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NWP modelling for urban air pollution forecasting: possibilities and shortcomings

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Summary

During the last decade a substantial progress in Numerical Weather Prediction (NWP) modelling and in the description of urban atmospheric processes have been achieved. Present NWP models are approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale. In combination with the recent scientific developments in the field of urban atmospheric physics and the enhanced availability of high-resolution urban surface characteristics, the capability of the NWP models, which provide high quality urban meteorological data, will therefore increase. Nevertheless, existing operational Urban Air Quality Forecasting Systems and the corresponding Urban Air Pollution (UAP) models often employ simple local measurements and meteorological pre-processors with a poor description of the temporal and spatial evolution of meteorological variables at urban scale. Clearly, present UAP models could benefit largely from utilising meteorological data from NWP models to give a physically consistent basis for the urban air quality forecasts. Possibilities and shortcomings of NWP models to provide meteorological data for UAP modelling are discussed in the paper.

This overview- report was prepared for the International Symposium on ‘Scale Interactions in Models and Policies for Air Quality management’ (SIMPAQ-2000) and presented at the meeting of the Working Group 2 (WG2): ‘Mixing height and energy budget’ of the COST Action 715 ‘Meteorology applied to urban air pollution problems’, Antwerp, Belgium, on 12-13 April 2000.

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1. Introduction

During the last decade a substantial progress in Numerical Weather Prediction (NWP) modelling and in the description of urban atmospheric processes have been achieved. Present NWP models are approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale. In combination with the recent scientific developments in the field of urban atmospheric physics and the enhanced availability of high-resolution urban surface characteristics, the capability of the NWP models, which provide high quality urban meteorological data, will therefore increase. Nevertheless, existing operational Urban Air Quality Information Forecasting Systems (UAQIFS) and the corresponding Urban Air Pollution (UAP) models often employ simple local measurements and meteorological pre-processors with a poor description of the temporal and spatial evolution of meteorological variables at urban scale (see Figure 1). Clearly, present UAP models could benefit largely from utilising meteorological data from NWP models to give a physically consistent basis for the urban air quality forecasts.

II. Possibilities and shortcomings of NWP models to provide meteorological data for UAP modelling

The main problem in the urban air pollution (UAP) forecast is to predict episodes with high pollutant concentration in urban areas, where most of well-known modelling methods, based on in-situ meteorological measurements, failed to produce realistically the meteorological parameters evolution. So, the main focus of further studies should be on improvements of forecasts of the meteorological parameters for UAP models for episodes that enhance local scale and urban phenomena description (low winds, stable stratification, local air circulations, topographic effects, breeze conditions, internal boundary layers, urban heat island, etc.).

Uncertainties of UAP models are often associated with the meteorological fields, e.g. Svensson (1996) demonstrated that relative errors in meteorological variables simulated in a model may be larger than the uncertainties in the chemical part. Many projects are aimed at developing UAP dispersion models and chemical transformation, and at improving the knowledge about pollutants and emissions. However, no significant efforts are put on improvements of forecasts for meteorological parameters in UAP models for episodes.

Historically UAP forecasting and numerical weather forecasting were developed separately and had no close co-operation. It was, however, reasonable for the previous decades, when the resolution of NWP models was too poor for city-scale air pollution forecasting. The situation has been changed nowadays and this requires a revision of the conventional conception of the urban air pollution forecasting.

Modern nested NWP models are approaching resolution of the meso- and city-scale. For example, the Danish operational system consists of several nested models named DMI-HIRLAM ‘G’, ‘N’, ‘E’ and ‘D’, where the high resolution model ‘D’, covering an area around Denmark, has 5 km horizontal grid and uses boundary values from the large scale model ‘E’. The HIRLAM (Sattler 1999, Rasmussen et al. 1999) and LM (Saito 1998, LM 1999) models

