Approaches for urbanization of DMI-HIRLAM NWP model

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Abstract

The increased resolution of the numerical weather prediction models in national weather centres allows nowadays addressing more specifically urban meteorology forecasts. This has required also by the urban air pollution and emergency preparedness modelling communities. Different approaches for the models' urbanisation based on the recent developments of the EU-funded project FUMAPEX on integrated systems for forecasting urban meteorology, air pollution and population exposure are presented here. Issues of parameterising the urban roughness sublayer and surface exchange fluxes and the role of the urban soil layers are addressed with an advanced city-scale version of DMI-HIRLAM. Recommendations, especially with respect to the choice of one of the urban modules depending on a specific problem, model resolution, or metropolitan area are given.

1. Introduction

The urban areas have significant influence on the meteorological processes and atmospheric flow, its turbulence regime, the microclimate, and, accordingly modify the transport, dispersion, and deposition of atmospheric pollutants within these areas. The main influencing urban features are:

- Local-scale non-homogeneities, such as sharp changes of roughness and heat fluxes;
- Sheltering effects of buildings on wind velocity;
- Redistribution of eddies, from large to small, due to buildings;
- Trapping of radiation in street canyons;
- Effects of urban soil structure;
- Different diffusivities of heat and water vapour in the canopy layer;
- Anthropogenic heat fluxes, including the so-called urban heat island;
- Urban internal boundary layers and urban mixing height;
- Effects of pollutants (including aerosols) on urban meteorology and climate;
- Urban effects on clouds and precipitation.

Unfortunately, at the current moment the urban classes and urban scale parameterizations are not well represented in the Numerical Weather Prediction (NWP) models. Due to a high resolution of modern NWP models, reaching the city scale, the improvements of existing parameterizations of urban atmospheric processes and urban physiographic data classifications became urgently needed. This was a focus of the EU-funded FUMAPEX project entitled "Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure" (*Baklanov et al., 2005*). One of the main objectives of this project was related to improvement of urban boundary layer parameterizations in NWP models as well as model physiographic data for urban areas with a subsequent evaluation of simulated urban meteorology. Within this project a set of NWP models, including the DMI version of the HIgh Resolution Limited Area Model (HIRLAM), was used for urbanization.

The improved urban meteorological forecasts will also provide information to city management regarding additional stressing of urban climate (e.g. urban runoff and flooding, icing and snow accumulation, high urban winds or gusts, heat or cold stress in growing cities and/or a warming climate). Moreover, the availability of reliable urban scale weather forecasts could be a relevant support for emergency management of fires, accidental toxic emissions, potential terrorist actions, etc.

2. Methodology for NWP model urbanization

The strategy to improve NWP models includes the following aspects for the urbanization of relevant submodels or processes (*Baklanov et al., 2002; 2005*). The first aspect is related to the model down-scaling, including increasing vertical and horizontal resolution and nesting (one- and two-way) techniques. The second consists of the modified high-resolution urban land-use classifications, parameterizations, and algorithms for roughness parameters in urban areas based on morphologic methods. The third is represented by specific parameterizations of the urban fluxes. The fourth is connected with the modelling and parameterization of meteorological fields in the urban sublayer. And the fifth aspect includes calculation of the urban mixing height based on prognostic approaches.

2.1 Resolution and nesting

The increased computer power and implementation of grid nesting techniques allowed modern NWP models to approach the resolution necessary for the city-scale. For example, the Danish operational NWP system (*Sass et al., 2002; Unden et al., 2002*) recently consists of several nested models named DMI-HIRLAM-S05 and -T15, with horizontal resolutions of 5 and 15 km, respectively (*Yang et al., 2005*). The previous nested versions G45, E15, and D05 (operational prior 14 June 2004) had 45, 15, and 5 km resolution, correspondingly. The vertical resolution of the operational versions is 40 levels, but it was also tested for up to 60 levels. DMI runs and performs verification also for high resolution (1.4 km) experimental versions of DMI-HIRLAM (e.g., -U01, -I01) with domains covering Denmark and the Island of Sjælland, where the city of Copenhagen is located (*Mahura et al., 2005a; Baklanov et al., 2005*).

For high resolution, the verification and sensitivity studies with NWP models vs. measurement data were also performed for several episodes in European cities: Helsinki, Oslo, Bologna, Valencia, Copenhagen (*Neunhaeuserer et al., 2004; Fay et al., 2005; Baklanov et al., 2005b; Fay & Neunhaeuserer, 2005; Berge et al., 2002*).

2.2 Urban land-use classification and algorithms for roughness parameters

At present, most of the NWP models do not consider any urban class at all, or might include only one urban class for all types of urban surfaces.

Typical surface characteristics can be attributed to distinct categories of urban neighborhoods. Such a classification can be performed based on land use maps, aerial photos, or fields surveys. Digital land-use classification (LUC) datasets can help to define different urban classes, but unfortunately, most LUCs are classified by functional aspects (residential, industrial) and not by surface morphometry or surface cover. Focusing on meteorological aspects, *Ellefsen (1991)* made classification according to building contiguity, construction, and materials. *Fehrenbach et al. (2001)* have automated the classification of urban climatological neighborhoods from satellite image analysis. The morphometric parameters help to describe the roughness and turbulence characteristics over a particular urban surface; and hence, the following three most important characteristics can be outlined (*Piringer & Joffre, 2005; Baklanov et al., 2005a*).

First, it is the urban cover. Two dimensional plan aspect ratios describe surface fraction of a particular surface type per total plan area (as viewed from above), e.g. the plan area ratios of buildings, vegetation, impervious surfaces, dominant street directions, etc. Second, it is 3D morphometric parameters describing configuration of urban buildings (i.e. mean building height, frontal aspect ratio, surface enlargement, normalized building volume, characteristic inter-element spacing, canyon width, etc). Third, it is the urban materials (e.g., construction materials of buildings roofs and walls) important for estimation of radiative properties and the storage heat flux densities.

