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► **To cite this version:**

A. Baklanov, P. Mestayer, A. Clappier, S. Zilitinkevich, S. Joffre, et al.. On the parameterisation of the urban atmospheric sublayer in meteorological models. *Atmospheric Chemistry and Physics Discussions*, 2005, 5 (6), pp.12119-12176. hal-00327985

**HAL Id: hal-00327985**

**<https://hal.science/hal-00327985v1>**

Submitted on 18 Jun 2008

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# On the parameterisation of the urban atmospheric sublayer in meteorological models

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Received: 1 September 2005 – Accepted: 27 September 2005 – Published: 24 November 2005

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## Abstract

The increased resolution of numerical weather prediction models allows nowadays addressing more specifically urban meteorology and air pollution processes and forecasts. This has triggered new interest in modelling and describing experimentally the specific features and processes of urban areas. Recent developments and results performed within the EU-funded project FUMAPEX on integrated systems for forecasting urban meteorology and air pollution are reported here. Issues of optimum resolution, parameterising urban roughness and surface exchange fluxes and the role of the urban soil layers are addressed with advanced meso- or sub-meso meteorological models. Recommendations, especially with respect to advanced urban air quality forecasting and information systems, are given together with an assessment of the needed further research and data.

## 1. Introduction

During the last decade, substantial progresses in both meso-meteorological and numerical weather prediction (NWP) modelling and the description of urban atmospheric processes have been achieved. For instance, state-of-the-art nested NWP models can use land-use databases down to 1 km resolution or finer, enabling to provide high quality urban meteorological data. Thus, NWP models are now approaching the necessary horizontal and vertical resolution to provide weather forecasts for the urban scale (e.g. Baklanov et al., 2002).

Many urban features can influence the atmospheric flow, its turbulence regime, the microclimate, and, accordingly modify the transport, dispersion, and deposition of atmospheric pollutants within urban areas, namely:

- Local-scale non-homogeneities, such as sharp changes of roughness and heat fluxes;

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- Sheltering effects of buildings on the wind-velocity;
- Redistribution of eddies, from large to small, due to buildings;
- Trapping of radiation in street canyons;
- Effect 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 the urban mixing height;
- Effects of pollutants (including aerosols) on urban meteorology and climate;
- Urban effects on clouds and precipitation.

Despite the increased resolution and various improvements, current operational NWP models still have several shortcomings with respect to urban areas, such as:

- Urban areas are mostly described by similar sub-surface, surface, and boundary layer formulations as for rural areas.
- These formulations do not account for specific urban dynamics and energetics or for their impacts on the simulation of the atmospheric urban boundary layer (UBL) and its intrinsic characteristics (e.g. internal boundary layers, urban heat islands, precipitation patterns).
- Additionally, NWP models are not primarily developed for air pollution and emergency modelling, and their outputs need to be designed as suitable input for such urban-scale models.

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Nevertheless, in recent years, a number of parameterisation schemes have been developed to estimate the components of the surface energy balance (net radiation, sensible heat flux) and other UBL parameters. For instance, the COST-715 Action (Fisher et al, 2005a, b; Piringer and Joffre, 2005) reviewed several approaches for the specific treatment of UBL features and surface energy budget (SEB).

A palette of urban SEB schemes and models are now available (e.g., Oke et al., 1999; Grimmond and Oke, 1999a; Masson, 2000; Dupont, 2001; Martilli et al., 2002), but they have not all been validated to the same degree. They range from simple transformations of some key coefficients in exchange schemes developed for natural surfaces to detailed modules computing quasi-explicitly the radiative and turbulent energy exchanges of each built element category, e.g., the ground surface, walls and roofs, treated in group by type. Furthermore, even more detailed models and software are available to compute the thermo-radiative budgets of, or interactions with, elemental building surfaces. These tools may be used to analyse experimental data from validation campaigns, to run numerical experiments for urban areas, or to perform sensitivity analysis studies. Some of the SEB developments were derived from, e.g., the SOLENE (Groleau et al., 2003), POV RAY (Lagouarde et al., 2002), and DART (Gastellu-Etchegorry et al., 2004) studies.

The development and validation of these SEB models brought to light and helped to quantify several specificities of the urban canopy energetics:

- Net radiation varies in time at the local scale with solar orientation and in space with district morphology, which is not much different from its rural counterpart on average;
- The diurnal cycle of the turbulent sensible heat flux is large but highly variable, strongly dependent on district structure, and often positive at night. In the dense city centres, this flux is limited by a strong aerodynamic resistance (high zom/zot roughness length ratio), favouring heat storage;
- A large heat storage in building materials, rather than in the ground, as a function

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of building density and morphology;

- A low but highly variable latent heat flux;
- A hysteresis in the diurnal cycles, with phase lags between the energy budget components due to heat being diverted from the budget and provisionally stored in the building materials in the morning at the expenses of the sensible heat, while the stored heat is released in the evening and at night.

Therefore, to improve meteorological forecasts for urban areas and to provide the high-resolution meteorological fields needed by urban air quality (UAQ) models, it is required to implement specific urban surface layer and surface energy balance parameterizations into meso-meteorological and NWP models, or so to speak to ‘urbanise’ these models.

The improvement of UBL formulations and parameterisations using urban physiographic data classifications in NWP models together with the evaluation of the induced improved simulation of urban meteorology for NWP and UAQ forecasting is one of the main aims of the EU-funded FUMAPEX project (Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure; Baklanov et al., 2005<sup>1</sup>). This paper reviews works and advances achieved within FUMAPEX with respect to: (i) Finer spatial grid resolution and model downscaling; (ii) Detailed physiographic data and land-use classification; (iii) Calculation of effective urban roughness; (iv) Estimation of urban heat fluxes; (v) Urban canopy and soil sub-models.

<sup>1</sup>Baklanov, A., Hänninen, O., Slørdal, L. H., Kukkonen, J., Sørensen, J. H., Bjergene, N., Fay, B., Finardi, S., Hoe, S. C., Jantunen, M., Karppinen, A., Rasmussen, A., Skouloudis, A., and Sokhi, R. S.: Integrated systems for forecasting urban meteorology, air pollution and population exposure, Atmos. Chem. Phys. Discuss., submitted, 2005.

## 2. FUMAPEX methodology for urbanization of city-scale meteorological models

The FUMAPEX strategy to improve NWP and meso-scale meteorological models includes the following aspects for the urbanisation of relevant submodels or processes:

- (i) Model down-scaling, including increasing vertical and horizontal resolution and nesting techniques (one- and two-way nesting);
- (ii) Modified high-resolution urban land-use classifications, parameterizations and algorithms for roughness parameters in urban areas based on the morphologic method;
- (iii) Specific parameterization of the urban fluxes in meso-scale models;
- (iv) Modelling/parameterization of meteorological fields in the urban sublayer;
- (v) Calculation of the urban mixing height based on prognostic approaches.

Apart the Urban Air Quality Information and Forecasting Systems (UAQIFS) per se, improved urban meteorological forecasts will also provide information to city management regarding additional hazardous or stressing 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.

The following meso-meteorological and NWP models of FUMAPEX partners were used for urban conditions or for different variants of the 'urbanisation' scheme (user/developer teams are in brackets, cf. Appendix): 1. DMI-HIRLAM (DMI); 2. Local Model LM (DWD, MeteoSwiss, EPA Emilia-Romagna); 3. MM5 (CORIA, met.no, UH); 4. RAMS (CEAM, Ariantet); 5. Topographic Vorticity-Mode (TVM, Schayes et al., 1996) Mesoscale Model (UCL); 6. Finite Volume Model FVM (EPFL); 7. SUBMESO model (ECN).

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## 2.1. Increased grid resolution and nesting of NWP models

Increased computer power and the implementation of grid nesting techniques allowed modern NWP models to approach the resolution necessary for the city-scale. The FUMAPEX strategy for improving UAQIFS includes, first of all, increasing model resolution and down-scaling (with one- or two-way nesting) of NWP models with different resolutions (Fig. 1).

For example, the recent Danish operational NWP system (Sass et al., 2002) consists of several nested models named DMI-HIRLAM-S05 and –T15, with horizontal resolutions of 5 and 15 km, respectively. The previous nested versions G45, E15 and D05 (operational prior to 14 June 2004) had 45, 15 and 5 km resolution, correspondingly. The vertical resolution of the operational versions is 40 levels, but it was increased up to 60 levels for test runs. In FUMAPEX, DMI runs also several experimental versions of DMI-HIRLAM (e.g., U01, I01) with a horizontal resolution of 1.4 km over Denmark and the Sjælland Island, where the city of Copenhagen is located (Baklanov et al., 2002; Fay et al., 2005; Mahura et al., 2005a).