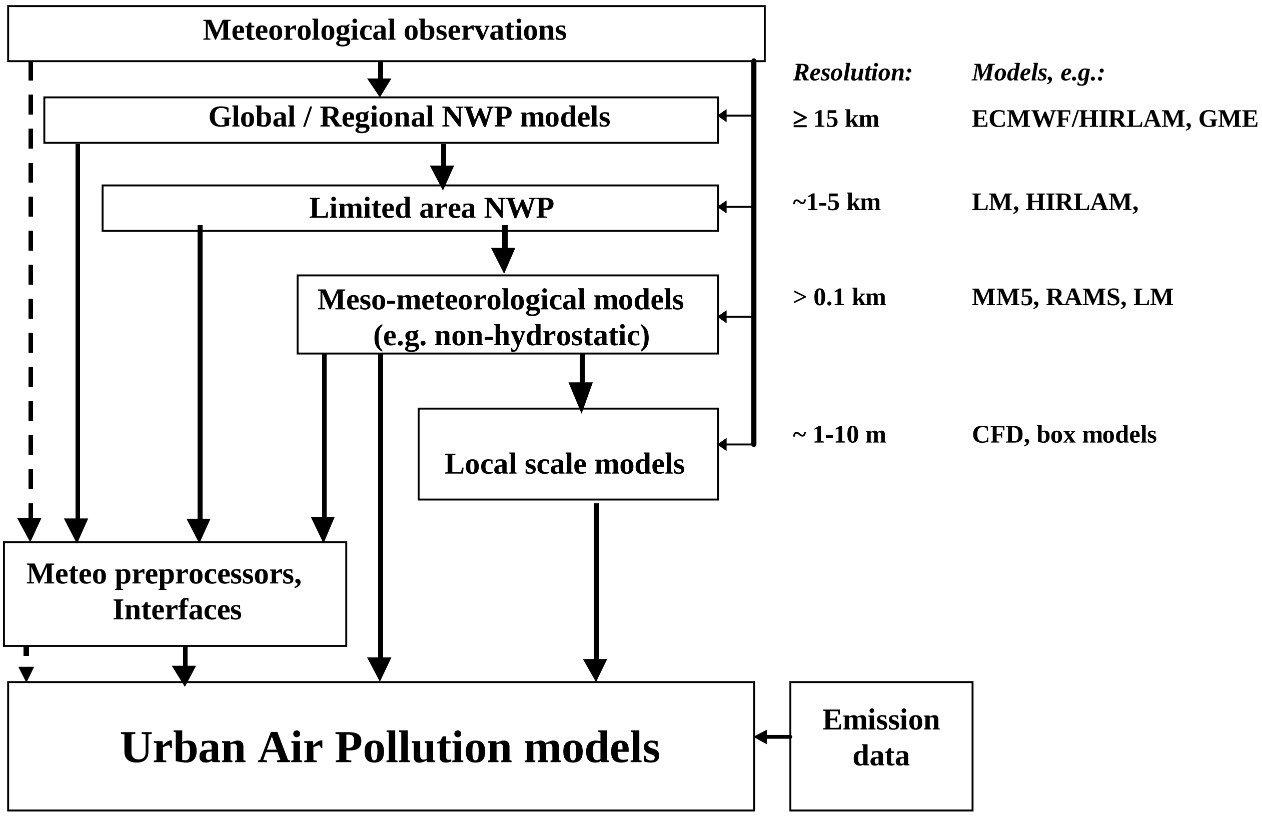

Figure 1. Current regulatory (dash line) and suggested (solid and dash lines) ways for systems of forecasting of urban meteorology for UAQUIFS:s.

use land-use databases down to 1 km resolution or lower (see Figure 2). Operational Urban Air Quality Information Systems and correspondingly UAP models, as a rule, use simple in-situ meteorological measurements and meteorological pre-processors (Fisher et al., 1999). They don't use numerous possibilities of NWPs to improve the urban air quality forecasts, but modern UAP models need more complex meteorological forecast data (Fenger et al. 1998). In this context, it is very important:

- to link meteorologists/NWP modellers with urban air pollution scientists and 'end-users' of UAQIFS,
- to develop parameterisations of the urban effects in NWP models and
- to develop an interface from NWP to UAP models.

Some European countries (e.g. Norway, Italy, France, Switzerland) run works in this direction and have showed that it is a very promising way (Clean City Air 1999, Masson 2000). The US EPA still uses simple UAP regulatory methods, however US scientists show (Pielke & Uliasz 1998, Byun & Ching 1999) a pure understanding of the perspectives of this way as well.