Proceeding from the urban LUC, the calculation of the main aerodynamic characteristics of urban areas (such as the roughness length and displacement height) can be performed based on the morphometric or morphologic methods. With morphometric methods, the ranking of these aerodynamic characteristics depends on the model intrinsic requirements for input data as discussed, for example, by *Bottema & Mestayer (1998); Grimmond & Oke (1999b); Bottema (1997).* With morphologic methods, a more empirical and pragmatic approach based on the visual observation of the physical structure of the urban canopy (e.g., from aerial photography) can be considered, as for example, shown in survey of experimental data by *Grimmond & Oke (1999b)* or defined by a written description and model photography by *Ellefsen (1991)*.

2.3 Urban fluxes and sublayer parameterization

The simulation of the urban canopy effects in urban-scale NWP models can be considered with respect to the following two main approaches. The first approach is related to modification of existing non-urban approaches (e.g., the Monin-Obukhov similarity theory, MOST) for urban areas. In this case the proper values for the effective roughness lengths, displacement height, and heat fluxes (adding the anthropogenic heat flux (AHF), heat storage capacity and albedo change needs to be found, as for example, suggested by *Zilitinkevich & Baklanov (2005)* a new analytical model for the urban roughness sublayer. The second approach, alternatively, represents the effects of buildings by adding the source and sink terms in the momentum, energy, and turbulent kinetic energy equation. Different parameterizations (*Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002*) have been developed to estimate the radiation balance (shading and trapping effect of the buildings), heat, momentum and turbulent fluxes inside the urban canopy considering a simple geometry of buildings and streets (3 surface types: roof, wall and road). A combination of these two approaches with a more detailed evaluation of LUC can be realized, for example as given by *Dupont et al. (2005ab)* for research version of the MM-5 model.

2.4. DMI approach based on improved urban roughness and fluxes

The first simplified urban module (DMI module) is based on two following requirements. First, it should be relatively cheap computationally and as close as possible to parameterizations of the surface/boundary layer in the parent NWP models. Second, it needs to split the surface layer over urban areas into two/three sub-layers. This splitting distinguishes the roughness layer (where MOST can be used with correction to the urban roughness) and the urban canopy layer (where MOST does not work and new analytical parameterizations for the wind and eddy profiles have to be considered).

This module includes algorithms for calculating the following urban parameters for the NWP model and steps for each grid cell having urban features. These items are : (i) land use classification which, at least, includes one urban class; (ii) displacement height for the urban (and forest) canopies; (iii) urban and effective roughness (and flux aggregation); (iv) stability-dependent urban roughness lengths for momentum; (v) urban anthropogenic heat fluxes; (vi) urban storage heat fluxes by the objective hysteresis model (*Grimmond et al., 1991*) or specific roughness lengths for heat and moisture; (vii) albedo correction for urbanized surfaces; (viii) prognostic mixing height parameterizations; (ix) parameterization of wind and eddy profiles within the canopy layer.

Note, it is reasonable to use this approach for a relatively cheap simulation and NWP models with a low vertical resolution (i.e. first vertical level is higher than 20 m), when other more complex models of the urban sub-layer would not significantly affect the results or would be too expensive computationally for operational forecasting applications. This module, with some simplifications, was implemented and tested with the city-scale DMI-HIRLAM NWP model for case studies in the Copenhagen metropolitan area and surroundings.

Effect of the urban canopy roughness

The MOST should not be applied inside the urban canopy. Thus, the classical MOST theory with a modified calculation of the urban roughness cannot give a satisfying solution for the urbanization of NWP model. To avoid or minimize this problem, it is suggested to consider the MOST profiles in NWP models only above an elevated level of the order of the displacement height. Therefore, in the suggested algorithm, the roughness for urban areas is characterized by, at least, two parameters: the roughness length and the displacement height. Theoretical aspects of such an approach were discussed by *Rotach (1994, 1999), Belcher & Coceal (2002), Belcher et al. (2003), Zilitinkevich et al. (2005b)*, *Fisher et al. (2005a*).

Roughness parameters for urban areas are calculated by modified algorithms based on the morphological methods. The displacement height can be calculated only for grid cells shown as urban class following *Fisher et al. (2005a).* In a general case of very inhomogeneous surfaces (such as urban areas) in order to include mutual effects of neighboring cells it would be reasonable to simulate the effective roughness fields separately for different situations (e.g., seasons, wind directions) and to build a kind of effective roughness maps library. For such a strategy, the flux aggregation technique of *Hasager et al. (2003)* was tested in the DMI-HIRLAM model but only for non-urban areas. It is because there is not enough experimental data to verify urban areas parameterizations and to check the applicability of the linear approximation of the technique for urban conditions.

Nevertheless, most of NWP models consider the roughness length as a constant for each grid cell. Experimental data (*Arya, 1975*; *Joffre, 1982; Wood & Mason, 1991)* showed that it can depend on temperature stratification. The algorithm for recalculation of the effective roughness separately for the stable or unstable situations (based on a new stability-dependent parameterization of the urban roughness length for momentum) was suggested by *Zilitinkevich et al. (2005a).* A simple heuristic model of *Zilitinkevich & Baklanov (2005)* for the vertical profiles of the momentum flux and mean wind velocity within the urban canopy can be also suggested. It considers the vertical wind profile inside the canopy (below the displacement height) as an analytical function of the average building height, size and density, as well as of some meteorological parameters.

Note, the suggested improvements, based on the canopy profile model and displacement height, do not required to substantially modify the NWP model for calculation of the prognostic variables on the main computational levels, because the first computational model level is usually above the canopy, so that the canopy parameterization can be used only for diagnosis of 10 m wind in NWP.