The German DWD Local Model LM (Doms and Schättler, 1999) is currently operated as a nest within the Global Model for Europe. LM has a resolution of 7 km for the Central and Western Europe. In 2003, it became operational for that area with a resolution of 2.8 km. For the FUMAPEX study, both the horizontal and vertical resolution of LM were increased to 1.1 km and 43 layers, respectively, as required by the 1-way self-nesting version of LM (Fay and Neunhaeuserer, 2005).

In Norway, the non-hydrostatic MM5 model (Grell et al., 1994) is nested with the HIRLAM NWP model (Berge et al., 2002). The latter model is operated on a 10 km horizontal resolution for North-Western Europe. A domain with a resolution of 3 km has been set up for the region around the city of Oslo in which MM5 is one-way nested with HIRLAM. A two-way nesting takes place between the 3 km resolution domain and a 1 km resolution area covering Oslo. The MM5 output is input to the Air Quality Model of the Norwegian Institute for Air Research.

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FUMAPEX partners performed verification and sensitivity studies with their NWP models versus measurement data for several episodes in different European cities: Helsinki, Oslo, Bologna, Valencia, Copenhagen (Neunhaeuser et al., 2004; Fay et al., 2005; Baklanov et al., 2005b). Results for the verification of the LM model using different resolutions are discussed by Fay and Neunhaeuser (2005) and for the Norwegian urban nested MM5-HIRLAM system by Berge et al. (2002). Verifications for high-resolution versions of the DMI-HIRLAM modelling system were carried out for Copenhagen by Baklanov et al. (2005) and Mahura et al. (2005a).

Figure 2 presents one example of the verification results for the DMI-HIRLAM-U01 research model with a 1.4-km resolution for May 2005. It shows better prediction of the diurnal cycle of the average wind velocity at 10 m than with the S05-version.

The verification runs underlined that increasing the resolution (down to 1 km) brings some improvement to the skill of the meteorological forecast. Nevertheless, it will be also very important for further improvements to have more detailed surface features databases and to increase the quality of the land-use classification (LUC) for urban areas.

## 2.2. Urban land-use classification and algorithms for roughness parameters

Surface characteristics such as albedo, thermal properties, roughness, or moisture availability significantly control the surface energy balance partitioning of any type surface. In contrast to most natural surfaces, urban landscapes show a much larger range and variability of surface characteristics. However, most of the NWP and meso-meteorological models still do not consider any urban class at all, or include only one urban class for all types of urban surfaces. In view of the wide range of urban surface types, it is not possible to single out one set of universal urban surface values, which would be valid for all types of urban neighbourhoods worldwide. Therefore, much more detailed surface information than in existing NWP models is needed.

Typical surface characteristics can be attributed to distinct *categories* of urban neighbourhoods. Such a classification can be performed based on land use maps or aerial

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photos. Digital LUC datasets can help to define different urban classes and are a source of increasing importance. Unfortunately, most LUCs are classified by functional aspects (residential, industrial) and not by surface morphometry or surface cover. Focussing on meteorological aspects, Ellefsen (1991) classified North American cities into 17 Urban Terrain Zones (UTZ) according to building contiguity, construction, and materials. Fehrenbach et al. (2001) have automated the classification of urban climatological neighbourhoods from satellite image analysis. However, no universal classification scheme exists. Historical development results in a huge variety of urban neighbourhood types worldwide. The more complete a description scheme is, the more it is restricted to a specific (historical) region, e.g., UTZs are difficult to apply to European cities because typical morphometry and building materials are different.

An appropriately chosen set of *surface parameters* can be related to specific physical processes. For example, it is not surprising that the area covered by vegetation drives the magnitude of the latent heat flux, or that morphometric parameters help to describe the roughness and turbulence characteristics over a particular urban surface. Therefore, the following three most important characteristics can be outlined (cf. Piringer and Joffe, 2005, for a summary).

(i) The *Urban cover*: Two dimensional plan aspect ratios (“plan area fractions”) describe the 2-D 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. It can also include dominant street directions in a grid cell.

(ii) The *Three dimensional structure*: 3-D morphometric parameters describe the configuration of urban buildings (it can include vegetation as well). They are used in the BEP model to parameterize drag and turbulence production (see Sect. 4) or in the SM2-U model to simulate storage heat flux densities and surface temperatures (see Sect. 5). The most important morphometric parameters to be used in urban meteorology models include: the mean building height, frontal aspect ratio, surface enlargement, normalized building volume, characteristic inter-element spacing, canyon width, building breadth, etc. For many cities, authorities provide digital 3-D building data sets, which are a

powerful tool for the analysis of urban surface forms. Such high resolution data can provide detailed measures of 3-D parameters, and additionally vertical profiles, e.g., of building volume density and sky view factors.

(iii) *Urban materials*: This information (e.g., construction materials of buildings roofs and walls) is of great importance especially for the estimation of radiative properties (e.g. surface albedo) and the determination of storage heat flux densities. Detailed analysis of aerial photos or field surveys can provide the necessary information.

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, ranking these aerodynamic characteristics depends on the model intrinsic requirements for input data. Bottema and Mestayer (1998) and Grimmond and Oke (1999b) reviewed methods to deduce aerodynamic properties from a set of morphometric parameters. Tests of the models against individual datasets showed poor performances. The simplified model of Bottema (1997) gave relatively better results and additionally can be applied across the full range of building density parameters. Considering its relatively low input requirements, it is an efficient alternative. More simple models cannot be recommended, especially due to their limited range of applicability. As to the “recommended rule of thumb” of Grimmond and Oke (1999b), one should keep in mind that it does not include any building density dependency of roughness and, therefore, will overestimate roughness for low and high densities, and underestimate it at medium densities.

With morphologic methods a more empirical and pragmatic approach can be considered, based on the visual observation of the physical structure of the urban canopy (e.g., from aerial photography). From survey of experimental data, Grimmond and Oke (1999b) offered a first-order evaluation of the roughness parameters of urban zones, separated into only 4 categories. These categories are associated with 4 flow regimes: (1) Low height and density – isolated flow; (2) Medium height and density – wake interference flow; (3) Tall and high density – skimming flow; (4) High rise – chaotic or mixed

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flow.

Ellefsen (1991) designed a scheme to identify 17 types of urban terrain zones that are defined by a written description and model photography. Furthermore, Grimmond and Oke (1999b) adapted this scheme to their proposed 4 urban roughness categories, offering physical description, matrix of typical photographs, and table of the most probable non-dimensional roughness parameters. For the above mentioned categories the classical Davenport classification of effective terrain roughness was revised by including explicitly the urban terrains (Davenport et al., 2000; Mestayer and Bottema, 2002).

Depending on the choice of the urbanisation approach (see Sect. 2.3) different urban LUCs are possible. In our studies for different cities, from 3 to 9 types of urban types were considered. Figure 3 presents two examples of the urban land-use classification, prepared following the above mentioned improved morphologic method, for the Copenhagen and Marseilles urban areas. The urban topographic databases BDTopo (French National Geographic Institute) for Marseilles and the AIS Land-use database (Danish Environmental Research Institute) for Copenhagen were used to analyse urban structures in order to characterise the morphology of settlements and land coverage (Long et al., 2002; Mahura et al., 2005b). The accuracy of the computed descriptive statistics was estimated for different sizes of grid cells. It was found that individual cells of 200×200 m represent best the structure of each urban district with respect to both high resolution and statistical representativeness (Long, 2003). Therefore, mean variables describing the buildings morphology and land covers were computed for this size cells onto a grid and composed as layer themes in GIS: building average height, perimeter, volume, compactness; plan area, vegetation and pavement densities, etc.

### 2.3. Urban fluxes and sublayer parameterisation

Simulating urban canopy effects in urban-scale NWP and meso-meteorological models can be considered with the following two main approaches:

1. Modifying the existing non-urban approaches (e.g., the Monin-Obukhov similarity

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theory MOST) for urban areas by finding proper values for the effective roughness lengths, displacement height, and heat fluxes (adding the anthropogenic heat flux (AHF), heat storage capacity and albedo change). In this case, the lowest model level is close to the top of the urban canopy (displacement height), and a new analytical model is suggested for the urban roughness sublayer which is the critical region where pollutants are emitted and where people live (Zilitinkevich and Baklanov, 2005).

2. Alternatively, source and sink terms are added in the momentum, energy and turbulent kinetic energy equation to represent the effects of buildings. 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), the heat, the momentum and the turbulent fluxes inside the urban canopy, considering a simple geometry of buildings and streets (3 surface types: roof, wall and road).