For example, modern models of atmospheric chemistry and aerosol deposition demand much more meteorological data as input (Herrmann et al., 2000), such as humidity distribution, cloud characteristics:

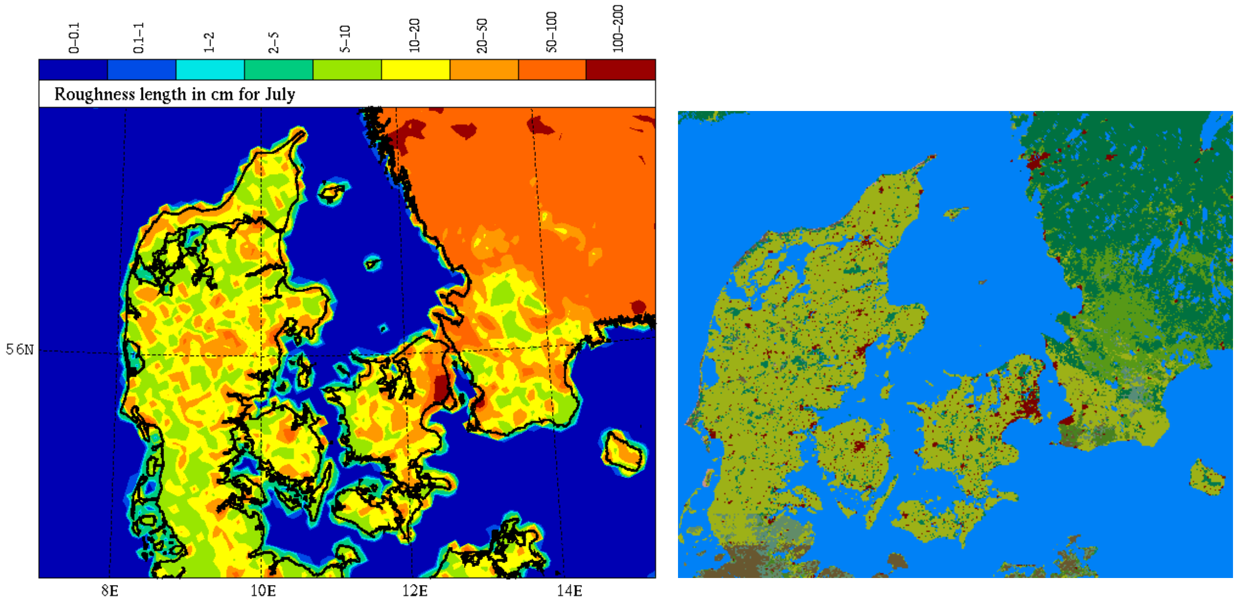

Figure 2. Surface roughness (left) and land use (right, purple colour is percentage of urban areas) in the operational DMI-HIRLAM-D model, based on high resolution physiographic data (Sattler 1999).

cloud water, top and base of a cloud, intensity and type of precipitation, radiation characteristics etc. Existing meteorological pre-processors, based on simple meteorological measurements and parametrisations, can not provide this information. Attempts to apply 3-D meso- and local-scale models separately don't give input data of sufficient quality, because they don't support data assimilation from a net of meteorological measurements, GPS profiles and NWPs.

From the other side, NWP models in connection with increasing capacities of computers in the last years have considerably increased the spatial (vertical and horizontal) resolution and depth of the PBL parameterisations and practically become close to meso- and local-scale models.

Nevertheless, in most of NWP models, urban and non-urban areas are treated mostly similarly, e.g., through similar sub-surface, surface, and boundary layer formulations (Tana & Bornstein 1999). No different/ additional mechanisms or physics exist to account for urban specific dynamics and energetics and for their impacts on the atmospheric boundary layer. Recent efforts have suggested various modelling approaches to link the different physics of the canopy and urban boundary layers (Rotach 1993; Fenger et al. 1998, Masson 2000). So, it is one of important objectives for the further studies: to improve resolution and parameterisations of the urban effects in NWP models.

One of important aspects is the improved prediction of urban air temperature fields, parameterisation of the urban surface/turbulent sensible and latent heat fluxes, especially the water evaporation, implementation and verification of the full force-restore soil model for urban areas.

In this content a new and very important problem is to assimilate surface characteristics into the urban scale NWP - based on high resolution (up to 10 m) satellite data, e.g. remotely sensed heat fluxes of urban areas (Parlow, 1999). Algorithms for assimilation of surface temperature, albedo and snow cover started to be developed and tested (Clean City Air 1999, De Ridder 2000). This information is certainly crucial for the modelling quality.

Urban roughness parameterisation as a critical point (Grimmond and Oke 1999) should be improved by providing and verification of the geometrical model for computing the roughness parameters of urban areas (Guilloteau & Mestayer 2000, Grimmond & Oke 1999).

Urban effects on precipitation pattern can be very considerable, but nowadays their studies are based solely on investigator intuition rather than on a description of contribution of the physical processes by numerical models (Lin & Bornstein, 1999). So, improvement of the urban effect parameterisations in NWP modes will increase understanding of this important problem.