Surface energy budget in urban areas

For NWP models in which the *surface* may be high above the urban canopy (average roughness level or displacement height), the surface energy budget can be rewritten based on (*Piringer & Joffre, 2005*) in the following form for the urban areas:

$$Q^* = K{\downarrow} - K{\uparrow} + L{\downarrow} - L{\uparrow} = H + LE + Q_A + \Delta Q_S$$

where Q^* - net all-wave radiation [in W/m^2]; $K{\downarrow}$ - incoming and $K{\uparrow}$ - outgoing, reflected shortwave radiation; $L{\downarrow}$ - incoming longwave radiation from the sky and surrounding environment ‘seen’ from the point; $L\uparrow$ - outgoing longwave including both that emitted from the surface and the reflected incoming longwave; H - turbulent sensible heat flux; LE - turbulent latent heat flux; Q_A - anthropogenic heat flux from sources within the urban canopy and ΔQ_S is an imbalance term. The last term includes the storage heat flux in the urban canopy elements, the ground and the air layer, extending from the surface to a level where the vertical heat exchange divergence is negligible (i.e., the constant flux layer). In the model most of these terms are simulated for urban grid cells of model domain as usual with corresponding urban characteristics, but the two last urban terms - Q_A and ΔQ_S - as well as the albedo for urban areas need to be defined and parameterized.

Urban anthropogenic heat flux calculation

Following estimations of the average AHFs for cities in different climatic zones *(Oke, 1978*), the reference values for a fully urbanized area (e.g., city centre or high building district) are ranging from 60 to 200 W/m^2 depending on the city size. Information on the spatial distribution of AHFs over a city is not available from monitoring data and is difficult to obtain from measurements (*Pigeon et al., 2005*). Therefore, *Baklanov et al. (2005a)* suggested several calculating methods for the urban AHF based on assumed dependency on (e.g., proportionality to) other relevant urban characteristics. The first method (most frequently used) considers AHF as a function of the population density distribution (using maps with a high resolution in urban areas). The second method is based on the nocturnal brightness of urban areas (obtained from high resolution satellite images). The third method uses the land-use classification to estimate the percentage of urban classes. The last two methods are based on evaluation of emission inventory for specific pollutants typical in urban areas as well as from monitoring or simulated fields of air pollution concentration for such specific pollutants.

Urban storage heat fluxes

Storage heat fluxes in the urban canopy are evaluated by two different approaches. First, the heat storage capacity effect can be calculated using specific parameterizations for the temperature and moisture roughness lengths of urban areas. Most of NWP models consider for their surface layer profiles that the scalar roughness length is equal to the roughness for momentum. However, for urban areas, they generally can differ by 2-3 orders of magnitude. Theoretical studies (*Zilitinkevich, 1970; Brutsaert, 1975*) suggest that the ratio between these two mentioned is a function of the roughness Reynolds number. Thus, the formulation of *Brutsaert & Sugita (1996)*, for example, can be suggested for urban areas. The heat storage in the urban fabrics/buildings, including hysteresis, can be parameterized from the radiation and surface cover information using the empirical objective hysteresis model of *Grimmond et al.* (*1991*) with the empirical coefficients deduced from re-analysis of the Multi-City Urban Hydro-Meteorological Database (*Grimmond & Oke*, *1999a*).

Urban albedo effects

Radiative properties (such as albedo and emissivity) of buildings and ground-covering materials are very different from those of natural grounds and vegetation, while the vertical structure of spaces between buildings provides shade and radiation trapping. In addition, they have not only horizontal but also vertical and/or slanted orientations, which strongly alter the radiative transfer and energy budget. The heat flux to/from the ground changes with the surface material (i.e. concrete, soil, etc.). On an urban scale, the anthropogenic flux can be a noticeable fraction of the annual solar input and thus, influences the local air stability.

3. Urbanization of DMI-HIRLAM NWP model for Copenhagen

3.1 General approach for urbanization

Originally, three modules were considered for urbanization with the DMI-HIRLAM model (Fig. 1). The first, the DMI module includes a new diagnostic analytical parameterization of the wind profile into the urban canopy layer (*Zilitinkevich & Baklanov, 2005*) and corrections to the surface roughness (with the incorporation of the displacement height) for urban areas and heat fluxes (additional AHF, e.g., via heat/energy production/use in the city, heat storage capacity, and albedo change) within existing physical parameterizations of the surface layer in NWP models with higher resolution and improved land-use classification. The second, the Swiss Federal Institute of Technology (EPFL) module - Building Effect Parameterization (BEP) - is based on the urban surface exchange parameterization submodel (*Martilli, 2001; Martilli et al., 2002*). It was first tested with the research meso-meteorological FVM and TVM models. The third, the Ecole Centrale de Nantes (ECN) module - Soil Model for Sub-Meso Scales Urbanized version (SM2-U) - is based on the detailed urban area soil and sublayer model (*Dupont, 2001; Dupont et al., 2005ab*). It was tested with the large eddy simulation SUBMESO and MM5 models. Additionally to the above mentioned modules, the flux aggregation technique of *Hasager et al.* (2003) was tested in the DMI-HIRLAM model for non-homogeneous surfaces. However, it has not been tested yet for urban areas.

The main idea of the general urban module architecture was to build it as much as possible independently of a type of NWP model, and to allow a simple implementation into different models. Note, that it is not always possible to build it as a completely independent one. Often internal subroutines and programs of urban modules need to be modified substantially in order to satisfy main requirements and formats of NWP model. There is also a freedom on how to implement: either to incorporate it inside the NWP model code or to call a separate module from NWP. The algorithm used is presented in Fig. 1. The initialization module is called only once when the model is initialized for simulations, and then the modules are called on each time step during the simulation. These can be also built as an interface/post-processor block separated from the NWP model. In such a case, the urban sublayer model will be run separately (using previously simulated NWP data as a fist approximation) and will improve the meteorological fields in an area close to and inside the urban canopy with a higher resolution.