In a first stage, three FUMAPEX modules for NWP model urbanisation (Fig. 4) were developed for further testing and implementation into NWP models or their post-processors. It included the following modules:

1. The DMI module: Based on the first approach, it includes a new diagnostic analytical parameterisation of the wind profile into the urban canopy layer (Zilitinkevich and Baklanov, 2005) and corrections to the surface roughness (with the incorporation of the displacement height) for urban areas and heat fluxes (adding the additional AHF, e.g., via heat/energy production/use in the city, heat storage capacity and albedo change) within existing physical parameterisations of the surface layer in NWP models with higher resolution and improved land-use classification. It is realised in the city-scale version of the DMI-HIRLAM model.

2. The EPFL module of the Building Effect Parameterisation (BEP): Based on the second approach and the urban surface exchange parameterisation submodel

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(Martilli et al., 2002). It was first tested with the research meso-meteorological FVM and TVM models and now is considered for incorporation into the DMI-HIRLAM and LM NWP models.

3. The ECN module: Based on the detailed urban area soil and sublayer SM2-U model (Dupont, 2001; Dupont et al., 2005). It was first tested with the large eddy simulation SUBMESO research model and is also considered for incorporation into the DMI-HIRLAM NWP model.

Additionally to the above mentioned approaches, the flux aggregation technique of Hasager et al. (2003) was installed in the DMI-HIRLAM model for non-homogeneous surfaces. However, it has not yet been tested for urban areas.

The main idea of our urban module architecture was to build it as much as possible independently of the type of NWP models, and to allow a simple implementation into different models. Note that it is not possible to build it as a completely independent module, but the urban modules were modified substantially to satisfy the main requirements and formats of NWP models.

There is also freedom on how to implement the module: either to incorporate it inside the NWP model code or to call the separate module from the NWP code. The algorithm to call the module by the NWP model is presented in Fig. 4. The initialisation module is called only once when the model is initialised for simulations, and then the urban modules (1, 2, 3 or 4) – on every time step during the simulation.

The urban canopy modules can be built as an interface/post-processor module separated from the NWP model. In such case, the urban sublayer model will be run separately (using previously simulated NWP data as a first approximation) and will improve the meteorological fields in an area close to and inside the urban canopy with higher resolution (cf. one example in Sect. 4). Obviously, such a strategy is less promising, because it does not yield any improvement of the meteorological forecast in urban areas and cannot allow feedbacks. For UAQ modelling/forecasting and improvements of UAQIFS, this approach can, however, be very useful and easier to implement, be-

cause it does not require any modification of the operational NWP model (which is usually complex and time-demanding). Thus, in such a novel approach for improving the FUMAPEX UAQIFS strategy, one can consider the urban sublayer modules (including several upper layers and surrounded areas) as interface modules between the NWP and UAQ models.

### 3. Approach based on improved urban roughness and fluxes

The first simplest urban module (the DMI module of the FUMAPEX ‘urbanization’ scheme in Fig. 4) is based on the following requirements: (i) to be relatively cheap computationally and as close as possible to the parameterisations of the surface/boundary layer in the parent NWP models, (ii) to split the surface layer over urban areas into two/three sub-layers (see Fig. 4 in Fisher et al., 2005b). This split distinguishes: (i) the roughness layer (including logarithmic layers), where MOST can be used with correction to the urban roughness, and (ii) the urban canopy layer, where MOST does not work and new analytical parameterisations 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 model grid having urban features:

- (i) Land-use classification, including at least one urban class and several urban sub-classes;
- (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,

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- (vi) Urban storage heat fluxes by the Objective Hysteresis Model (OHM, Grimmond et al., 1991) or specific roughness lengths for heat and moisture;
- (vii) Albedo correction for urbanised surfaces;
- (viii) Prognostic mixing height parameterisations;
- (ix) Parameterisation of wind and eddy profiles within the canopy layer.

It is reasonable to use this approach for relatively cheap simulations and for NWP models with a low vertical resolution (first computational vertical level is higher than 20 m), when other more complex models of the urban sub-layer (e.g., BEP and SM2-U) would not much affect results or would be too expensive 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.

### 3.1. 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 urbanisation of NWP model. To avoid or minimise 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 characterised by, at least, two parameters: the roughness length and the displacement height. Theoretical aspects of such an approach were discussed by Rotach (1994, 1998), Belcher and Coceal (2002), Belcher et al. (2003), Zilitinkevich et al. (2005b) and the COST-715 Action (Fisher et al., 2005a).

Roughness parameters for urban areas are calculated by the modified algorithm (see Sect. 2.2) based on the morphological methods. The displacement height is calculated only for grid-cells tagged as urban class following Fisher et al. (2005a). The roughness length is calculated for each grid-cell in the following way: (i) constant values in each



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urban sub-class are tabulated for the urban class; (ii) effective roughness is calculated based on values and percentages of each land-use class and urban sub-classes in the cell; (iii) at each time step, the roughness value is recalculated due to effect of temperature stratification.

In the general case of very inhomogeneous surfaces, such as urban areas, in order to include mutual effects of neighbouring cells it would be reasonable to simulate the effective roughness fields for grid-cells of a given city separately for different situations (e.g., for different 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 at the current stage only for non-urban areas, because there is not enough experimental data to verify urban areas parameterisations and to check the applicability of the linear approximation of the technique for urban conditions.

Nevertheless, most of NWP and meso-meteorological models consider the roughness length as a constant for each grid cell. Experimental data (Arya, 1975; Joffre, 1982; Wood and Mason, 1991) showed that it can depend on temperature stratification. This effect can be considerable especially for very rough surfaces, like the urban canopy. Therefore, the algorithm for recalculation of the effective roughness separately for stable or unstable stability, based on a new stability-dependent parameterisation of the urban roughness length for momentum, is suggested. The interpolation formulae for the effective roughness length are the following: for neutral, moderately stable and very stable stratification regimes:

$$Z_{0m\text{-effective}} = \frac{Z_{0m}}{1 + C_{0S}Z_{0m}/L + C_{0v}Z_{0m}u_*/v}, \quad (1)$$

where  $C_{0v} \approx 10$ ,  $C_{0S} = 10C_u \kappa^{-1} \approx 50$  are empirical constants; and for unstable stratification:

$$\frac{Z_{0m\text{-effective}}}{Z_{0m}} = [C_0 - (C_0 - 1) \exp(-C_1 Z_{0m}/|L|)], \quad (2)$$

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where  $C_0$  and  $C_1$  are empirical constants. The theoretical background for these formulations, their verification versus experimental data and choice of the constants are discussed in details by Zilitinkevich et al. (2005a).

However, just modifying the current rural MOST approaches for urban areas with specific values for the effective roughness lengths and displacement height, still does not solve the main problem, i.e., how to describe the vertical structure of meteorological parameters inside the urban canopy? We can suggest here to apply the new simple heuristic model of Zilitinkevich and Baklanov (2005) for the vertical profiles of the momentum flux and the mean wind velocity within the urban canopy. 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.

It is noteworthy that the suggested improvements based on the canopy profile model and displacement height do not required to substantially modify the NWP model itself, because the first computational model level is usually above the canopy, so that the canopy parameterisation can be used only for diagnostic calculation of the wind for higher resolution UAQ modelling outside the NWP model or for diagnosis of 10 m wind in NWP.

### 3.2. Surface energy budget in urban areas

In general, the SEB in urban areas can be written in the following way (Piringer and Joffre, 2005):

$$Q^* = K \downarrow - K \uparrow + L \downarrow - L \uparrow = H + LE + Q_{As} \quad [\text{W/m}^2] \quad (3)$$

where  $Q^*$  – net all-wave radiation;  $K \downarrow$  – incoming shortwave radiation;  $K \uparrow = \alpha_0 \cdot K \downarrow$  – outgoing, reflected shortwave radiation where  $\alpha_0$  – surface albedo;  $L \downarrow$  – incoming longwave radiation from the sky and surrounding environment ‘seen’ from the point;  $L \uparrow = \varepsilon_0 \sigma T_0^4 + (1 - \varepsilon_0) L \downarrow$  – outgoing longwave including both that emitted from the surface consistent with its emissivity  $\varepsilon_0$  and absolute surface temperature  $T_0$ , and the

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reflected incoming longwave;  $H$  – turbulent sensible heat flux;  $LE$  – turbulent latent heat flux ( $L$  is the latent heat of vapourisation);  $Q_{As}$  – specific urban anthropogenic surface heat flux. Thus, the urban formulation differs from the non-urban one only by the  $Q_{As}$  term.

This formulation is suitable for detailed urban canopy models (see e.g. Sects. 4 and 5), when the *surface* is just millimetres above ground and the canopy layers are within the simulation domain. For meso-scale meteorological and NWP models in which the *surface* may be high above the urban canopy (average roughness level or displacement height), the SEB can be rewritten in the following form:

$$Q_* = K \downarrow - K \uparrow + L \downarrow - L \uparrow = H + LE + Q_A + \Delta Q_S \quad [\text{W/m}^2] \quad (4)$$

where  $Q_A$  is the anthropogenic heat flux from sources within the urban canopy and  $\Delta Q_S$  is an imbalance term, which 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).