Additionally, NWP models are not oriented especially to the atmospheric pollution modelling, so they have some different limitations and strengths (Pielke and Uliash 1998) and their outputs need to be developed in order to be used as input to urban- and mesoscale air quality models. So, development of met pre-processors (from NWP) and interfaces to UAP models is a very important item.

Main high-level pollution episodes happen during periods with stably-stratified boundary layer. The Monin-Obukhov similarity theory, used in most of the models, does not work in case of the stable-static stability atmospheric boundary layer and needs to be improved (Zilitinkevich et al. 1998). Existing atmospheric dispersion models for the stably-stratified boundary layer have a poor description of pollution processes due to, first of all, estimation of the SBL height, vertical profile parametrisation, non-adequate dispersion parameterisation and topographical effects (Fisher et al. 1998). For example, for strong stably-stratified ABL, the conventional methods for the SBL height estimation (like the bulk Ri - method) can give a unrealistic mixing height. New approaches and parametrisations, based on an improved similarity theory and non-local characteristics of turbulence, should be realised for NWP/UAP models.

An important task in the evaluation of UAP-model inputs and results is the spatial effects and scale interaction between non-obstacle resolving NWP models and the obstacle resolving micro-scale UAPs (e.g. Baklanov 2000). The new European regulations (EC/99/30) require prediction of local peak values (very high percentiles) at specific points (hot spots), which can only be determined by the obstacle resolving UAP-models. So, the delivery of input parameters for those obstacle resolving UAPs, as well as the sensitivity analysis of improved parameterisations and physiographic fields on meteorological input fields for UAP models will be a focus point of further studies.

III. Suggested improvement strategy

In order to resolve these issues, new innovative studies are needed in the UAQIFSs, that are specifically tailored to the following objectives (Figure 3):

- An improved urban meteorology and air pollution modelling system suitable to be applied to any European urban area on a basis of available operational weather forecast.
- A model interface capable to connect mesoscale meteorological model results to updated UAP and atmospheric chemistry models.
- An evaluation of the relevance to air pollution simulations of a detailed description of local circulation and urban meteorology.
- Roughness and land use parameters should be revised and the addition of a urban heat source should be evaluated for its effects on turbulence, stability, heat fluxes in NWPs and accordingly on the mixing height module and on transport/dispersion calculations in the urban areas.
- Surface characteristics based on satellite data and additional urban meteorological measurements should be assimilated into urban scale NWP models. Algorithms for assimilation of the surface temperature, albedo and snow cover should be developed and

