentration would be underpredicted.

We therefore compared also the predicted and measured O_3 concentrations, whenever the measured O_3 values were available. The O_3 concentrations were measured at the stations of Töölö, Vallila and Tikkurila (cf. Fig. 1). The agreement of predicted and measured O_3 values was good, although it was slightly worse compared with the corresponding results for NO_2. In particular, both computed and measured results at Töölö show that the formation of NO_2 from NO is in most cases limited by the availability of O_3, and in some cases O_3 is completely depleted.

The predicted regional background NO_2 concentration varies from a minimum of 8% in the urban area to a maximum of 56% in the suburban area, of the total measured NO_2 concentration. The regional background concentrations can therefore also have a substantial influence on the predicted urban NO_2 concentrations.

3.2. The statistical concentration parameters and annual average concentrations

For NO_2, the national guidelines are defined on a monthly basis, as the 99th percentile of the hourly values and the second highest daily mean value. Figs. 4a–d show the statistical concentration parameters, defined in the national guidelines, for the daily NO_2 concentration. Due to technical reasons, we have divided the year into 12 equally long periods, representing the months (these are not identical with the calendar months).

In Figs. 4a–d, the predicted statistical parameters agree fairly well with the measurements, except for some of the highest measured values, which are slightly underpredicted. According to the measurements, the national guideline values are exceeded at the stations of Töölö, Vallila and Leppävaara; most exceedings take place in winter or in spring.

Figs. 5a and b present a compilation of the predicted and measured results of NO_x and NO_2. The figure presents the annual average concentration, and the highest values of the statistical concentration parameters, which are compareable to the national guidelines for the daily and hourly concentrations. The difference between the measured and predicted annual mean concentrations varies from 14 to 37% ($|\overline{C_P} - \overline{C_O}|/\overline{C_O}100\%$) at the stations of Vallila, Leppävaara and Tikkurila, and at the station of Töölö the corresponding figure is 63%.

The annual comparison of the observed and predicted NO_2 concentrations shows a good agreement for all measuring stations. The national air quality guideline