Correspondingly, in the model most of the terms of Eq. (4) are simulated for urban grid cells as usual with corresponding urban characteristics, but we need to define and parameterise two new urban terms:  $Q_A$  and  $\Delta Q_S$  as well as the albedo for urban areas.

### 3.2.1. Urban anthropogenic heat flux calculation

Following estimations of the average anthropogenic heat fluxes (AHFs) for cities in different climatic zones (Oke, 1978), reference values for a full urban area (100% of urban class; e.g., city centre or high building district) are in the range from 60 to 200 W/m<sup>2</sup>, 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 (e.g., Pigeon et al., 2005, showed for Toulouse that  $Q_A$  estimates are very uncertain and consequently can display negative values during summer months). Therefore, we suggest calculating methods for the urban AHF based on an assumed dependency on

(e.g., proportionality to) other relevant urban characteristics, which are available in the models, e.g.:

1. Population density using maps with a high resolution in urban areas;
2. Nocturnal radiation emissions (brightness) over urban areas based on high resolution satellite images;
3. Land-use classification as a percentage of urban subclasses (central part, urban, sub-urban, industrial, etc.);
4. Emission inventory for specific pollutants typical of urban areas (e.g.,  $\text{NO}_x$  from traffic emissions, etc.);
5. Monitoring or simulation fields of air pollution concentration for such specific pollutants (see above #4).

The first method for AHFs as a function of the population density distribution in urban areas is the one most frequently used and was tested for FUMAPEX NWP models.

For the second method based on the nocturnal brightness of urban areas, it is suggested to use the simple dependence:  $Q_A = I_{\text{In}} Q_{A_{\text{max}}}$ , where  $I_{\text{In}}$  is the normalised light intensity (max value is 1), and  $Q_{A_{\text{max}}}$  is a scale (max) value of the AHFs for 100% of urban surface (from  $50 \text{ W/m}^2$  for small/medium cities and up to  $200 \text{ W/m}^2$  for large mega-cities in industrially developed countries). However, it is important to notice that the brightness of urban areas is different for industrial vs. developing countries, and hence the method should be corrected accordingly.

The third method using land-use classification as a percentage of urban classes was tested for the Copenhagen and Krakow study in COST-715 (see Piringer and Joffre, 2005). The anthropogenic part to the urban surface fluxes was approximated according to a coarse urban LUC: (i)  $75 \text{ W/m}^2$  for the city centre, (ii)  $40 \text{ W/m}^2$  for city periphery areas, and (iii)  $20 \text{ W/m}^2$  for other urban-suburban areas.

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The last two methods (Eqs. 4 and 5), based on urban emissions or air pollution, can be easily used in atmospheric pollution forecasting models, because such information is usually available in the simulation.

### 3.2.2. Urban storage heat fluxes

Storage heat fluxes in the urban canopy are considered in our system by two different approaches. First, the heat storage capacity effect can be calculated using specific parameterisations for the temperature and moisture roughness lengths of urban areas. Most of NWP and meso-meteorological models consider for their surface layer profiles that the scalar roughness length,  $z_{0t}$ , is equal to the roughness for momentum,  $z_{0m}$ . However, for urban areas, they are generally very different (up to 2–3 orders of magnitude). Theoretical studies (Zilitinkevich, 1970; Brutsaert, 1975) suggest that the ratio  $z_{0t}/z_{0m}$  is a function of the roughness Reynolds number. Thus, the formulation of Brutsaert and Sugita (1996) for example can be suggested for urban areas. Including the modification of Joffre (1988) of Brutsaert assumption concerning the level under which the log-profile is not valid by using the Reichardt's profile, the following formulation can be recommended for various bluff types of roughness over a wide range of the roughness Reynolds number ( $0.1 \leq Re_* \leq 100$ ):

$$z_{0t} = z_{0m} \left[ 20 \exp(-7.3 \kappa a_c Re_*^{0.25} Sc^{1/2}) \right], \quad \text{for } Re_* > 0.15 \quad (5)$$

where  $a_c$  is the inverse turbulent Schmidt number ( $=K_H/K_M$  for  $z_{0t}$  or  $K_E/K_M$  for  $z_{0q}$ ) and  $Sc$  the Schmidt number ( $=\nu/D_c$ ,  $D_c$  is the molecular diffusivity of the particular property, i.e., heat, moisture but also gaseous compounds). The original Brutsaert's formula had a coefficient 7.4 instead of 20 in the first term of the right-hand side and was valid for  $Re_* > 2$  (rough case only). Equation (5) matches the corresponding expression (6) valid for aerodynamically smooth case at  $Re_* = 0.15$ , i.e.:

$$z_{0t} = 30(\nu/u_*) \exp \left[ -13.6 \kappa a_c Sc^{2/3} \right] \quad \text{for } Re_* < 0.15. \quad (6)$$

However, this and other existing formulations are very uncertain, rarely verified and cannot consider all the mechanisms of the urban heat storage.

Therefore, the heat storage in the urban fabrics/buildings, including hysteresis, can be most easily parameterised from the radiation and surface cover information using the empirical objective hysteresis model (*OHM*) of Grimmond et al. (1991):

$$\Delta Q_S = \sum_{i=1}^n (\lambda_i \alpha_{1i}) Q^* + \sum_{i=1}^n (\lambda_i \alpha_{2i}) \partial Q^* / \partial t + \sum_{i=1}^n (\lambda_i \alpha_{3i}) \quad [\text{W/m}^2] \quad (7)$$

where the  $\lambda_i$  are the plan fractions of each of the  $n$  surface types in the area of interest and the  $\alpha_{1-3i}$  are the corresponding empirical coefficients. These  $\alpha$  coefficients have been deduced from a re-analysis of the Multi-city Urban Hydro-meteorological Database obtained from ten sites in seven North American cities Grimmond and Oke (1999a).

### 3.2.3. Urban albedo effects

Radiative properties (such as albedo and emissivity) of building 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 transfers and energy budget. The heat flux to or from the ground changes with surface material: concrete, tarmac, soil, etc. Anthropogenic energy use can be a noticeable fraction of the annual solar input and thus, influences the local air stability.

### 3.3. Sensitivity tests and verification for Copenhagen

Sensitivity tests and verification of this approach of NWP urbanisation were performed using the DMI-HIRLAM research version (1.4-km resolution) for the Copenhagen (CPH, Denmark) and Malmö (MAL, Sweden) metropolitan areas and surround-

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ings. Independent runs were performed for several specific cases: (i) one control run with no modifications in the ISBA surface scheme (Noilhan and Planton, 1989); (ii) a modified urbanised 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<sup>2</sup>).

5 Following the simulation results, it was found that incorporating actual urban *roughness* values modified the structure of the surface layer wind field over urban areas (Fig. 5a). During daytime, the wind velocities were lower by 1–4 m/s. With a roughness  $z_{0m}$  of 2 m, this effect became more visible and pronounced not only near CPH and MAL, but also for other less urbanised areas. At night, this effect was smaller. The average differences in velocities were 2.4 and 2 m/s for CPH and MAL, respectively. For temperature, the urban roughness effect did not contribute significantly compared to the wind effect.

10 Incorporation of the *anthropogenic heat flux* showed (Fig. 5b) well pronounced differences (starting at 16:00 UTC) for simulated wind fields over the CPH urban cells. Then, the altered area extended farther inland of the Sjælland Island, and the difference rapidly increased to 1.5 m/s by 18:00 UTC. It also became well pronounced over MAL reaching the same value. For MAL, during the late evening – early morning hours the difference became the largest reaching a maximum of 2.1 m/s, and again by 10:00 UTC no difference was visible. For temperature, AHF increased the temperature above the urban cells, except that it was smaller during the 09:00–15:00 UTC-period with a minimum at noon. For both urbanised areas, this increase was on average up to 1°C (max 2.3°C) but with a large variance.

25 The analysis of the diurnal cycle at the urban Værløse station (55.77° N, 12.33° E) located in central Copenhagen showed that the diurnal variability of the wind direction was modelled in all runs with practically no differences between the control and modified runs. A similar situation was observed for the suburban Jegersborg station (55.77° N, 12.53° E) and the Kastrup station (55.62° N, 12.65° E) located not far from the seashore (so that urban effects were minimised during the studied day due to eastern winds).

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Inspecting the wind velocity daily cycle at an urban station (Fig. 6, top) shows that between 07:00–19:00 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. It is noteworthy that for the suburban station, the modification including the improved roughness showed a better fit to observational data compared with all other runs. For temperature (Fig. 6, bottom), on the other hand, the fit to observations was now better for the urban compared to the suburban station (not shown) for the modified run with the AHF. Modifications of roughness did not improve the fit. Moreover, in this specific example, we did not include the storage heat flux, therefore 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) improves this shortcoming.