3.2 Land-use classification for Copenhagen metropolitan area

The high quality land-use classification data is a crucial input in NWP modeling. The CORINE dataset (*CORINE, 2000*) providing a better representation of orography and identification of urban surface features was used to prepare LUC for high resolution runs over the domain shown in Fig. 2a. For the DMI and EPFL modules only the general information about existence of the urban class in each grid cell of modelling domain is needed. For the ECN module, for each grid cell the classification was represented by 7 types of covers/surfaces among which three urban related surfaces were considered (*Mahura et al., 2005b*). These are the vegetation over paved surfaces (e.g., trees on the road side: VEGA), paved surfaces located between the sparse vegetation elements (ART), and building/roofs (BAT) (see Fig. 2b).

The classification followed the “mosaic” approach, where each cell may contain up to 7 different types of surfaces. Further, the cells, where a contribution of urban type into the cell has existed, were assigned to different types of urban districts having different properties. Note, that to obtain detailed characteristics of urban related properties as well as to improve quality and resolution of the land use and urban subclasses the classification of other databases can be used. For Denmark, for example, these are the Areal Informations Systemets (resolution of 25 m) and building resolved GIS databases of urban structures (BlomInfo A/S).

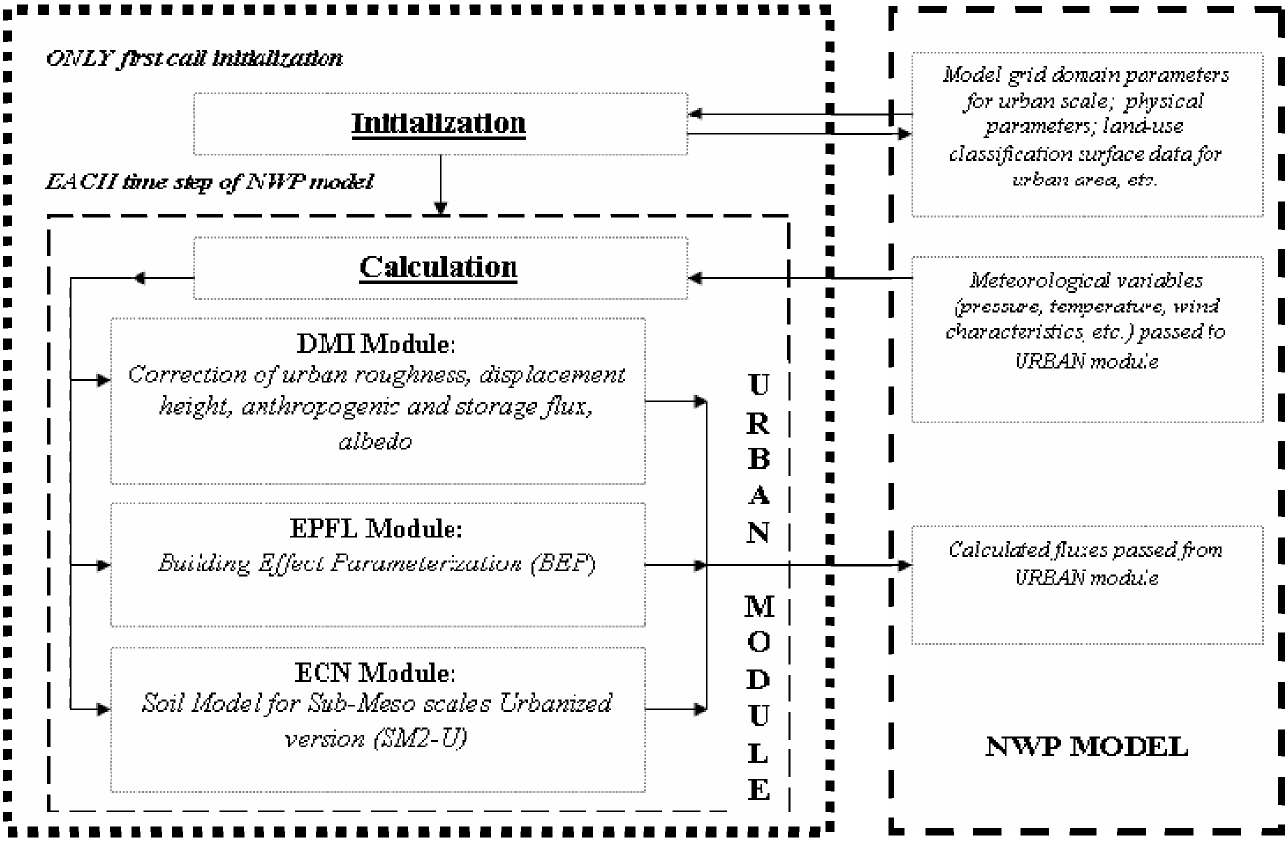
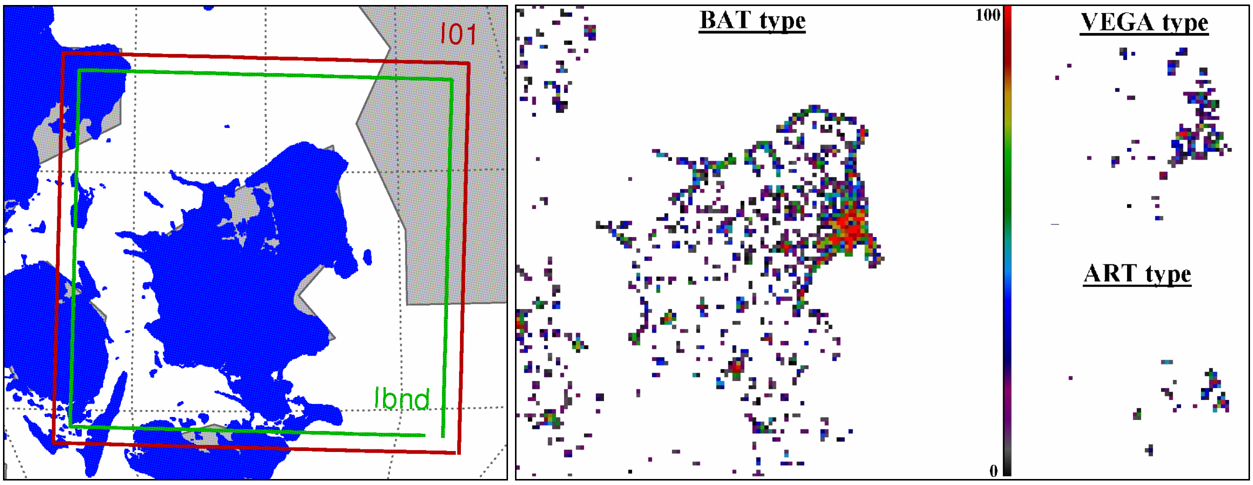


Figure 1. General scheme of the DMI-HIRLAM NWP urbanization.



