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METEOROLOGICAL PRE-PROCESSING AND ATMOSPHERIC DISPERSION MODELLING OF URBAN AIR QUALITY AND APPLICATIONS IN THE HELSINKI METROPOLITAN AREA

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ACADEMIC DISSERTATION in applied physics.

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Abstract

This theses describes the boundary-layer parameterisation model, which is applied as a meteorological pre-processor by Finnish regulatory dispersion models. The parameterisation scheme is based on the energy-flux method, which evaluates the turbulent heat and momentum fluxes in the boundary layer.

A comparison of the model predictions with those of the corresponding scheme of Berkowicz and Prahm, using the same synoptic input data is presented. The comparison shows the basic physical differences between these two models. Some numerical results calculated by these two pre-processors differ substantially, while the results for net radiation are statistically nearly identical.

Meteorological profile data from Finnish sounding stations is compiled and the inversions (the temperature of the atmosphere increases with altitude) are classified according to the total depth of the inversion and the stability of the boundary layer, which was estimated directly from the temperature gradient in the layer from the ground up to 100 meters. The persistence of the inversions and the influence of cloudiness and wind speed on the temperature gradient are also addressed. The specific problems of an urban area is tackled, using measurements from a meteorological mast situated in the Helsinki metropolitan area by comparing them to those from the radiosonde profiles at the rural site of Jokioinen. Several common schemes for the height of the stable boundary layer are compared to results from our own method developed at Finnish Meteorological Institute (FMI). Based on this analysis a modification to the FMI method is suggested.

An integrated modelling system for evaluating the traffic volumes, emissions from stationary and vehicular sources, and atmospheric dispersion of pollution in an urban area is described. The dispersion modelling is based on combined application of the Urban Dispersion Modelling system for stationary sources (UDM-FMI) and the road network dispersion model (CAR-FMI). The system includes also a meteorological pre-processing model (MPP-FMI) and a statistical and graphical analysis of the computed time series of concentrations. The modelling system contains a method, which allows for the chemical interaction of pollutants, originating from a large number of urban sources.

An application of the integrated modelling system for estimating the NO_X and NO_2 concentrations in the Helsinki metropolitan area in 1993 is presented. The thesis finally presents a comparison of model predictions with the results of an urban measurement network.

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[I] Karppinen, A., Joffre, S. M. and Vaajama, P., 1997: Boundary layer parameterisation for Finnish regulatory dispersion models. *International Journal of Environment and Pollution* **8**, pp. 557-564.

[II] Karppinen, A., Joffre, S. M. and Kukkonen, J., 2000: The refinement of a meteorological preprocessor for the urban environment. *International Journal of Environment and Pollution* **14,** pp. 565-572.

[III] Karppinen, A., Joffre, S. M., Kukkonen, J. and Bremer, P., 2001: Evaluation of inversion strengths and mixing heights during extremely stable atmospheric stratification, *International Journal of Environment and Pollution* **16**, (in print).

[IV] Karppinen, A, Kukkonen, J., Elolähde, T.,Konttinen, M., Koskentalo, T. and Rantakrans, E., 2000: A modelling system for predicting urban air pollution, Model description and applications in the Helsinki metropolitan area. *Atmospheric Environment* **34**, pp 3723-3733.

[V] Karppinen, A, Kukkonen, J., Elolähde, T.,Konttinen, M. and Koskentalo, T., 2000: A modelling system for predicting urban air pollution, Comparison of model predictions with the data of an urban measurement network. *Atmospheric Environment* **34**, pp 3735-3743.

The author has had an active role in all phases of the research reported in this thesis. He has been involved in the planning of the calculations, the development of the computer programs, and the interpretation of the results. The author has written the first version of Publications **I-V**. He is responsible for all calculations in Publications **I,II,IV,V** and most of the calculations in Publication **III**.

1 Introduction

This theses describes an integrated urban pollution modelling system, discusses predicted concentration distributions of nitrogen oxides in the Helsinki metropolitan area. and addresses the testing of the model against the results of an air quality monitoring network.

The integrated atmospheric dispersion modelling system developed at FMI is based on a combined application of the Urban Dispersion Modelling system for stationary sources (UDM-FMI) and the road network dispersion model CAR-FMI (Contaminants in the Air from a Road). Both dispersion models include a treatment of the chemical transformation of nitrogen oxides. The dispersion modelling system was refined to take into account the chemical interaction of pollutants from a large number of individual sources.

This theses also describes and revises the method (FMI-MPP) used to estimate the turbulence parameters from surface meteorological observation and compares some basic physical properties of the method against other commonly used similar methods. Special emphasis is taken to study the stable conditions and the different turbulence characteristics of rural and urban conditions.

2 Aims of the study

The aims of this thesis were:

1) to describe the method used to estimate the turbulence parameters from surface meteorological observation and to compare some basic physical properties of the method against other commonly used similar methods.

2) to study the potential errors of the meteorological pre-processing system when applied in urban environment and to revise the parameterisation method accordingly

3) to examine the behaviour of the stable mixing height calculation scheme routinely

used at FMI, by comparing the mixing height results calculated using rural meteorological profile data (Jokioinen) vs. urban meteorological profile data (Kivenlahti)

4) to refine the stable mixing height calculation scheme to better suit the conditions in a heterogeneous environment

5) to combine the meteorological modelling system, traffic flow and emission modelling systems together with the urban dispersion modelling system for assessing the air quality in Helsinki Metropolitan area

6) to evaluate the performance of the modelling system by comparing the calculation results with available experimental data in the Helsinki Metropolitan area

3 Background

Air pollution models are valuable tools for regulatory purposes, policymaking and research applications. The most efficient method in air pollution research is commonly the combined use of measurements and modeling.