It is important to remark that, in comparison with the original (non-urbanised) one, the computational time for this urbanised version of the model is almost the same. So, this variant of the urban parameterisations in NWP models is computationally very cheap.

#### 4. Building Effect Parameterization (BEP) module: modified version for NWP

The second module option of Fig. 4 was realised with the Building Effect Parameterization (BEP) model, developed by the Swiss partner EPFL. It is based on the urban sub-layer parameterisation suggested by Martilli et al. (2002) with modifications for implementation into NWP models and several further improvements (e.g., Hamdi and Shayes, 2005).



## 4.1. Module description

The aim of the urban sub-layer parameterisation developed at the EPFL (Martilli et al., 2002) is to simulate the effect of buildings on a meso-scale atmospheric flow. It takes into account the main characteristics of the urban environment: (i) vertical and horizontal surfaces (wall, canyon floor and roofs), (ii) shadowing and radiative trapping effects of the buildings, (iii) anthropogenic heat fluxes through the buildings wall and roof.

In this parameterisation, the city is represented as a combination of several urban classes. Each class is characterised by an array of buildings of the same width located at the same distance from each other (canyon width), but with different heights (with a certain probability to have a building with height). To simplify the formulation we assume that the length of the street canyons is equal to the horizontal grid size. The vertical urban structure is defined on a numerical grid.

In this method developed by Martilli et al. (2002) the contributions of every urban surface type (canyon floor, roofs and walls) on the momentum, heat and turbulent kinetic energy equation are computed separately.

First, the contributions of the horizontal surfaces (canyon floor and roofs) are calculated using the formulation of Louis (1979) based on the MOST. The roughness lengths used for this calculation are representative for the local roughness of the specific surface types (roofs or canyon floor) and not for the entire city, as it was considered in the first module (Sect. 3.1).

Second, the exchange of momentum and turbulent kinetic energy on the vertical surfaces (walls) are parameterised as the effect of pressure and drag forces induced by the buildings. The temperature fluxes from the walls are a function of the difference between the air temperature and the wall temperatures. They are parameterised using the formulation of Clarke (1985) proposed by Arnfield and Grimmond (1998) in their urban energy budget model.

The energy budget is computed for every mentioned surface (canyon floor, roofs

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and walls). Initially, the direct and infrared radiations at the surfaces are calculated to take into account the shadowing and radiative trapping effects of the buildings. Then, the surface temperatures of roofs, walls and canyon floor are solved by heat diffusion equation in several layers in the material (concrete or asphalt).

## 5 4.2. Sensitivity to urban parameters

In order to use the parameterisation of Martilli et al. (2002) in a mesoscale model a number of input parameters have to be evaluated. These parameters characterise the urban environment and they can be classified in three different groups. The first group is consisted of parameters characterising the buildings and streets geometry (street width and direction, building width and height). The second group includes parameters characterising the building and street materials (heat capacity and diffusivity, albedo and emissivity, street and roof roughness length). And the third group has parameters characterising the energy produced inside the buildings (indoor temperature). These different input parameters producing various effects on the momentum and the energy fluxes, they influence the wind and the temperature (Fig. 7).

The wind velocity is mainly affected by the buildings walls drag force, which produces a negative momentum flux. Consequently, the higher are the buildings, the lower is the wind velocity inside the urban canopy (Fig. 7c).

The temperature is influenced by two different energy sources: the anthropogenic sources (building indoor temperature) and natural sources (direct solar radiation and infrared radiation). When the streets are much larger than the buildings, the buildings have almost no effects. The urban area is like a dry smooth ground: the temperatures are especially influenced by the heat capacity, thermal diffusivity, albedo and emissivity of the streets (Fig. 7b).

When streets width and buildings width are comparable, the decrease of the night temperatures is attenuated. This can be due to two different effects. At first, the radiation trapping between building walls and streets stores the energy inside the urban canopy. Consequently, when buildings are high and streets are narrow the decrease

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of the night temperatures is low. At second, during the day, the energy coming from the sun is always much higher than the energy coming from the buildings. But during the night, the energy produced by the buildings can increase the temperature (if the building is heated). Consequently, the variation of the building indoor temperature will affect the outdoor temperature only during the night (Fig. 7a).

#### 4.3. Verification versus the BUBBLE experiment

The parameterisation has been tested on the city of Basel (Switzerland) and verified versus the BUBBLE experiment (Basel Urban Boundary Layer Experiment: Rotach et al., 2005). In a first step, the meteorological fields produced by the Local Model (LM) which is used by the Swiss meteorological institute (MeteoSwiss) as the aLMo version with a 7 km×7 km resolution, are interpolated onto a 1 km×1 km grid. In a second step, the meteorological fields are recomputed at the highest resolution solving the momentum, energy and turbulent kinetic energy budget in the boundary layer and in the surface layer. The recomputed results are compared with the LM results and the data measured during BUBBLE. This comparison shows clearly that the module improves the simulated meteorological parameters. The urban parameterisation decreases the wind velocity and increases the temperature in the urban surface layer (Fig. 7d).

During the day, the difference between the simulated results from LM and the recomputed results with the parameterisation are larger than during the night. The LM data clearly underestimate the temperature at all stations. The results obtained with the urban parameterisation are very close to the measurements in the city centre (stations Ue1 and Up11) while it slightly overestimates the temperature at the city boundary (stations Se1, Sp3, Sp7, Re1) (Fig. 8).

The urban parameterisation developed by Martilli et al. (2002) shows a clear capacity to improve the results of NWP models (like LM or HIRLAM) by taking into account the effect of urban areas. However, the parameterisation should be further tested using different cities and longer periods.

## 5. The soil model for sub-meso scales urbanised version – SM2-U

The third module (Fig. 4) modified and tested for the urbanisation of meso-meteorological models includes the detailed urban area soil submodel SM2-U (Soil Model for Sub-Meso scales Urbanized version) module, developed by the ECN team (Dupont and Mestayer, 2004; Dupont et al., 2005<sup>2</sup>).

### 5.1. Model description

The physical basis of the urban canopy model SM2-U was developed from the ISBA rural soil model of Noilhan and Planton (1989) with the inclusion of urban surfaces and the influence of buildings and sparse vegetation, while keeping the force-restore soil model approach. The objective was twofold: to simulate the urban micro-climatology, and to evaluate the heat and humidity fluxes at the urban canopy-atmosphere interface with sub-mesoscale atmospheric models. SM2-U has the advantage of a unique model for both rural and urban soils that allows simulating continuously all districts of an urbanised area. The physical processes inside the urban canopy, such as heat exchanges, heat storage, radiative trapping, water interception or surface water runoff, are integrated in a simple way. The only horizontal exchanges inside the urban canopy are radiation reflections and water runoff from saturated surfaces; the wind advection within the canopy layer is not considered. Under the surface, the sub-grid scale transfers are ensured in the two underlying continuous soil layers.

While for a natural soil partly covered with vegetation ISBA computes the budgets for the whole ground-vegetation system, SM2-U separates in each computational cell eight surface types (Fig. 9): for natural grounds, the bare soil without vegetation, noted “bare”, the soil located between vegetation elements, “nat”, and the vegetation cover “vegn”; for the anthropised areas, the building roofs, “roof”, the paved surfaces with-

<sup>2</sup>Dupont, S., Mestayer, P. G., Guilloteau, E., Berthier, E., and Andrieu, H.: Parameterisation of the Urban Water Budget with the Sub-Meso Soil Model, J. Appl. Meteorol., submitted, 2005.

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out vegetation, “pav”, the vegetation elements over a paved surface (e.g., road side trees), “vega”, and the paved surface under the vegetation, “cova”; finally, the water surfaces, “wat”. Each surface type is characterized by its area density  $f_i$ , with  $\sum_i (f_i) = 1$ ,

for  $i \in \{\text{bare, nat, pav, roof, vega, vegn, wat}\}$  in each grid cell and  $f_{\text{vega}} = f_{\text{cova}}$ .

SM2-U computes the water budget in three soil layers. The thin “surface layer” acts as a buffer for the evaporation from the surface and for the precipitation water transfer to/from the second soil layer. This second, root-influenced layer contains the available water for vegetation transpiration. The third, sub-root layer, or “deep soil layer”, is used as a water reservoir to provide water to the root zone layer by diffusion in dry periods, as introduced by Boone et al. (1999) in the ISBA-3L version. There is one surface layer for each surface type but one root zone cell and one deep soil layer cell per grid mesh (Fig. 9). For vegetation, roofs, and paved surfaces an interception reservoir defines the maximum amount of retained liquid water. When the reservoir overflows the water runoff to the neighbour surface or to the draining network is computed explicitly (Dupont, 2001; Dupont et al., 2005<sup>2</sup>). While roof surfaces are assumed fully impervious, paved surfaces are semi-impervious and let water infiltrate downwards but not upwards.