(a) (b)

Figure 2. (a) Boundaries of the DMI-HIRLAM-I01 modelling domain and (b) spatial distribution of the urban related types of covers/surfaces in grid cells of modelling domain: BAT type - buildings/roofs; VEGA type - vegetation over paved surfaces; and ART type - paved surfaces located between the sparse vegetation elements) over the Copenhagen metropolitan area (percentage of urban class in each cell is given on 0-100% scale).

3.3 Building Effect Parameterization (BEP) Module

The Building Effect Parameterization (BEP) module includes the urban sub-layer parameterization suggested by *Martilli et al. (2002)* with modifications for implementation into

NWP models and several further improvements (e.g., *Hamdi & Shayes, 2005; Baklanov et al. 2005b*). The aim of the urban sub-layer parameterization developed at the EPFL is to simulate the effects of buildings on a meso-scale atmospheric flow. It takes into account the main characteristics of the urban environment such as: 1) vertical and horizontal surfaces (wall, canyon floor, and roofs), 2) shadowing and radiative trapping effects of the buildings, 3) anthropogenic heat fluxes through the building walls and roofs. In this parameterization, the city can be represented as a combination of several urban classes. Each class is characterized by an array of buildings of the same width located at the same distance from each other, but with different heights. To simplify the formulation the length of the street canyons is assumed to be equal to the horizontal grid size. The vertical urban structure is defined on a numerical grid.

The scheme of BEP calculations inside the DMI-HIRLAM NWP model is shown in Fig. 3. The urban sub-layer parameterization is composed of two subroutines. The structure of NWP models starts generally with an initialization step. During initialization, the model grid domain parameters, physical parameters, urban class fractions, and etc. are once read. The values of urban parameters for each of defined urban classes are priory given. These include sets of the building, radiation, roughness, street configuration, etc. related parameters. The thermal diffusivities, specific heats of materials, albedo and emissivities, roughness lengths for three types - walls, roofs, and ground - are given. The direction, lengths, and widths of streets for each urban class are given too. Moreover, the building's height and width as well as probabilities that a building has such heights were also specified. The initial temperature inside the buildings behind the walls and roofs are specified. Following the initialization, the program computes successively the pressure, advection and turbulent viscosity-diffusivity for each time step and each cell. The urban routine computes the urban effects for the diffusion-viscosity resolution within the turbulence part of the code. The calculation are done for the momentum, heat, and turbulent kinetic energy fluxes produced by buildings in urban cells of modelling domain.

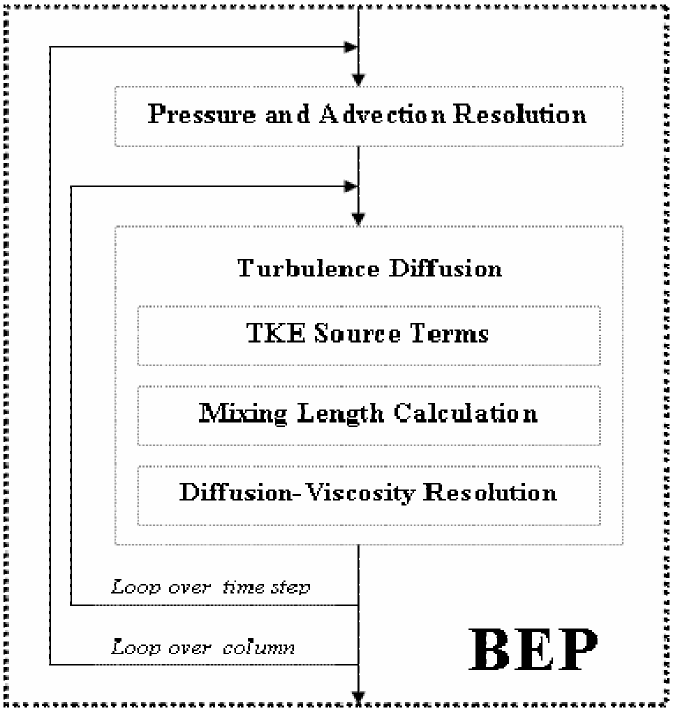


Figure 3. Scheme of BEP calculation done within the NWP model.