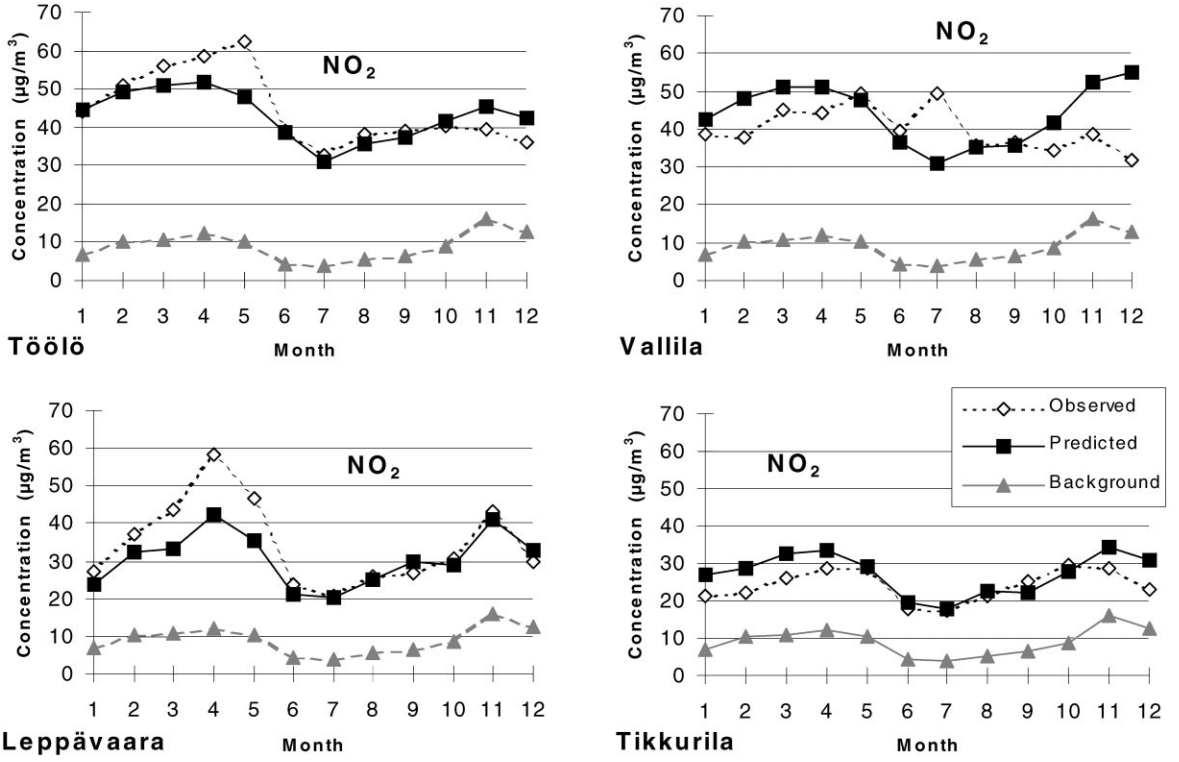

Fig. 3. a–d The predicted and measured monthly averages of NO_2 concentration (µg m^{-3}) at the four monitoring stations considered, together with the regional background concentrations in 1993.

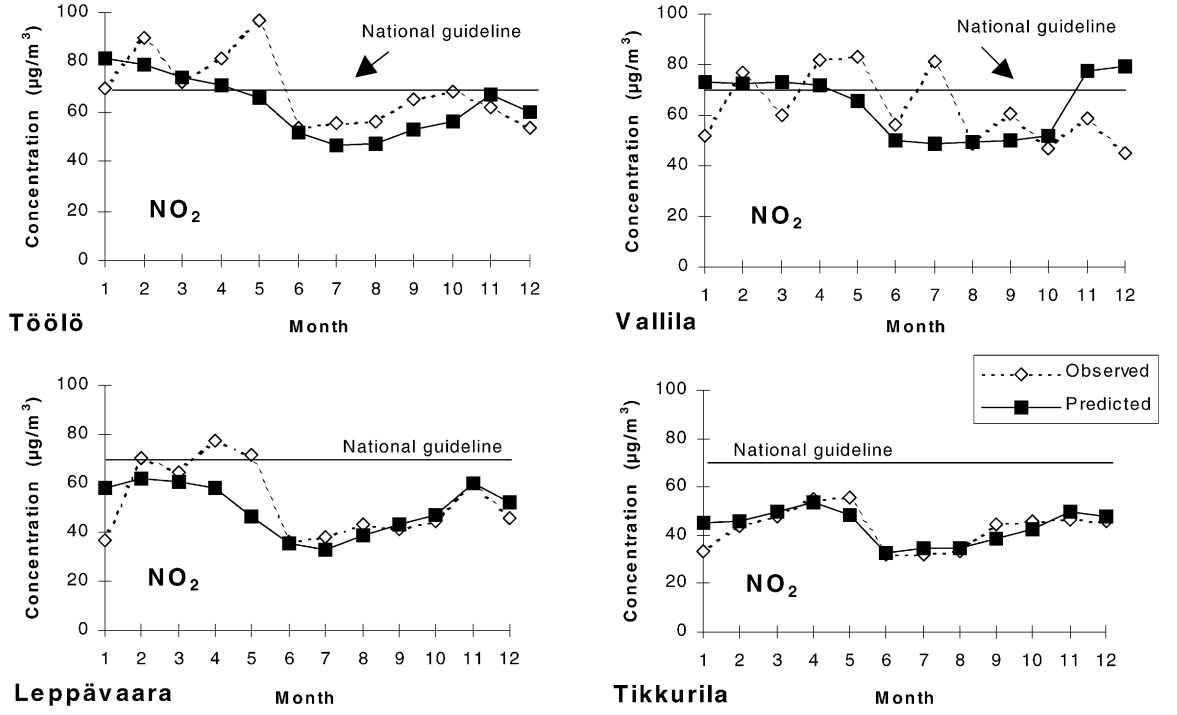

Fig. 4. a–d The predicted and observed second highest daily mean concentration of NO_2 during a month, compared with the national guideline, at the four monitoring stations considered in 1993.