Atmospheric dispersion models can be used for a wide variety of purposes, for instance:

- establishing source-receptor relationships,
- evaluation of the contribution to pollutant concentrations from various sources,
- estimating spatial concentration distributions and population exposure to pollution,
- optimisation for emission reduction strategies and analysis of emission scenarios,
- predicting the pollutant concentrations in time and
- analysing the representativity of measurement stations.

The models need as input parameters meteorological and geographical information, together with source and emission data. Errors in the predictions of the models are caused by:

- inaccuracies in estimating the model input values,
- deficiencies in modelling the physical and chemical phenomena,
- numerical inaccuracies of the models and
- random variability in the atmosphere.

A high priority should be given to evaluation of models, and their validation against good-quality databases in order to control the inaccuracies of the modelling methods.

The main objective of local scale dispersion models is quantifying of the concentrations of pollutants, which can cause adverse health effects for the population. In some cases, the objectives include also the deposition of pollutants and the influence of air pollution on the vegetation. Most of the local scale models have been developed for regulatory purposes.

Models based on Gaussian concentration distributions have been very widely used for regulatory purposes. Traditionally, these models have been based on Pasquill-Gifford stability categories and the dispersion parameterisations have been very straightforward. However, the models should be able to allow for the structure of the atmospheric boundary layer and the various local scale effects, for instance, the influence of buildings and obstacles, downwash phenomena and plume rise.

The latest generation of local scale models is used in combination with meteorological pre-processing models, which are based on scaling theories of the atmospheric boundary layer (ABL). In this case, the dispersion processes are described in terms of ABL scaling parameters and the boundary layer height. Some of these models include treatment of chemical transformation and deposition, plume rise, downwash phenomena and dispersion of particles (for more detailed discussion, see Kukkonen, 2000).

4 Influence of meteorology on the air quality

4.1 The meteorological pre-processing model

Meteorological factors have a substantial influence on the atmospheric dispersion of air pollution. Dispersion is particularly affected by the wind speed and direction, atmospheric turbulence and the occurrence of inversion layers, ambient temperature and the mixing height (e.g. Kukkonen et al., 1999). The turbulence parameters and mixing heights are not routinely measured so they have to be inferred from the available measurements, activity which is often referred as pre-processing the meteorological data.

The parameterisation schemes used in the dispersion models of the Finnish Meteorological Institute (FMI) are based on the energy flux method of van Ulden and Holtslag (1985), while the parameterisation of the boundary layer height is based on classical boundary layer models with a separate treatment for convective and stable conditions.

In the van Ulden-Holtslag's scheme, the turbulent heat and momentum fluxes in the boundary layer are estimated from synoptic weather observations. The original method has been slightly modified, as at high latitudes the net radiation at the surface correlates better with the sunshine duration than with the cloud cover.

The present method divides the net radiation into three parts: solar short-wave radiation, blackbody radiation from clouds and ground, and long-wave radiation of (isothermal) atmosphere. Short-wave radiation is approximated by a regression equation, which uses observed hourly sunshine time as the explaining variable in the regression model. The radiation from clouds is modelled by another regression equation, which uses the total cloudiness and cloud height as explaining parameters.

Energy partition in the FMI-model utilises the modified Priestley-Taylor model (van Ulden and Holtslag, 1985), which divides the evaporation into two parts. Consequently, there are only two empirical parameters to be evaluated in the FMI-model. These parameters depend on surface moisture conditions, which are estimated using synoptic weather codes and the amount of rain.

The parameterisation of the mixing height (MH) uses actual radio soundings and the previously calculated surface turbulence parameters. The summer MH parameterisation is based on a slab model for daytime and modelling the integral heat flux at night. For wintertime the MH evolution is driven by mechanical turbulence.

4.2 Intercomparison of meteorological pre-processing models

A comparison of the FMI model predictions with those of the corresponding model (OML, see Olesen et al., 1992) applied in National Environmental Research Institute of Denmark (NERI) is done, using the same synoptic input data for both models. The meteorological data has been collected from southern Finland for year 1983. The data was interpolated from 3-hourly measurements to hourly values.