The energy budget is computed for each surface type in the cell:

$$G_{s_i} = Q * _i - H_i - LE_i, \quad (8)$$

then the cell energy fluxes are obtained by averaging the individual fluxes weighted by the area density  $f_i$ . The net radiation flux  $Q^*$  is obtained from the classical four-components (downwards, upwards, solar and infrared) budget. The storage heat flux in soil/building materials  $G_s$  is computed as the residual of Eq. (8). To compute the aerodynamic heat fluxes  $H_i$  and  $LE_i$ , SM2-U determines the temperature  $T_{s_i}$  and specific humidity  $q_{vs_i}$  of each surface type, and one deep soil temperature  $T_{\text{soil}}$ . The equations for the water vapour fluxes from vegetation and natural soils (intercepted water evaporation plus vegetation transpiration) are identical to those of ISBA except that they use the surface type temperature instead of the average temperature. They are extended to the vegetation on paved surfaces. The water vapour fluxes from ar-

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tificial surfaces are determined in the same way as from the vegetation, by extending the concept of the surface wet portion. Evaporation and sensible heat fluxes are computed using the resistance approach, e.g.,  $H_f = \rho_{\text{air}} c_p (\theta_{s_i} - \theta_{\text{air}}) / r_{a h i}$ , where  $c_p$  is the specific heat of air at constant pressure,  $r_{a h i}$  the aerodynamic heat resistance,  $\theta_{s_i}$  the potential surface temperature,  $\rho_{\text{air}}$  and  $\theta_{\text{air}}$  the air density and potential temperature at the lowest atmospheric model level, or reference level. The aerodynamic heat and humidity resistances depend on the wind velocity at the reference level and on the heat and water vapour transfer coefficients, respectively. The heat transfer coefficient is calculated following the non-iterative algorithm of Guilloteau (1998) for non-equal momentum and heat roughness lengths,  $z_{0m}$  and  $z_{0t}$  respectively. Guilloteau's method is based on a combination of Högström's (1996) and Beljaars and Holtslag's (1991) formulations of the flux-profile relationships. It is inspired by Launiainen's (1995) method for stable stratification and generalises Byun's (1990) method for unstable stratification. The humidity transfer coefficient is set equal to that of heat. The computed surface temperatures are assumed to be the skin temperatures, but not the aerodynamic temperatures at canopy top level. To solve the problem of inconsistency between skin and aerodynamic temperatures, the heat roughness length is not assumed equal to the momentum roughness length, using the Reynolds number-dependent formulation of Zilitinkevich (1995)  $z_{0t}/z_{0m} = \exp(-\kappa C Re^{*1/2})$  where  $\kappa$  is the von Karman constant ( $\kappa=0.4$ ) and  $Re^* = z_{0m} u_* / \nu$  is the roughness Reynolds number with  $u_*$  the friction velocity and  $\nu$  the kinematic molecular viscosity of air;  $C$  is an empirical constant, set to 0.1 as recommended by Chen et al. (1997). However, it is probable that the numerical value of  $C$  should be revisited by a factor of ca. 10, since when compared to the model (Eq. 5) of Brutsaert and Sugita (1996) or Joffre (1988), which are close to each other, as  $Re^*$  varies between typical value of  $10^2$  to  $10^4$ , the Zilitinkevich model yields value of  $\kappa B^{-1} = -\ln(z_{0t}/z_{0m})$  between 0.1 and 4, while the Brutsaert-Joffre version varies between 5 and 22.

Bare soil water vapour fluxes depend on the relative humidity  $q_{u_i}$  at the ground surface and the surface temperature, while soil and vegetation heat capacity coefficients

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are, as in ISBA, dependent of the volumetric water content of the root zone layer; thus coupling the heat and water budgets. The natural surface temperature  $T_{s_i}$  is calculated by means of a force-restore equation of the surface layer heat, assuming that the layer is sufficiently thin to be all at the same temperature. The time evolution of  $T_{s_i}$  appears

$$\frac{\partial T_{s_i}}{\partial t} = C_{T_{s_i}} G_{s_i} - (2\pi/\tau)(T_{s_i} - T_{\text{soil}}) \quad \text{for } i \in \{\text{bare, nat, vega, vegn}\}, \quad (9)$$

where  $C_{T_{s_i}}$  is the inverse of the surface layer heat capacity and the parameter  $\tau=86\,400\text{ s}$  is the day duration. Inversely the deep soil temperature is determined by a return-to-equilibrium equation towards the temperature average of all surfaces in contact with the soil. The time evolution of the surface layer water content  $w_i$  is calculated with a similar force-restore equation adding a forcing term due to precipitation and a relaxation term towards equilibrium with the deep soil water content at equilibrium between capillarity and gravity forces.

The force-restore model does not apply to artificial surfaces because the thin surface materials respond rapidly to the environmental forcing while the underlying materials have insulating thermal properties, unlike natural soils. Normal heat conduction equations are used for these artificial covers, with two layers, a superficial layer which allows the model to respond quickly to the environmental forcing variations, and a second, inner layer which allows the artificial materials to store heat.

The three-dimensional structure heterogeneity and complexity of the canopy make it impossible to compute explicitly all physical processes in (sub-)mesoscale atmospheric simulations. In SM2-U the canopy horizontal dimensions are detailed while the influence of the vertical dimensions is parameterised. Building walls are integrated with the paved surfaces into a street canyon energy budget (Fig. 9b). Thus, the surface temperature of paved surfaces  $T_{s_{\text{pav}}}$  corresponds to an effective average temperature of street canyon surfaces. The building walls are accounted for in three ways: the heat flux through the walls; the heat storage capacity of walls; the radiative trapping inside the street.

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The conduction heat fluxes between pavement layers integrate the walls by adding in parallel the heat fluxes through building wall layers, weighted by the wall-to-paved area ratio (in practice approximated by  $2 H/W$ ). The heat fluxes through building walls are calculated in the same way as those through building roofs, with two layers and assuming a constant inner temperature.

The street canyon surface and second layer heat capacities  $C_{T^*pav}^{-1}$  are represented by two resistances in parallel for the walls  $C_{T^*wall}^{-1}$  and paved surfaces  $C_{T^*floor}^{-1}$  which depend on the wall/pavement layer thickness and volumetric thermal capacity:  $C_{T^*pav}^{-1} = C_{T^*wall}^{-1} S_{wall} / S_{pav} + C_{T^*floor}^{-1}$ , where  $S_{wall}$  and  $S_{pav}$  are, respectively, the total area of building walls and of paved surfaces in the cell.

The radiative trapping inside the street is modelled by introducing into the pavement radiation budget equation an effective albedo and effective emissivities, which depend on those of the street materials and on the canyon geometry. Based on Masson's (2000) calculations, these effective parameters have been related by Dupont et al. (2005)<sup>2</sup> to only one geometrical parameter, the street aspect ratio  $H/W$ .

### 5.2. Model validation and test

For a rural area, while ISBA determines only one surface temperature, SM2-U distinguishes vegetation ( $T_{s\ vegn}$ ) and bare soil ( $T_{s\ nat}$ ) surface temperatures. This modification has been introduced to allow the evaluation of vegetation influence on paved as well as natural surfaces. Indeed, computing a single temperature for a paved surface and vegetation would be erroneous, since they behave so differently. The representation of sparse vegetation mixed with artificial-surfaces is then as realistic as possible, especially in alternative scenarios of micro-climatology. This modification in the original part of the model generates computational changes in the calculation of the mean surface temperature, sensible and latent heat fluxes: this has been validated against the experimental data from HAPEX-MOBILHY and EFEDA campaigns (Dupont et al., 2005<sup>2</sup>). The urban hydrological components of the model have been



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validated against the experimental data obtained during ten years at the Rezé suburban site in the Nantes urban area (Berthier et al., 2001), with tests both on an annual scale and for stormy events (Dupont et al., 2005<sup>2</sup>). Finally the energy budget urban parameterisations have been validated for a densely built city centre against the measurements of Grimmond et al. (2004) at the Marseilles central site during the campaign UBL-ESCOMPTE (Mestayer et al., 2005), in a forced mode without soil-atmosphere feedback (Dupont and Mestayer, 2004), showing an excellent agreement on average (Fig. 10).