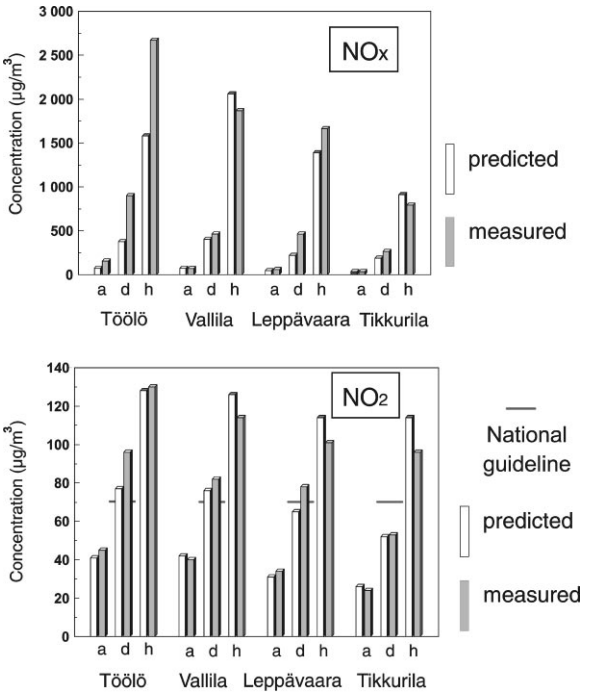

Fig. 5. a and b The predicted and measured yearly mean concentrations (denoted by a) and the statistical concentration parameters, compareable to the national guidelines for the daily (d) and hourly (h) concentrations, for NO_x and NO_2 in the Helsinki metropolitan area in 1993.

value for the second highest daily NO_2 concentration in a month (70 µg/m^3) was exceeded at three stations according to the measurements, and at two stations according to the computations. The difference between the measured and predicted annual mean concentrations varied from 4 to 13%.

3.3. Statistical analysis of the measured and predicted hourly concentration time series

Willmott (1981) discussed the application of various statistical parameters, which are utilized in the comparison of predicted and observed data sets. This analysis shows the inadequacies in using the correlation coefficient, its square and tests of their statistical significance. The root mean squared error (RMSE) and related measures as well as the index of agreement (IA) were recommended as alternative measures for making such comparisons.

We computed four statistical parameters, defined as follows (Willmott, 1981; Petersen, 1997):

The index of agreement;

$$IA = 1 - \frac{\overline{(C_P - C_O)^2}}{\overline{[|C_P - \overline{C_O}| + |C_O - \overline{C_O}|]^2}}, \quad (1)$$

The correlation coefficient:

$$\mathrm{Corr} = \overline{\left[\frac{(C_O - \overline{C_O})(C_P - \overline{C_P})}{\sigma_O \sigma_P}\right]} \quad (2)$$

The normalized mean square error:

$$\mathrm{NMSE} = \frac{\overline{(C_P - C_O)^2}}{(\overline{C_P})^2} \quad (3)$$

and

The fractional bias:

$$\mathrm{FB} = \frac{\overline{C_P} - \overline{C_O}}{0.5(\overline{C_P} + \overline{C_O})}, \quad (4)$$

where C_P and C_O are the predicted and observed concentrations, respectively, and σ_O and σ_P are the standard deviation of observations and predictions, respectively. The overbar refers to the average over all hourly values. IA, Corr and NMSE are measures of the correlation of the predicted and measured time series of concentrations, while FB is a measure of the agreement of the mean concentrations.

Table 2 presents the mean, the maximum and the standard deviation, together with the above mentioned statistical parameters for the measured and predicted hourly time series of NO_2 concentrations in 1993. The total number of data points is equal to the number of hours in a year.

The index of agreement (IA) varies from 0.0 (theoretical minimum) to 1.0 (perfect agreement between the observed and predicted values). For comparison purposes, we evaluated the values of IA assuming that the predicted values correspond to a random number distribution, $R(C_O)$, defined as

$$R(C_O) = 2\psi(0, 1)\overline{C_O}, \quad (5)$$

where $\psi(0, 1)$is a function, which produces random numbers in the interval from 0.0 to 1.0. The mean of both the random number distribution and measurement data is the same. The index of agreement were computed for the $R(C_O)$ distribution, corresponding to the time series at all four stations. In these cases IA varied from 0.39 to 0.41. Table 2 shows that the index of agreement varies from 0.69 to 0.79 at the stations considered; the correlation coefficients range from 0.50 to 0.65, and the normalized MSE from 0.28 to 0.45.