3.4 Soil Model for Sub-Meso scales Urbanized version (SM2-U) Module

The Soil Model for Sub-Meso Scales Urbanized version (SM2-U) is the urban extension of the force-restore model of *Noilhan & Planton (1989*). It is composed with 3 soil layers and a canopy layer. In each computational cell at the ground, 7 types of covers/surfaces are defined by their characteristics and urban surface density. The horizontal exchanges inside the urban canopy are not considered except radiation reflections and water runoff from saturated surfaces. The deep soil temperature and water content remain constant during the day. For temperature evolution of buildings and water surfaces a simple conduction equation is used, without force-restore process. Important processes like radiative trapping inside the street canyon are parameterized by an effective albedo of the street. The surface dynamical influence is represented through roughness lengths and displacement heights. Energy and water budgets are performed for each type of surface in order to deduce the heat and moisture fluxes to be set at the interface between canopy and atmosphere. The detailed description of the model and its validation results are given by *Dupont (2001), Dupont et al. (2004, 2005ab).* A modified version of SM2-U for the FUMAPEX meso-meteorological models is described by *Baklanov et al. (2005a).* Simulation results of typical climatological fluxes, surface temperatures, etc. for the Copenhagen metropolitan area are given by *Mahura et al. (2005b).*

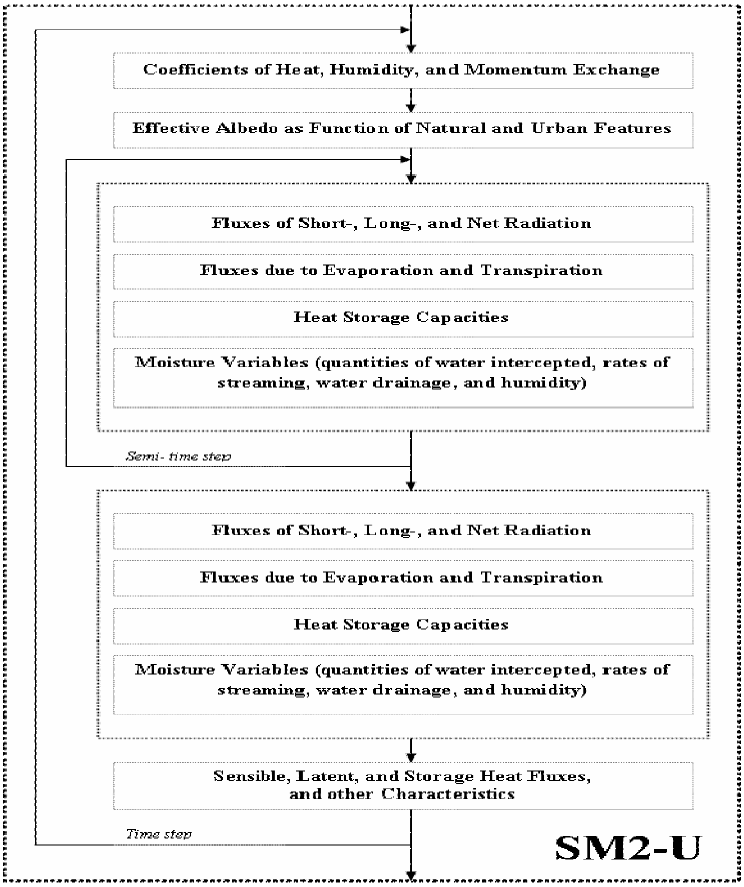


Figure 4. Scheme of SMU-2 calculation done within the NWP model.

The scheme of SM2-U implementation into the DMI-HIRLAM NWP model is shown in Fig. 4. During initialization, the model grid domain parameters for urban scale including latitudinal vs. longitudinal grids, time and space steps, physical parameters; land-use classification surface data for selected modelling domain including types of surfaces, their fractions and contribution into grid cells; building's temperature in domain, and etc. are once processed. Since NWP model does not provide detailed information on temperature and humidity characteristics of different types of surfaces, the list of initialized variables used during the initial time step of simulation includes the reading of 2D surface fields from the prepared surface data file. After initialization of 2D fields for these variables, the calculation of potential temperature, specific air humidity at saturation, dynamical velocity, roughness, etc. for different types of surfaces is done. Then, at each time step, the calculation is done for the urban surface temperature and moisture contents by solving the surface energy and moisture budget equations, and estimates the latent, sensible, and heat storage fluxes for different types of cover/surfaces at the grid points of domain. A set of other subroutines is used to calculate: 1) coefficients of heat, humidity, and momentum exchange; 2) radiative fluxes of short-, long-, and net radiation; 3) fluxes due to evaporation and evatranspiration; 4) effective albedo of the walls and streets; 5) incoming solar radiation and zenithal angle of the sun, and etc.

3.5 DMI-HIRLAM high resolution modelling and urbanization tests

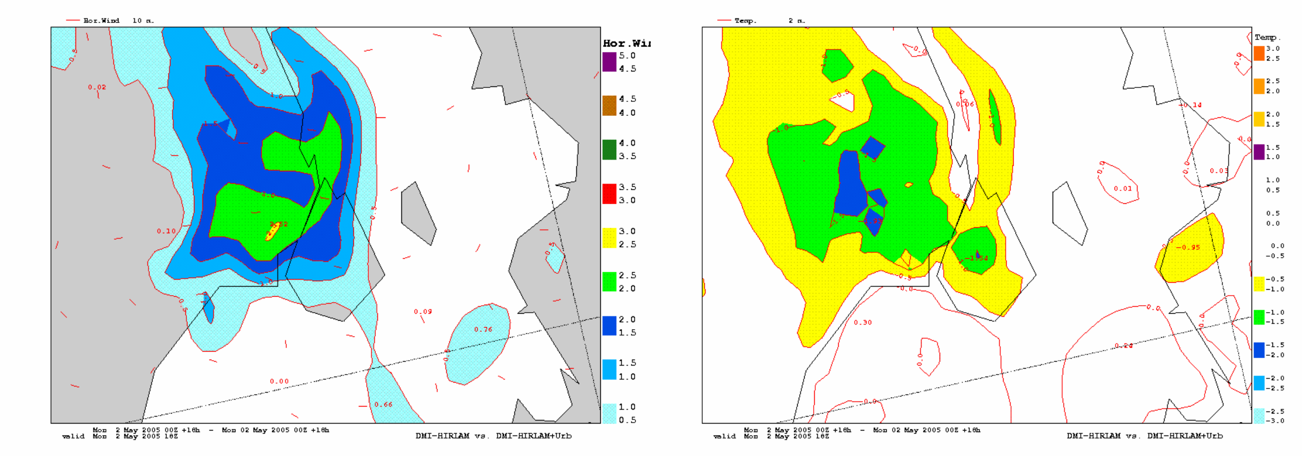
Several tests of DMI-HIRLAM were done in FUMAPEX (*Baklanov et al., 2002*). Since spring of 2004, for a new high resolution model called DMI-HIRLAM-I01 (for the Sjælland Island with the Copenhagen metropolitan area, Fig. 2a), the preparation of land-use classification and climate generation files were done. This model was also used for urbanization with both the BEP and SM2-U modules. Moreover, during spring-summer of 2005 the DMI-HILRLAM-U01 model (for whole Denmark) was run daily to estimate performance of high resolution modelling over territory of Denmark and surroundings (*Mahura et al., 2005b*) and in addition several typical specific cases/dates during this period were run employing the high resolution model urbanized with different modules. The meteorological fields' simulations were driven using boundary conditions of the DMI-HIRLAM-S05 model. The simulated output for selected dates (+ 24 hour forecast) was evaluated for the Copenhagen metropolitan area. The diurnal cycle of meteorological variables such as wind velocity (at 10 m) and temperature (at 2 m) as well as latent and sensible heat fluxes were analyzed comparing outputs of the control run vs. urbanized runs. At each UTC term, the difference fields on a 2D plane for mentioned variables were produced by subtracting outputs from the control run without any changes made vs. run with urbanization made.