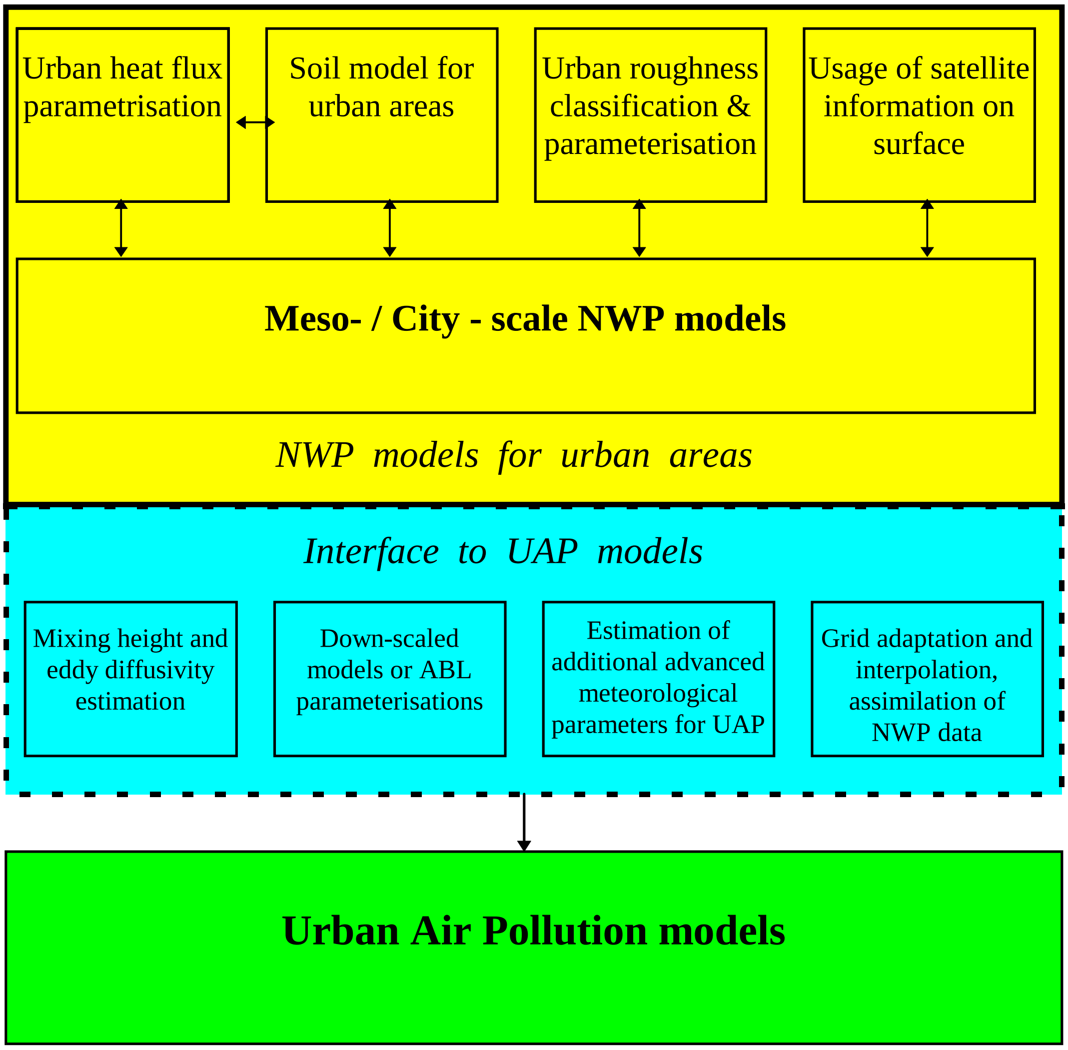

Figure 3. Scheme of the suggested improvements of meteorological forecasts (NWP) in urban areas and interfaces to UAP models for the Urban Air Quality Information Forecasting Systems.

tested for urban areas.

One of important problems to develop further the NWP models for urban areas is the improvement of boundary layer formulations/ parametrisations in NWP models and model physiographic data for urban areas and the evaluation of simulation of urban meteorology in NWP models:

- Improvement of the surface/turbulent sensible and latent heat fluxes and land-use for urban areas. Implementation and verification of the full Force-Restore soil model for urban areas.
- Improvement of the roughness parameters of urban areas. Implementation and verification of the geometrical model for roughness parameters in urban areas.
- Analysis of sensitivity of meteorological input fields for UAP models (wind fields, temperatures, turbulent characteristics) to the improved parameterisations and physiographic fields.
- Improvement of the similarity theory for the stably-stratified nocturnal urban boundary layer and its parameterisation within NWP models.
- Integration and validation of the results from the improved forecasting system.

The result of the suggested studies should improve forecasting capabilities of meteorological parameters for urban areas, and could be used by all NWP centres in Europe and in met-preprocessors.

As a practical step to realise the suggested strategy eighteen research groups, including meteorological institutes, UAP modelling organisations and end-users responsible for urban air quality, from ten European countries developed a proposal '***Integrated Systems for Forecasting Urban MEteorology for Urban Air Quality Information Systems (FUME)***' to the the Fifth Framework Programme of the European Commission.

Main Objectives

The main aim of the FUME proposal is to improve meteorological forecasts for urban areas, to connect NWP models to UAP models and to build improved UAQIFS enhancing the capabilities of forecasting the air quality in European cities. The improvement of urban meteorological forecast will also give potential contributions to city management regarding problems connected to urban weather, e.g. urban temperatures in growing cities and warming climate, urban runoff and flooding, icing and snow accumulation and urban wind climate, all factors that have implications on the quality of urban life, energy consumption and street maintenance programs.

The FUME project will proceed through the steps given below, each of which can be considered as a separated objective conducing to valuable deliverables:

1.CATALOGUING THE AIR POLLUTION EPISODES WITH A FOCUS ON RELEVANT METEOROLOGICAL VARIABLES.

- Identification and classification of various types of air pollution episodes in cities located in different European climatic and geographic regions.

- Key pollutants relevant to EU Air Quality Directives and the Daughter Directives (EC/96/62; EC/99/30) will be selected for the investigation considering the different regions/cities characteristics.

- Classification of meteorological conditions leading to pollution episodes and identification of the more relevant meteorological parameters to define these conditions in various European climatic regions.

- Compilation of datasets of concentration and meteorological data measured during air pollution episodes in different European climatic and geographic regions.