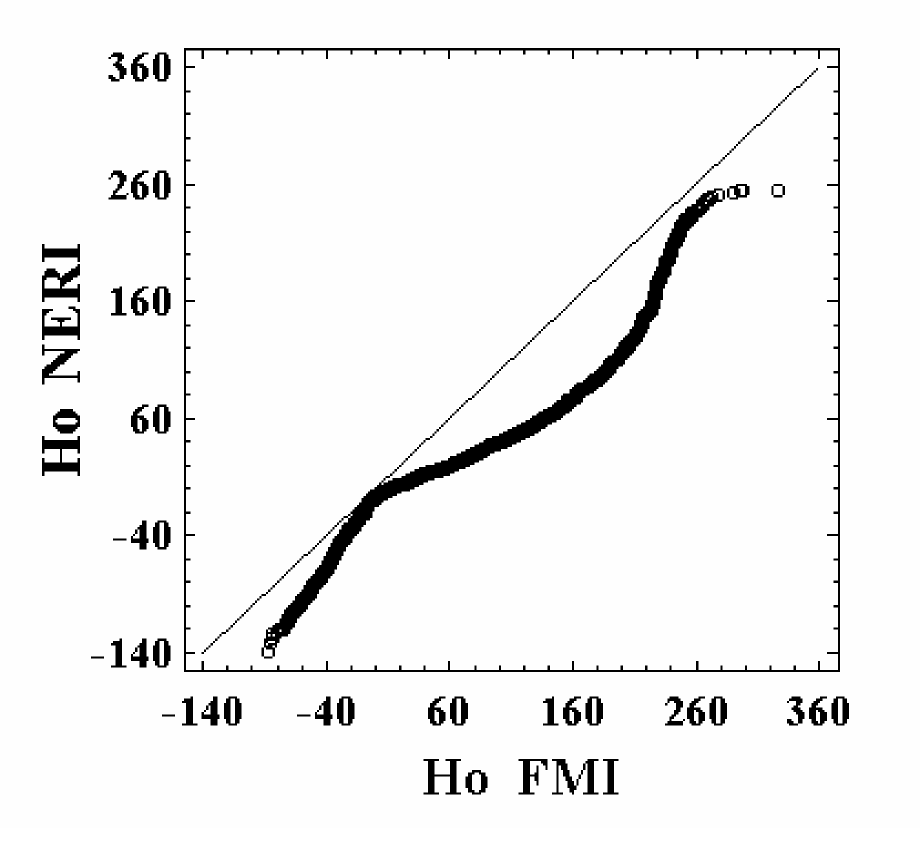


Figure 1. The quantile-quantile plot of estimates of the sensible heat flux.

The net radiation estimates, by the OML model and FMI-MPP model agree very well **[I]**, except for a slight difference for net radiation values in the range from 200 to 400 W/m^2. However, there are substantial differences in the computed turbulent heat flux estimates shown in Figure 1.

The ratio of stable to unstable situations as evaluated by these two models is almost the same. In stable conditions, the OML-model produces more negative energy flux values than the FMI- model. In unstable conditions, the FMI model produces larger turbulent heat flux values than the OML model. The results indicate that the two parameterisation schemes divide the available energy between the latent and sensible heat fluxes differently.

4.3 Modifications of the pre-processor in order to allow for urban conditions

The FMI meteorological pre-processor applied in combination with the regulatory atmospheric dispersion models in Finland was originally designed for non-urban areas only. In order to account for the urban conditions, the meteorological pre-processor has to be modified **[II]**.

The atmospheric surface layer is divided into two parts: a roughness sublayer of height z* and an inertial sublayer. Monin-Obukhov similarity laws are expected to be valid only in the inertial sublayer. Close to the ground surface, the local Reynolds stress profile is used to recalculate the relevant turbulence parameters. In order to allow for the influence of urban conditions, we have evaluated the roughness length z_o and introduced the zero-displacement height d for the Helsinki metropolitan area, using a computational method discussed by Rotach (1997).

In stable conditions, the height of the urban roughness sublayer z* is used as a lower limit for the Monin-Obukhov length L, as L can be interpreted as the depth of the mechanically well-mixed layer. It is therefore plausible to assume that the Monin-Obukhov length $L \geq z^* \equiv L_{min}$, since the roughness sublayer height z* is the height, at which the urban roughness elements are by definition generating a more intense turbulence field.

The influence of these modifications has been analysed by computing the dispersion parameters used in the FMI dispersion modelling system, and comparing the revised parameters with the previous "non-urban" model computations.

In unstable conditions, the urban vertical dispersion parameters are approximately half of the corresponding rural values, at an effective dispersion height near the zero-plane of displacement. Clearly, the urban roughness elements give rise to enhanced turbulence above the roof top level and one would therefore expect the urban dispersion parameters to be larger within this layer, compared with the corresponding non-urban parameters.

However, the introduction of the displacement height and the exponentially decreasing Reynolds stress results in clearly smaller numerical values of turbulence parameters in the layer between roof top level and displacement height. This effect can be seen to be consistent with the generally accepted picture of turbulent flow changing to laminar flow close to a surface. In this case we can consider the urban roughness sublayer as a layer within which the spatial average of Reynolds stress increases from zero to its value in the inertial sublayer (Rotach, 1993).

In neutral conditions, the variation of the dispersion parameters with height is similar, compared with the unstable cases. However, in stable conditions the imposed limit of the Monin-Obukhov length substantially changes the situation. In extremely stable conditions, the urban dispersion parameters exceed the corresponding rural values with a large margin; the key factors influencing this ratio are stability and height of the roughness sublayer.

The modifications can have a substantial influence on the computed concentrations (Figure 2) for the ground level or near the ground level sources (e.g., traffic). The re-evaluated friction velocity and dispersion parameters result in clearly lower concentrations in stable atmospheric stratification, and slightly higher concentrations in neutral and unstable atmospheric stratification, respectively.