3.6 Results of tests for Copenhagen

The sensitivity tests and verification of the simplified approach of the DMI-HIRLAM NWP urbanization were performed using high resolution (1.4 km) research version for the Copenhagen metropolitan area and surroundings. Independent runs were performed for several specific cases: (i) one control run with no modifications in the ISBA surface scheme (*Noilhan & Planton, 1989*); (ii) a modified urbanized version including urban roughness (up to 2 m when the urban class is 100% in a grid-cell) and anthropogenic heat fluxes (up to 200 W/m^2). Several results are discussed.

For 30 March 2005, the comparison of simulated and observed diurnal cycle at the urban Værløse station (55.8ºN, 12.3ºE) located in central Copenhagen showed that the diurnal variability of the wind direction was modeled in all runs with practically no differences between the control and modified runs. Inspecting the wind velocity daily cycle at an urban station shows that between 07-19 UTC the run with the AHF reflects better the observed local maximum than the run with urban roughness, which alternatively better fits the observed local minimum. This means that the combined effect of both roughness and AHF should be included. Note, for the suburban station, the modification including the improved roughness showed a better fit to observational data compared with all other runs. For temperature, the fit to observations was better for the urban station for the modified run with the AHF. Modifications of roughness did not improve the fit. Since the storage heat flux was not included, a time shift of the temperature field is observed in the diurnal cycle, especially during the transitional morning and evening periods. The objective hysteresis model (*Grimmond et al., 1991*) can improve this shortcoming.

The urbanization of DMI-HIRLAM with more complex modules represented in Fig. 1 showed the following results. For example, during 12 April 2005, for wind velocity the effect of urbanization was pronounced over the Copenhagen metropolitan area. Note, throughout the day differences in wind velocities reached a maximum of more than 3 m/s (08-09 UTCs). Such difference was lower during the daytime with a minimum of less than 0.1 m/s at noon. For temperature, the highest difference of -1.4ºC was observed at 21 UTC (i.e. the urbanized version of NWP model showed the higher temperatures compared with non-urbanized). Moreover, this difference was almost negligible at noon, and it was lower than 0.2ºC during 09-15 UTCs. For the sensible heat fluxes, the difference was positive during 09-21 UTCs, with values higher than +100 W/m^2 between 15-18 UTCs. The difference became negative during 23-06 UTCs reaching a minimum of -125 W/m^2 at 06 UTC. For the latent heat fluxes, the difference was always positive during the day, except it became negligible (less than 0.5 W/m^2) during 18-21 UTCs. The maximum value of 11.5 W/m^2 was observed at 06 UTC.



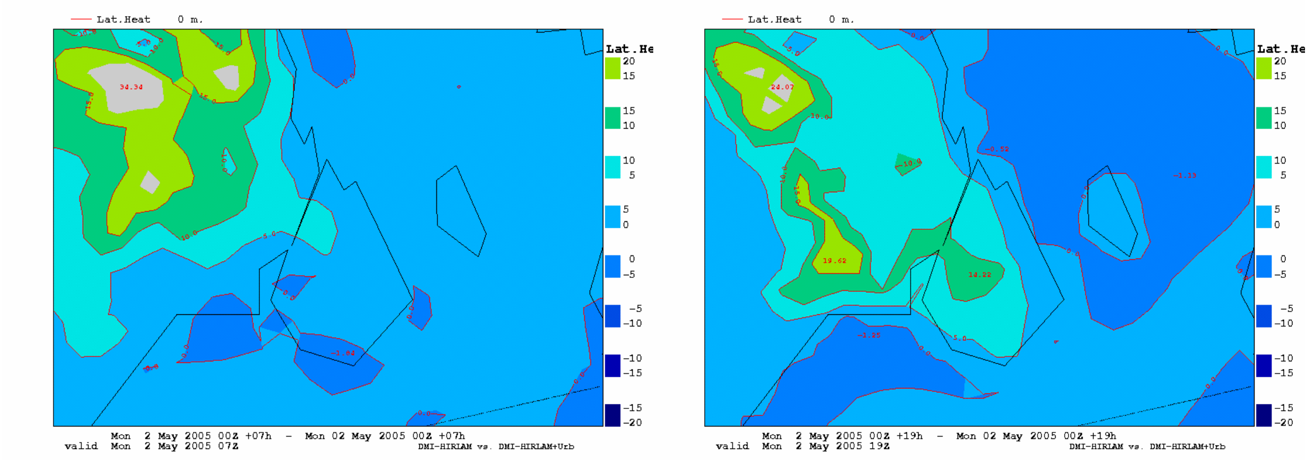
(a) (b)

Figure 5. Difference plots (between outputs of the DMI-HIRLAM vs. DMI-HIRLAM +Urb) for (a) wind velocity at 10 m and (b) air temperature at 2 m for forecasts at 18 UTC, 2 May 2005.