2. IMPROVEMENT OF THE QUALITY OF URBAN METEOROLOGICAL FORECASTING FOR URBAN AIR POLLUTION MODELS

Improvement of urban weather forecasts adapting NWP modelling systems to the urban scale and to the forecast of key meteorological parameters for pollution episodes modelling. A hierarchy of NWP models from large scale Global Circulation Models to high resolution Limited Area Models to mesoscale (non-hydrostatic) models to local-scale obstacle-resolving meteorological models will be employed.

Improvement of boundary layer formulations/parameterisations and physiographic data description for urban areas.

Development of assimilation techniques to introduce satellite remote sensed surface data in NWP models.

Development of interfaces to connect NWP to UAP models.

3. VERIFICATION OF THE IMPROVED MODELS AND UNCERTAINTY ANALYSIS

Evaluation of the improvements in the urban meteorological forecast capabilities on the basis of urban air pollution episode data previously collected and analysed.

Estimation of the sensitivity of forecasting UAP models to uncertainties in meteorological input data. Various NWP-model designs with respect to: horizontal and vertical resolutions, variable length of the forecasted meteorology, and assimilation of urban meteorological observations will be analysed.

4. APPLICATION TO REAL TIME URBAN AIR QUALITY INFORMATION SYSTEMS

Implementation of the new improved UAQIFS in four different European target cities, to take into account different cities climate, dimension, structure and sources characteristics influence. End users will be involved in the definition of the information required from the UAQIFS, different location end-users will collaborate to define content and format of needed forecasts and warnings, and the strategy of data dissemination to decision makers, authorities and to the public.

Demonstration of the new UAQIFS for selected episodes in each of the four target cities with the direct participation of local authorities and other end-users.

Expected results

The expected results comprise scientific advances as well as direct benefits for the End Users and the Citizens of urban areas in Europe:

– Urban air pollution episode datasets for different regions in Europe,

– Uncertainty analysis of different forecasting systems and improved parametrisations,

- Improving meteorological pre-processors and interface from NWP to UAP models,
- Application of results in UAQIFS: harmonisation and quality assurance,
- Improved UAQIFS for air pollution episodes and hence reliable information for the Citizen through the End User,
- Implementation and demonstration of improved UAQIFS in four European cities.

IV. Conclusions

1. During the last decade a substantial progress have been achieved in Numerical Weather Prediction modelling and in the description of urban atmospheric processes. Present NWP models are approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale.

2. Nevertheless, in most NWP models, urban and non-urban areas are treated similarly, e.g., through similar sub-surface, surface, and boundary layer formulations. No different/ additional mechanisms or physics exist to account for specific urban dynamics and energetics and for their impacts on the atmospheric boundary layer. Recent efforts have suggested various modelling approaches to link the different physics of the canopy and urban boundary layers. So, one of the important objectives for the further studies is to improve resolution and parameterisations of the urban effects in NWP models.

3. The main problem in the urban air pollution (UAP) forecast is to predict episodes with high pollutant concentration in urban areas, where most of well-known modelling methods, based on in-situ meteorological measurements, failed to realistically produce the evolution of meteorological parameters. Uncertainties in UAP models are often associated with the meteorological fields. However, no significant efforts are put on improvements of the forecasts for meteorological parameters in UAP models for episodes.

4. Historically UAP forecasting and numerical weather forecasting were developed separately and had no close co-operation. It was, however, reasonable for the previous decades, when the resolution of NWP models was too poor for the city-scale air pollution forecasting. The situation has been changed nowadays and this requires a revision of the conventional conception of the urban air pollution forecasting.

5. Improvements of resolution and parameterisations of the urban effects in NWP models are very important for the urban air pollution forecasting as well as for increasing the quality of the numerical weather forecasting, especially for urban areas, and simulation of the urban climate change.

6. As the first step to improve the prediction of urban air temperature and velocity fields in the DMI-HIRLAM model it is suggested to improve the parameterisation of heat and momentum fluxes in urban areas. It can include the urban surface/turbulent sensible and latent heat fluxes, especially the water evaporation, implementation and verification of the full force-restore soil model and the geometrical model for roughness parameters for urban areas (e.g. for Copenhagen).

7. This work can open a new direction of research/development at DMI to forecast/simulate the meteorological processes and antropogenic/industrial impacts on the atmospheric processes and the environment as an online-linked problem. It is quite clear what this way of on-line coupled NWP and air pollution/chemistry models has a good perspective and in the nearest future will be a basic method for the atmospheric environmental predictions as well as for weather and climate forecasting in urban areas.

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