Figs. 6a–d show the seasonal variation of the index of agreement. The monthly average IA values are above the random data limit at all times. The most problematic periods seem to be the spring and summer months from April to July (at Töölö, Vallila and Leppävaara) and the winter months November and December (at Vallila).

Table 2
The statistical analysis of the predicted and measured hourly time series of NO_2 concentrations in 1993 (the total number of data $N = 8760$). The statistical parameters have been defined in the text

NO_2	Töölö		Vallila		Leppävaara		Tikkurila	
Statistical parameter	Predict.	Measured	Predict.	Measured	Predict.	Measured	Predict.	Measured
Mean ($\mu g\ m^{-3}$)	43	45	44	40	31	34	27	24
Maximum ($\mu g\ m^{-3}$)	191	167	211	176	179	129	144	171
Stand. dev. ($\mu g\ m^{-3}$)	22	26	23	21	21	21	18	18
Index of agreement	− 0.75		0.69		0.73		0.79	
Correlation coeff.	0.57		0.50		0.54		0.65	
Normalised MSE	0.28		0.26		0.45		0.33	
Fractional bias	− 0.045		0.095		− 0.092		0.118	

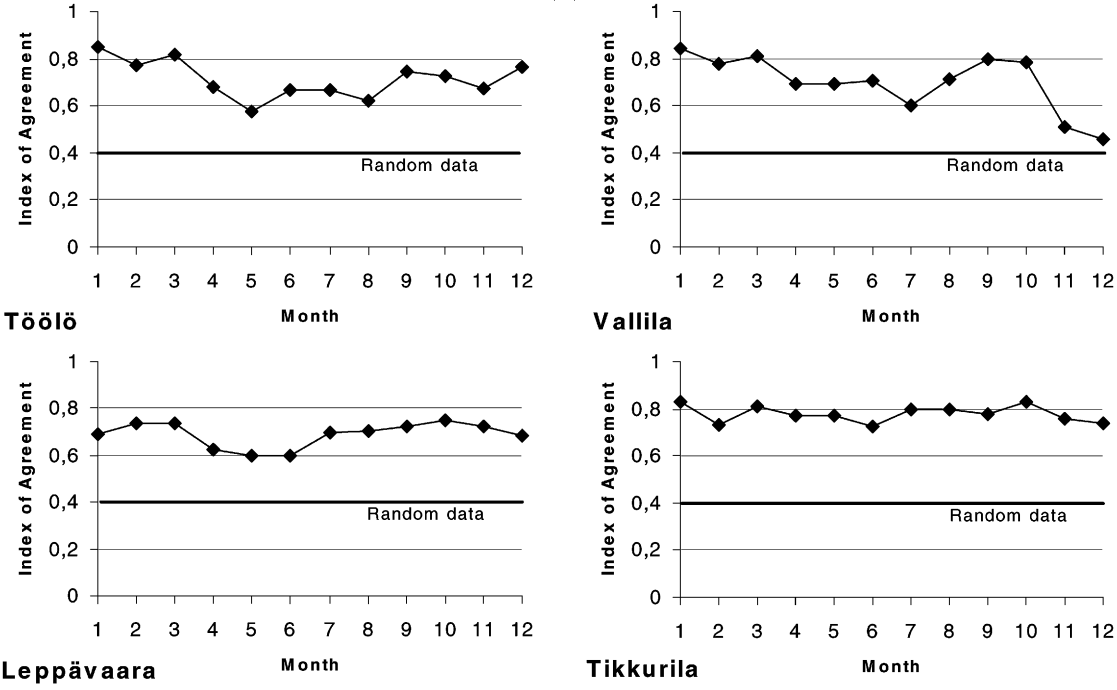

Fig. 6. a–b The index of agreement for the predicted and measured NO_2 concentrations at four measurement stations in Helsinki metropolitan area in 1993.