For the other example (2 May 2005) the difference plots for wind velocity at 10 m and air temperature at 2 m are shown in Fig. 5. The effect of urbanization was the best seen over the Copenhagen metropolitan area. Throughout the day, the highest differences in wind velocities reached 2.5 m/s at 18 UTC. Such difference was lower during the daytime (0.5 m/s at noon), and it was less than 1 m/s during 06-15 UTCs. For temperature, the higher differences of 1.5ºC were observed during 18-05 UTCs (maximum of 2.3 at 24 UTC). Moreover, this difference was the lowest (0.5ºC) at 12 UTC. For the latent heat fluxes, the difference plots at the morning and evening hours are shown in Fig. 6. The difference was positive during night and early morning hours, with the highest value +20 W/m^2 at 06 UTC. The highest negative difference (-24 W/m^2) was observed at 18 UTC in the south-western part of the Copenhagen metropolitan area. Moreover, no difference was observed between the urbanized vs. non-urbanized runs during 11-16 UTCs.

It can be summarized that in specific meteorological situations the urban effects may be of considerable importance over the large metropolitan areas such as Copenhagen. The urbanization gives a possibility to incorporate these effects into high-resolution NWP modelling.

The first module is the cheapest way of "urbanizing" the model and can be easily implemented into operational NWP model. The second module is a relatively more expensive (≈ 5-10 % computational time increase), but it gives a possibility to consider the energy budget components and fluxes inside the urban canopy. However, this approach is sensitive to the vertical resolution of NWP models and is not very effective if the first model level is higher than 30 meters. Therefore, an increase of the vertical resolution of current NWP models is required. The third module is considerably more expensive computationally than the first two modules (although it can optimized calculating only for the urban cells). However, it provides the possibility to accurately study the urban soil and canopy energy exchange including the water budget. Therefore, the second and third modules can be recommended for use in advanced urban-scale NWP models. Moreover, the first and second modules can be also realized as urban interfaces or post-processors of NWP data for urban air quality models making a link between the numerical weather forecasting and air pollution modelling communities.



(a) (b)

Figure 6. Difference plots (between outputs of the DMI-HIRLAM vs. DMI-HIRLAM +Urb) for the latent heat flux for (a) 07 UTC and (b) 23 UTC forecasts on 2 May 2005.

Further, evaluation of the urbanized DMI-HIRLAM NWP model is needed on the longer time periods and various meteorological conditions (especially, with a focus on the low wind conditions and precipitation). In particular, DMI additionally already prepared the boundary files data for July-August 2004 and May-August 2005 for future simulations employing the NWP model urbanized with the SM2-U as well as BEP modules. The analyses of simulated fluxes (served as input into the NWP model), urban modules performances, CPU usage, and other capabilities are planned.

4. Conclusions and recommendations

For the DMI-HIRLAM NWP model different parameterizations of the urban sublayer have been analyzed and tested. Several urban modules (developed by the DMI, EPFL, and ECN teams of the EU FUMAPEX project) have been suggested, and these can be chosen depending on a specific problem, model resolution, or metropolitan area. The DMI module is based on corrections of the surface roughness for urban areas and urban heat fluxes complemented with an analytical model for wind velocity and diffusivity profiles inside the urban canopy (*Zilitinkevich & Baklanov*, *2005*). The EPFL module is based on the urban sub-layer model (*Martilli et al.*, *2002; Hamdi & Schayes, 2005*) called Building Effect Parameterization (BEP) with special physical parameterizations of the urban surface exchange for the urban sub-layer implemented into (or after) the NWP model. The ECN module is based on the full force-restore soil submodel for urban areas (*Dupont & Mestayer, 2004; Dupont et al.*, *2005ab*) called the Soil Model for Sub-Meso scales Urbanized version (SM2-U). Note, the urban canopy models can also be implemented as an interface/post-processor module, separated from the NWP model. For the urban air pollution modelling/forecasting this can be very useful, but this procedure excludes any urban feedback in the NWP model.

It was found that implementation of the urban modules can improve the forecasted meteorological fields for urban areas in some specific cases. Simulation results with these urban modules showed that the radiation budget does not differ significantly for urban vs. rural surfaces, as the increased loss of a net thermal longwave radiation is partly compensated by a gain in net shortwave radiation due to a lower albedo. The turbulent fluxes of sensible and latent heat, as well as their ratio are variable, depending in particular on the amount of rainfall that fell during the preceding period. The storage heat flux usually is significantly higher in urban areas compared to densely vegetated surfaces. This cannot be explained entirely by a higher thermal inertia, as this quantity is only slightly higher for urban vs. rural environments. Other factors of importance are the low moisture availability and the extremely low roughness length for heat fluxes. The anthropogenic heat flux is a most typical urban energy component as it is absent over rural or natural surfaces.

The current versions of the considered urban modules have several shortcomings and have to be improved and further developed. For the first module, the complemented analytical model for wind velocity and diffusivity (as well as further for temperature and humidity) profiles inside the urban canopy has to be tested and verified vs. experimental data for different regimes. At present, the BEP module does not consider moisture and latent heat fluxes and does not completely incorporate the anthropogenic heat flux. Besides, recalculation of accessible meteorological fields in the lowest sub-layers is necessary. The SM2-U module needs further consideration of the building drag effect, whereas snow and ice have to be included for NWP modelling during winter periods.

It is obvious that these developments in process parameterizations and model resolution require more adequate data for validating, improving, and initializing NWP models. Hence, in the future there is a need to carry out urban field campaigns in order to provide data (to gain insights for development of simpler modules and parameterizations). Moreover, a potential of remote sensing methodologies and satellite observations should also be better explored and applied.

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