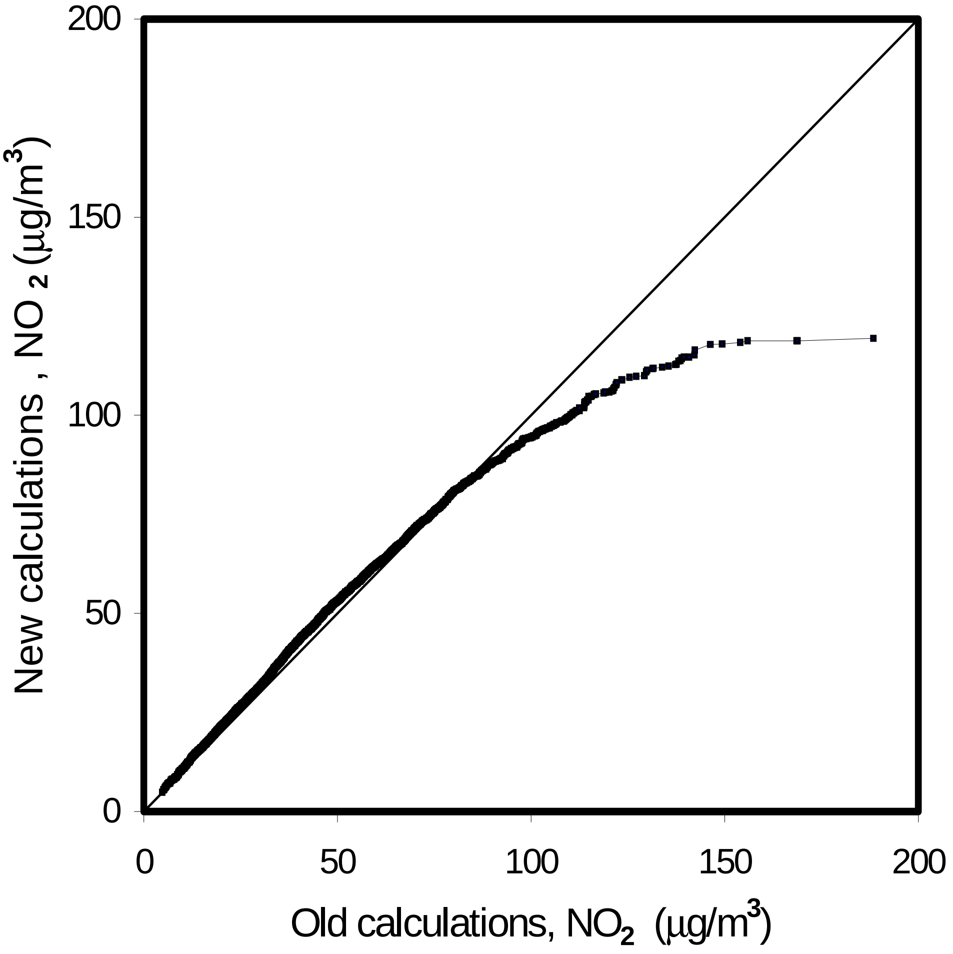


Figure 2. The cumulative distributions of calculated NO_2 *concentrations (old vs. new) at the monitoring station of Töölö, Helsinki in 1993.*

4.4 Inversion strengths and mixing heights during stable stratification

In Northern European conditions, the formation of a severe air pollution episode requires a strong ground-based inversion, by which cold air near the ground surface is blocked under the warmer air layer above. Particularly emissions from road traffic are then poorly dispersed. Emissions from tall stacks of e.g. heating plants may be emitted above the inversion height, and therefore these do not influence substantially pollution near the ground level.

Paper **[III]** discusses the results from a climatological study of surface inversions based on an experimental dataset from three Finnish sounding stations. The inversions were characterised according to their total depth and the stability of the boundary layer, which was straightforwardly estimated directly from the temperature gradient in the layer from the ground up to 100 meters. The persistence of the inversions as well as the influence of cloudiness and wind speed on the temperature gradient was studied.

Furthermore, the measurements from a meteorological mast situated in the Helsinki metropolitan area; particularly temperature inversions with a potential temperature gradient larger than 0.1 ^{o}C/m, were selected for further analysis.

The behaviour of the meteorological pre-processing model **[I]**, particularly the stable mixing height scheme, is analysed utilising this experimental database. The observed weak correlation between FMI-Jokioinen and FMI-Kivenlahti (FMI’s stable mixing height calculation scheme using radiosonde profiles at Jokioinen and mast profiles at Kivenlahti respectively) calculations is further studied by dividing the data according to wind direction into 12 sectors.

Figure 3 presents the partial correlations of calculated mixing heights in each wind sector. It is observed, that in nearly all wind sectors the correlation is very weak, indicating that the meteorological profiles measured at Jokioinen are significantly different compared to the suburban profiles measured at Kivenlahti. To get a reliable estimate of the mixing height at Helsinki area, it would be important to use local meteorological profile measurements instead of the rural meteorological profiles.