4. Conclusions

This paper presents a comparison of the predicted and measured concentrations of nitrogen oxides in the Helsinki metropolitan area in 1993. Both the measured and predicted data includes an hourly time series of the NO_x and NO_2 concentrations for one year. The comparison included data from two measurement stations in an urban environment (Töölö and Vallila in downtown Helsinki), and two suburban stations (Leppävaara and Tikkurila in the neighbouring cities of Espoo and Vantaa).

At three stations (Vallila, Leppävaara and Tikkurila), the predicted NO_x concentrations agree well with the measured data, although the model slightly underpredicts the concentrations. However, the modelling system clearly underpredicts the measured NO_x concentrations at the station of Töölö. This may be caused by the underprediction of emissions near a busy junction, the influence on dispersion of surrounding major

buildings and street canyons, and uncertainties in the representativeness and pre-processing of meteorological data.

At all the stations, the predicted NO_2 concentrations agree well with the measured data. The variation in time of the predicted and observed NO_2 concentrations is also similar, except for some deviations at the urban station of Vallila. At the station of Töölö the predicted NO_2 concentrations agree clearly better with the measured values, compared with the corresponding results of NO_x. The formation of NO_2 from NO is in most cases limited by the availability of ozone at Töölö, and the O_3 concentration is in some cases completely depleted. The predicted NO_2 concentrations can therefore be realistic, if the the urban background concentrations of NO_2 and O_3 are predicted right, although the predicted NO_x concentration would be underpredicted.

The predicted statistical parameters corresponding to the national guidelines agree well with the measurements, except for some of the highest measured values, which are slightly underpredicted. The agreement of the model predictions and measurements was better for the two suburban measurement stations, compared with the two stations located in downtown Helsinki. This was expected, taking into account the limitations of the modelling system.

In conclusion, the modelling system was fairly successful in predicting the urban NO_x concentrations, and successful in predicting the urban NO_2 concentrations. The integral dispersion modelling system (UDM-FMI and CAR-FMI) has also been applied nationally in numerous other cities. The model predictions and results from an urban measurement network have been compared in several other cities; for instance in the city of Turku. The agreement of predicted and measured NO_2 concentrations was very similar to the results presented in this paper (Kukkonen et al., 1998; Pietarila et al., 1997).

The modelling system developed has been an important assessment tool for the local environmental authorities, and the results of these computational methods have been utilized by the municipal authoritites in urban planning. For instance, we have assessed emissions, NO_2 concentrations and potential NO_2 exposures in the Transportation System Plan for the Helsinki Metropolitan Area (Helsinki Metropolitan Area Board, 1999). This study evaluated environmental impacts for future traffic planning and land use scenarios in the area. Three alternate scenarios for the year 2020 were considered: (i) a "business-as-usual" scenario, (ii) a scenario, which emphasizes the use of private cars and widely dispersed land-use, and (iii) a scenario, which assumes a transportation system based on mainly public transport and compact land-use. The results can be utilized, e.g, in order to check the contingency of air quality with national and European Union air quality guidelines and limit values.

The modelling system, as presented in this paper, does not explicitly allow for the influence of individual buildings and other obstructions. However, the system has recently been extended to include also the street canyon dispersion model OSPM (Hertel and Berkowicz, 1989; Niittymäki et al., 1999). More detailed nested computations, allowing also for the influence of buildings, can be performed for a smaller part of the modelling area.

The modelling system presented is based on the so-called quasi-steady-state assumptions, i.e., it is assumed that pollutant concentrations can be treated as though they resulted from a time sequence of different steady states. This assumption can be invalid particularly during peak concentration episodes, caused by accumulation of air pollution, and in the presence of complex photochemical reactions. It would therefore be useful to compare the results of the presented computations with the ones obtained using Eulerian grid (for instance, Yamartino et al., 1992) or Lagrangian models (for instance, Williams and Yamada, 1990). In these modelling systems the interactions of meteorology and chemistry can be accounted for dynamically, and at least in principle in real-time.

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