Based on these validation simulations, a series of additional simulations were performed to assess the impact on the heat fluxes of the wall parameterisations representing the canopy influence. At first the effective albedo and emissivities of the street canyon were replaced by those of the street canyon floor, i.e. asphalt albedo and emissivity. Most of the results were identical; the main impact is an increase in the root mean square difference between measurements and simulations but the averaged diurnal cycles are very similar to those of Fig. 10. The net radiation is slightly lower during the day due to the larger albedo (0.08 for the pavement and only 0.04 for the effective albedo at midday) while the replacement of the effective emissivities (0.97 and 0.99, for the atmospheric absorption and infrared emission, respectively, in the basic simulations) by the asphalt emissivity (0.94) has little impact due to compensating influences. The further simulations differ either in aggregating the two layers of the artificial surfaces (roofs, walls and pavements) in only one layer with the same (averaged) transfer coefficients or in suppressing the walls. With one averaged layer the model does not reproduce well the early morning warming of the artificial surfaces because the layer is too thick, impeding the model fast response to environmental forcing variations; in the case when this unique layer has the same thickness as the first, surface layer of the base case the model does respond rapidly to the forcing variations but does not simulate well the amount of heat stored in the artificial materials, because the layer is too thin. Thus, two layers for representing artificial surfaces appear as a necessary compromise, whereby the first thin layer allows the model fast response, and

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the second layer ensures the storage capacity. When the walls are not simulated, the sensible heat fluxes are much less well simulated: the stored heat is smaller during the day, which results in a larger daytime sensible heat flux and a smaller nocturnal heat release inducing a negative nocturnal sensible heat flux.

After validation of the model with the Rezé site measurements, alternative simulations put in light the influence of the local water budget on the local climatology (only local effects may be demonstrated when the model is run in the stand-alone mode). Figure 11a displays the mean surface temperature diurnal cycle of the month of July 1996 in the reference simulation. Four new simulations were run with only slight differences in the inputs and the resulting differences in the mean temperature cycle are shown in Fig. 11b. All four runs simulate the suburban site behaviour if 1996 had been a dry year (precipitation rates divided by 1000) while the weather remained otherwise unchanged (the general climatology of the French Atlantic coast around Nantes is very mild). Soil dryness is shown to neatly increase day-time surface temperatures, the difference exceeding  $1.5^{\circ}\text{C}$  between 9 a.m. and 4 p.m. (solid line). Observations of the energy budget components (not shown) show that, in the reference simulation the sensible and latent heat fluxes share equally about 85% of the net radiation (maximum  $440\text{ W/m}^2$ ), while the last 15% are stored in the ground during day-time. At night, the negative net radiation (ca.  $40\text{ W/m}^2$ ) is balanced by the storage heat release for two third and by a small negative sensible heat flux for one third. With the dry soil, the latent heat flux drops to about 12% of the net radiation while the storage heat flux remains unchanged and the sensible heat flux balances some 73% of the budget. The second alternative includes vegetation watering: every day between 7 a.m. and 8 p.m. water is poured at a rate of  $1\text{ mm/h}$  ( $1.45\text{ kg m}^{-2}\text{ s}^{-1}$ ) over the bare soil and 50% of the vegetation cover (figuring grass cover share). This moderate daily watering is shown to be sufficient for compensating the soil dryness influence on the local climate: the upper soil layer remains close to saturation and the energy budget cycle appears very similar to that of the reference case. Consequently the surface temperature is the same as in the reference case.

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The last two simulations show the influence of realistic and antagonist layouts of the suburban settlement. In the case when the pavement of the road and parking lots is replaced by a stabilised grassy soil, which takes advantage of the evening watering to increase evapotranspiration, the mean temperature decreases 2°C more all day long, and even 2.5°C at midday. On the contrary, the covering of vegetated surfaces by pavement strongly increases day-time surface temperatures, up to 5.5°C around noon (i.e. a raise from 24 to 30°C), without effect of the evening watering since the soil water does not percolate upwards through the pavement. In this last case the energy budget is largely perturbed since the heat storage is more than doubled, reaching 35% of the net radiation, while the sensible heat flux reaches 93% of the net radiation, the budget being balanced by a large negative latent heat flux due to the downward flux of water vapour to the dry surface.

The CPU computational expenses are rather high, e.g. for the SUBMESO model urbanised with SM2-U, one diurnal cycle run is equal approximately to 4.2 h on the NEC-SX6 supercomputer (on one processor).

## 6. Conclusions and recommendations

Different parameterisations of the urban sublayer for NWP models have been analysed and tested with different meso-meteorological models. Several options for the integrated FUMAPEX urban module usable with NWP models have been suggested. The first version includes three main modules, which can be chosen depending on the specific problem, model resolution or city area:

1. Corrections of the surface roughness for urban areas and urban heat fluxes (adding the anthropogenic heat flux, heat storage capacity and albedo change). This can be complemented with an analytical model for wind velocity and diffusivity profiles inside the urban canopy (Zilitinkevich and Baklanov, 2005).
2. The urban sub-layer model BEP (Martilli et al., 2002; Hamdi and Schayes, 2005)

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with special physical parameterisations of the urban surface exchange for the urban sub-layer implemented into (or after) the NWP model.

3. The SM2-U full force-restore soil submodel for urban areas (Dupont and Mestayer, 2004; Dupont et al., 2005<sup>2</sup>).

5 The fourth combined module, including all non-overlapping mechanisms from the SM2-U and BEP models, is under development.

It was shown that the implementation of the urban modules can significantly improve the forecasted meteorological fields for urban areas. The first module is the cheapest way of “urbanising” the model and can be easily implemented into operational NWP models as well as in Global/Regional Climate Models. 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 m. Therefore, the increasing of the vertical resolution of current NWP models is required. The third module is considerably more expensive computationally than the first two modules. 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 are recommended for use in advanced urban-scale NWP and meso-meteorological research models. This will be demonstrated for NWP models in a forthcoming paper. The third module maybe very useful for implementation into research submeso-scale or micro-meteorological models (e.g., SUBMESO) for large eddy simulation or assessment (non-prognostic) studies. The first and second modules can be also realised as urban interfaces or post-processors of NWP data for UAQ models.

25 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

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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.

One sophisticated way to simulate the storage heat flux for urban areas can be realised using the BEP (Sect. 4) or SM2-U (Sect. 5) modules. One goal is to simplify the parameterisation of the storage heat flux in NWP models' simulations for main types of urban areas and concentrations of urban elements. Use of these modules can give a possibility to suggest a simplified classification of the urban storage heat fluxes for main urban classes to be used in NWP models.

#### Further improvements in NWP and UAQ forecasting systems

The next step should be the intercomparisons of urban modules with(in) the operational NWP models (such as HIRLAM and LM) and their verification with respect to urban meteorological forecasts.

The urban canopy models are also suggested (and successfully tested for module 2, see Sect. 4.3) to be implemented as an interface/post-processor module, separated from the NWP model. In this case, the urban sublayer model will be run separately, using ready NWP data as a first approximation, and it will improve meteorological fields of higher resolution close to and inside the urban canopy.

Such a novel approach has, of course, a clear drawback as it does not improve the meteorological forecast for the urban area and does not allow feedbacks. However, for the urban air pollution modelling/forecasting and improvements of the UAQIFS, this approach can be very useful and easier to realise, because it does not require any modifications of the operational NWP model (which are usually very difficult and time consuming). This approach thus consider the urban sublayer models (together with

several upper layers and surrounded areas) as interface modules between the NWP and UAQ models.

The current versions of the considered urban modules have several shortcomings and have to be improved and further developed. For the first approach (module 1), the complemented analytical model for wind velocity and diffusivity profiles inside the urban canopy (Zilitinkevich and Baklanov, 2005) has to be tested with different NWP models and meteorological preprocessors, and carefully verified vs. experimental data for different regimes. Besides, it is advisable to extend this model for temperature and humidity profiles. The current version of the second module (BEP) does not consider the moisture and latent heat fluxes and does not completely incorporate the anthropogenic heat flux. Therefore, these should be included into a new version of the BEP module. Besides, recalculation of accessible meteorological fields in the lowest sub-layers is necessary. The third module (SM2-U) needs further development considering the building drag effect (it will be realised in module 4), whereas snow and ice have to be included for NWP during winter periods, especially for northern areas. The existing version of this module, when run for every grid-cell, is too expensive for operational NWP models, therefore the module has to be optimised by making calculations only for the urban cells.

It is obvious that these developments in process parameterisations and model resolution require more and more adequate data for validating, improving and initialising NWP or meso-meteorological models. There is a need for carrying out urban field campaigns in the future to provide data from which insights may be gained in order to devise simpler models and parameterizations for complex models. The existing measurements have limitations which arise due to inescapable constraints on field programmes in cities, including:

- Availability of suitable and representative instrument sites, allowing for security, power, data transmissions, neighbour comfortability, public safety, accessibility, and planning permission;

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- Height and positioning of sensors to meet the needs of the researchers, such as adequate height, so that the appropriate surface type is within the upwind fetch and observational foot-print for sensors;
- Duration of instrument deployment and data capture rates during the campaign, as few campaigns can be long term, yet measurements are needed in all seasons;
- Sufficient sensors to deploy a number of reference instruments at well exposed rural sites so that influences due to the city can be differentiated from the daily and diurnal changes in prevailing meteorological situation;

There is a real need for long measurement runs, so that a variety of conditions are sampled, and that instrumental techniques can be compared against each other. Potential of remote sensing methodologies and satellite observations should also be better exploited.