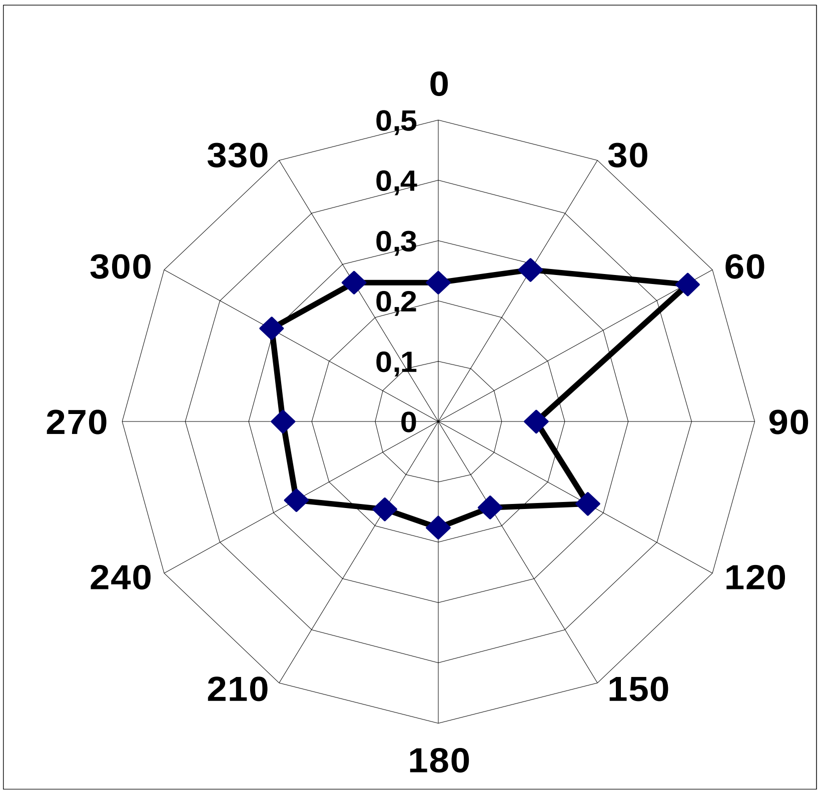


Figure 3. Partial correlations between the calculated mixing heights. The results of FMI-mixing height calculation scheme using rural (Jokioinen) data are compared against the results of FMI-mixing height calculation scheme using urban (Kivenlahti) data.

The correlation of the calculated mixing heights is weakest for southerly (from the sea) winds. This is quite an expected result, as the effect of the sea is not observed on the mixing heights calculated using the soundings at Jokioinen, which is located 100 km north from the Helsinki area.

The best correlation was obtained for the NE direction, which is one of the most “non-urban” directions around Kivenlahti mast. However, before any final conclusions can be made, a more detailed study on the possible local screening effects of the mast structure for this wind direction must be performed.

Other commonly used schemes for determining the height of the stable boundary layer, reported by Fisher et al. (1998), were also tested against the FMI-method and against each other. Based on this analysis a modification is suggested to the FMI-MPP method.

5 Dispersion modelling in the Helsinki Metropolitan Area

Short-range atmospheric dispersion models have been developed and applied at the Finnish Meteorological Institute since the early 1970's. The following regulatory models are available: the urban dispersion modelling system (Karppinen et al, 1998), various models for local dispersion of vehicular pollution (e.g. CAR-FMI), the air pollution information system, the dispersion model of odorous compounds and a hybrid plume model for local-scale dispersion (Nikmo et al, 1999). All of these models are routinely used in connection with a meteorological pre-processing model. Some of these models have been reviewed by Kukkonen et al. (1997).

Similar urban scale modelling systems have also been developed in other European countries. Examples of these are the Danish OML model (Olesen, 1995a) and the UK-ADMS system of the United Kingdom (Carruthers et al., 1995). These models, as the UDM-FMI system, also apply ABL scaling with the surface layer similarity theory. On the other hand, various local scale Gaussian models using the Pasquill (or equivalent) stability classes are still widely used in practical applications in many European countries (see: Moussiopoulos et al., 1996).

A detailed description for the CAR-FMI model can be found in Härkönen et al., (1995), (1996) and (1997a). The predictions of the CAR-FMI model have been compared against experimental roadside datasets in Härkönen et al., (1997b) and Kukkonen et al. (2000).

5.1 Emission and atmospheric dispersion modelling system for an urban area

Paper **[IV]** presents an overview of the structure of the integrated modelling system developed and used at FMI, including the dispersion models and the meteorological pre-processor model.

The dispersion models are based on Gaussian plume equations for various source categories. The meteorological pre-processor **[I]**, includes a mathematical parameterisation of the atmospheric boundary layer (ABL), based on the surface layer similarity theory.

The modelling system describes the dispersion processes in terms of ABL scaling parameters (the Monin-Obukhov length scale, the friction velocity and the convective velocity scale) and the boundary layer height. For instance, the dispersion parameters are written explicitly as a function of these quantities (Karppinen et al., 1998). The application of ABL scaling is physically a better approach than the use of the traditional discrete stability categories (e.g., the Pasquill classes). Clearly, the diffusion properties of the ABL are continuous functions of the atmospheric stratification.

Both experimental and theoretical investigations have shown that dry and wet deposition processes, chemical transformation, plume rise and downwash can substantially influence atmospheric concentrations. All these processes are included into the model framework, including a treatment of the chemical transformation of nitrogen oxides. A new model has been developed for evaluating the chemical interaction of pollution from a large number of individual sources. This model allows for the interdependence of urban background NO, NO_2 and O_3 concentrations and NO and NO_2 emissions from various source categories.

The model also allows for the influence of a finite mixing height and inversion layers, as this can be of crucial importance especially in stable atmospheric conditions.

The mathematical structure of the modelling system is based on state-of-the-art methodology. Results of domestic investigations have been used for evaluating some climate-dependent parameters. The numerical procedures and the computer codes have been developed at the FMI.

The UDM-FMI system has been tested and validated against national urban air quality measurements (e.g., Nordlund and Rantakrans, 1987) and the experimental data of the Kincaid, Copenhagen and Lilleström field dispersion trials (these datasets are described in detail in Olesen, 1995b).

The integrated modelling system includes emission models for stationary and vehicular sources and a statistical analysis of the computed time series of concentrations. The modelling system is depicted in Figure 4.

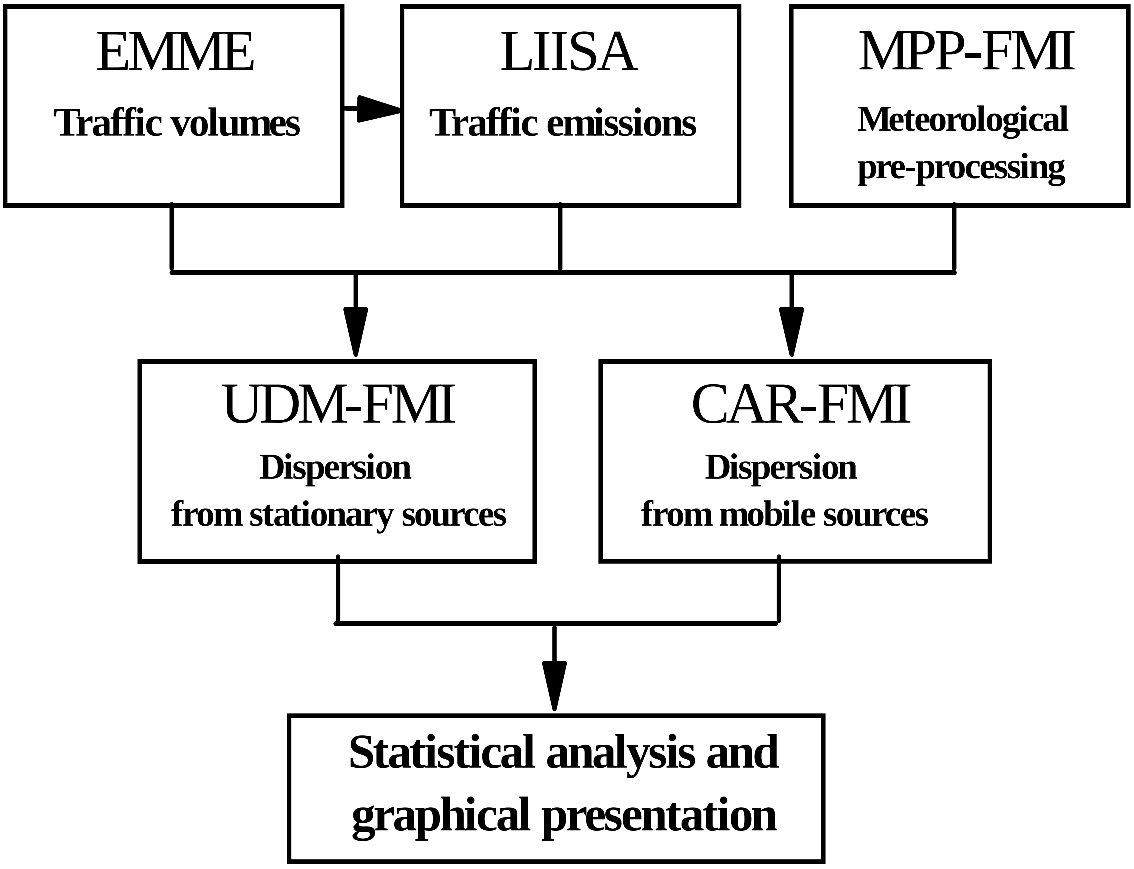
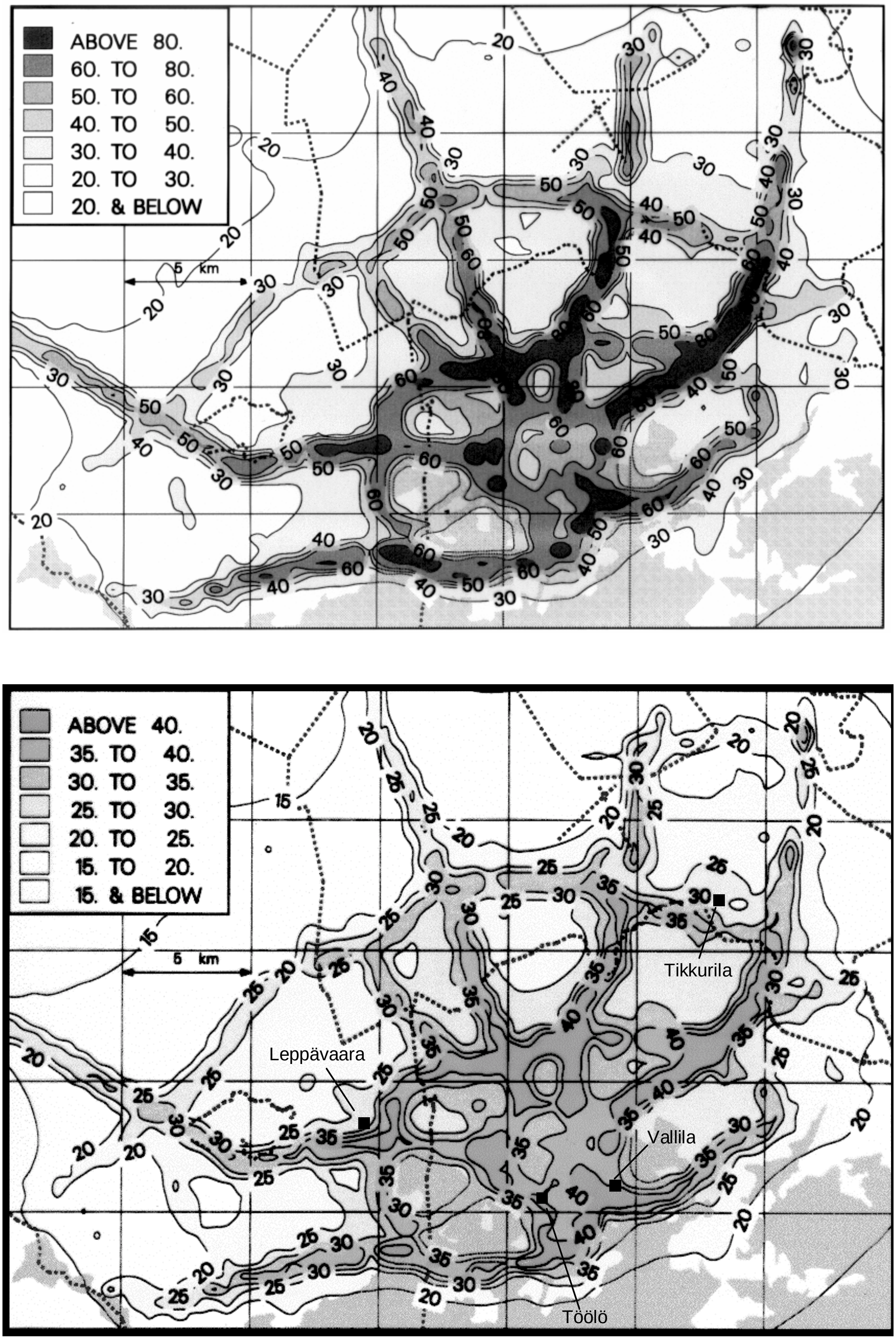


Figure 4. An overview of the modelling system.

The concentrations of nitrogen oxides and nitrogen dioxide have been computed in the Helsinki metropolitan area for one year, 1993. The concentration time series were computed on a receptor grid, which contains approximately 10000 receptor points. The receptor point network covers the whole Helsinki metropolitan area (approx. 900 km^2), and the largest grid intervals are 500 m. A more densely spaced grid was applied in the Helsinki downtown area, the grid interval being 100 m. In the vicinity of the major roads in the area, the smallest grid interval was 50 m. The variable receptor grid is required in order to evaluate isoconcentration curves with adequate accuracy from the computed data.

The NO_2 concentrations in Helsinki are generally comparable with those in the major Central European cities (Jol and Kielland, 1997, Kukkonen et al., 1999). In other Finnish cities the NO_2 concentration levels are usually somewhat lower than those in the capital (Kukkonen et al., 1999).

Figures 5a-b show the computed annual means of NO_x and NO_2 concentrations at the ground level in the Helsinki metropolitan area in 1993. The legend in the top left-hand corner shows the absolute values of the pollutant concentration.



Figures 5a-b. Predicted spatial distribution of the yearly means of NO_x *(upper) and* NO_2 *(lower) concentrations (*$\mu g\ m^{-3}$*) in the Helsinki metropolitan area in 1993.*

5.2 Comparison of model predictions with the data of a measurement network

Paper **[V]** discusses the comparison of model predictions and the results of the air quality monitoring network in the Helsinki metropolitan area (YTV) in 1993. Hourly NO and NO_2 concentration data has been utilized from two urban, two suburban and one rural measurement station operated by the Helsinki Metropolitan Area Council.

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. (1988). The original modelling system, without any adjustments or calibration based on the data considered here has been utilized in this study.

The data for this study is selected from the permanent multicomponent stations (Aarnio et. al., 1995, Hämekoski and Koskentalo, 1998). 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 metres 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 metres from the nearest busy street. The 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.

As discussed in **[IV]**, 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.

At three stations (Vallila, Leppävaara and Tikkurila), the predicted NO_x concentrations agree well with the measured data, although the model slightly under predicts 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 urban background concentrations of NO_2 and O_3 are predicted right, although the predicted NO_x concentration would be under predicted.

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.

6 Discussion

The basic physical ideas of the FMI pre-processor (FMI-MPP) and the corresponding model applied in Sweden and Denmark (Berkowicz and Prahm, 1982) are similar, while the measurements required by the models are somewhat different. In FMI-MPP model the short wave radiation is estimated by a regression equation, which uses observed hourly sunshine duration as the regression model variable. The radiation from clouds is modelled by another regression equation, which uses the total cloudiness and the cloud height as parameters. The method of Berkowicz and Prahm uses two regression models, one for daytime and one for nighttime, which apply synoptic measurements of cloudiness as the most important variable.

The modelling of the net radiation differs substantially in these two models, but the numerical results are nearly the same. The partitioning schemes for the turbulent sensible and latent heat are clearly different in the models. The Berkowicz/Prahm-model evaluates the surface resistances and the humidity deficit in a fairly complicated way. The FMI model utilises the modified Priestley-Taylor model (van Ulden and Holtslag, 1985), which divides the evaporation into two components. Consequently, in the FMI model only two empirical surface moisture parameters have to be evaluated. The numerical results of these two partitioning schemes also differ substantially, but the ratio of stable to unstable situations as evaluated by the two models is almost the same.

The meteorological pre-processor has been modified in order to better represent urban conditions. We have re-evaluated the roughness length, introduced the zero-displacement height and divided the surface layer into a roughness sublayer and an inertial sublayer. The friction velocity and Monin-Obukhov length are re-evaluated using an empirically developed exponential Reynolds-stress profile in the roughness sublayer.

The influence of the urban modifications of the FMI-MPP were investigated, by computing the dispersion parameters used in the UDM-FMI dispersion modelling system, and comparing the revised parameters with the corresponding previous "non-urban" parameters. These modifications have a substantial influence on the computed concentrations for the ground level or near the ground level sources (e.g., traffic). The re-evaluated friction velocity and dispersion parameters result in lower concentrations in very stable atmospheric stratification, and raised concentrations in neutral and unstable atmospheric stratification, respectively.

Based on the analysis utilizing rural and urban meteorological profile data a modification was made to the FMI-MPP stable mixing height calculation method. The modified FMI–scheme gives physically resonable stable mixing heights and also the correlation of the time-series of calculated mixing heights with the widely used Zilitinkevich interpolation scheme is good.

The urban dispersion modelling system described in **[IV]** is based on Gaussian plume equations for various source categories. The modelling system describes the dispersion processes in terms of ABL scaling parameters (the Monin-Obukhov length scale, the friction velocity and the convective velocity scale) and the boundary layer height.

Our modelling system contains a novel method, which allows for the chemical interaction of pollutants, originating from a large number of urban sources. The system properly takes into account, for instance, the depletion of O_3 in the urban area. This phenomenon can have a substantial influence on the computed results particularly in episodic conditions, in which the atmospheric diffusion conditions are unfavourable.

The system presented is based on 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 is not valid e.g. during peak concentration episodes, caused by accumulation of air pollution, and in the presence of complex photochemical reactions. In the future, the results of the presented computations will be compared 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.

The modelling approach adopted has certain inherent limitations, both concerning the evaluation of emissions and atmospheric dispersion. Gaussian dispersion modelling does not allow for the detailed structure of buildings and obstacles. However, the terrain in the area is flat and the average height of the buildings is fairly low (most buildings are lower than 15 - 20 m). The computed concentrations should be interpreted as spatially averaged values (on the scale of the grid spacing, varying from 50 to 500 m), while for instance, inside a street canyon the actual concentrations can vary substantially on the scale of tens of meters.

On the other hand, the use of fairly simple dispersion models facilitates the evaluation of the hourly time series of meteorological and emission conditions for one year, which is required for the computation of statistical concentration parameters, defined in national health-based air quality guidelines.

It was also possible to include emissions from a large number of sources (this study included 5000 line sources, 169 point sources and area sources), a substantial number of receptor points (10000), and to use a sufficiently dense computational grid.

Estimation of emissions also contains inherent limitations. Near the junctions of roads and streets there is acceleration and deceleration of the traffic flow, as well as stops and occasional congestion, which causes increased emissions. The emission modelling takes properly into account the influence of vehicle acceleration and deceleration on the emissions. The emissions, however, are assumed to be distributed evenly along each line source in the numerical computations, although these can be strongly concentrated in the immediate vicinity of the junctions. This effect can cause an underprediction of traffic emissions near major junctions.

The predicted statistical parameters corresponding to the national guidelines agree well with the measurements, except for some of the highest measured values, which are underpredicted **[V]**. 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.

The modelling system, as presented in this theses, 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; Granberg et al., 2000). More detailed nested computations, allowing also for the influence of buildings and detailed traffic conditions can be performed for a smaller part of the modelling area.

7 Conclusions

The basic mathematical structure of the FMI pre-processor is described and the model predictions are compared with those of the corresponding model applied in Sweden and Denmark. The meteorological pre-processor is modified in order to better represent urban conditions. We re-evaluated the roughness length, introduced the zero-displacement height and divided the surface layer into a roughness sublayer and an inertial sublayer. The friction velocity and Monin-Obukhov length are re-evaluated using an empirically developed exponential Reynolds-stress profile in the roughness sub layer.

These modifications can have a substantial influence on the computed concentrations for the ground level or near the ground level sources. The re-evaluated friction velocity and dispersion parameters result in clearly lower concentrations in stable atmospheric stratification, and slightly higher concentrations in neutral and unstable atmospheric stratification, respectively

A modification is suggested to the FMI-MPP stable mixing height calculation method. The modified FMI–scheme gives very similar results for the stable mixingh heights as the Zilitinkevich interpolation scheme. The study also clearly showed the importance of using urban meteorological profile data as input for the meteorological preprocessor instead of the routinely used rural profile data.

An overview of the other components (emissions, dispersion, atmospheric chemistry) of the modelling system is accompanied with computational results of the nitrogen oxides (NO_x) and nitrogen dioxide (NO_2) concentrations in the Helsinki metropolitan area in 1993. A comparison of model predictions with the results of an urban measurement network is also presented.

The modelling system was fairly successful in predicting the urban NO_x concentrations, and successful in predicting the urban NO_2 concentrations. The integrated 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, e.g. in the city of Turku (Pietarila et al., 1997). The agreement of predicted and measured NO_2 concentrations was very similar to the results presented in this theses.

The modelling system developed has been an important assessment tool for the local environmental authorities, and the municipal authorities have utilized the results of these computational methods 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.

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