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## Appendix A: Acronyms of partners

Arianet:	Environmental consulting company ARIANET s.r.l, Milan, Italy
CEAM:	The Mediterranean Centre for Environmental Studies Foundation, Valencia, Spain
CORIA:	COmplexe de Recherche Interprofessionnel en Aérothermochimie, Université de Rouen, France
DMI:	Danish Meteorological Institute, Copenhagen, Denmark
DWD:	German Weather Service, Offenbach, Germany
ECN:	Ecole Centrale Nantes, Nantes, France
EPA Emilia-Romagna:	Environmental Protection Agency of region Emilia-Romagna, Bologna, Italy
EPFL:	Ecole Polytechnique Fédérale de Lausanne, Switzerland
EPHYSE:	Institut National de la Recherche Agronomique, Bordeaux, France
GREYC:	Groupe de REcherche en Informatique, Image, Automatique et Instrumentation de Caen, France
MeteoSwiss:	National Weather Service of Switzerland
Met.no:	Norwegian Meteorological Institute, Oslo, Norway
UCL:	Université Catholique de Louvain, Belgium

*Acknowledgements.* The authors are grateful to L. Laursen, B. Amstrup, C. Petersen, A. Rasmussen, K. Sattler (DMI), S. Leroyer, I. Calmet (ECN), N. Long (GREYC), S. Dupont (EPHYSE), M. Piringer (ZAMG), G. Schayes (UCL), B. Fay (DWD), M. Rotach (MeteoSwiss), R. Sokhi (UH), S. Finardi (Arianet), A. Martilli (CIEMAT) and many other FUMAPEX and COST 715 partners for collaboration, discussions and constructive comments. Financial support of this study came from EU FUMAPEX (EVK4-CT-2002-00097) project.

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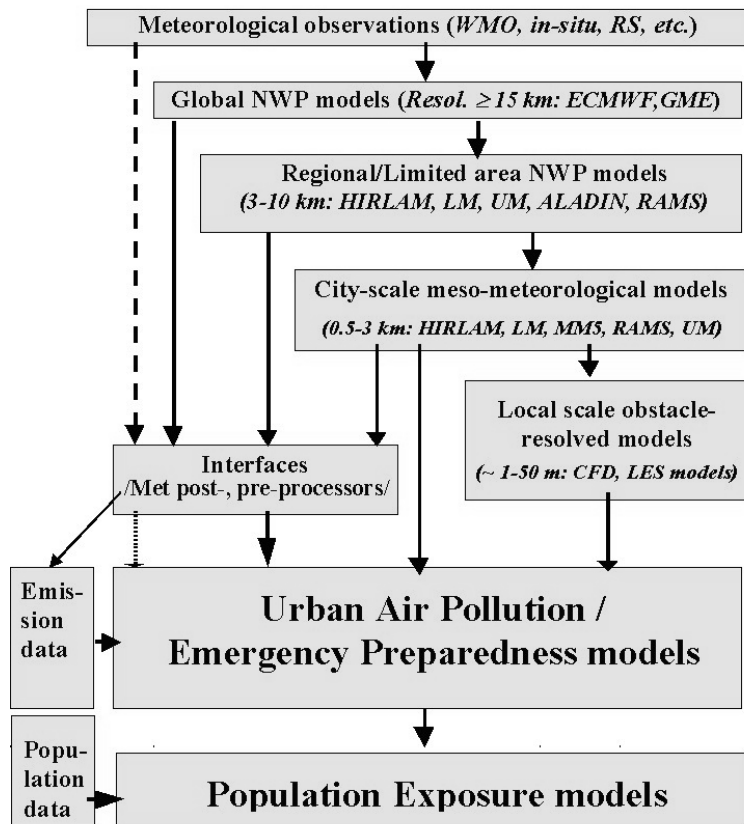
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**Fig. 1.** Current regulatory (dash line) and suggested (solid line) ways for forecasting systems of urban meteorology within UAQIFs by downscaling from the adequate NWP models to the urban scale (adapted from Baklanov et al., 2002).

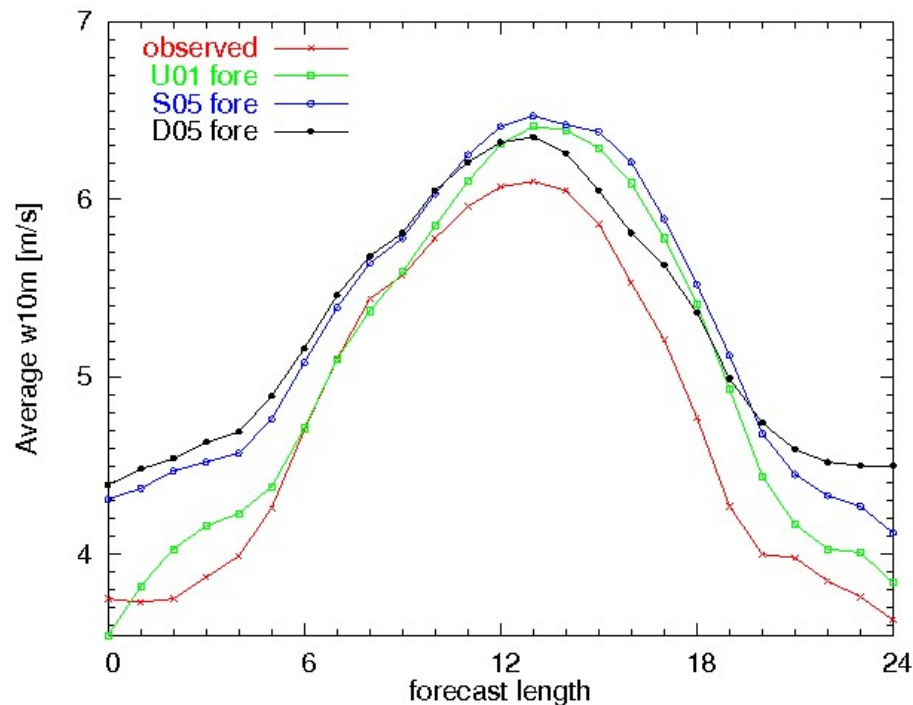
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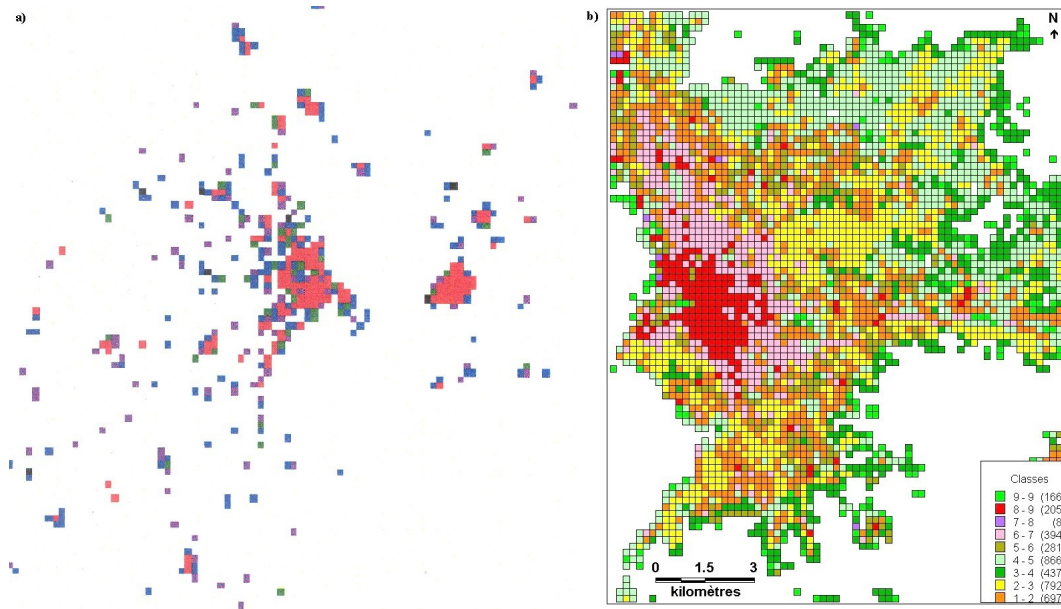
**Fig. 2.** Diurnal variation of average wind velocity (in m/s) at 10 m between observational data and three DMI-HIRLAM-S05, -U01, and -D05 model versions for 00:00 UTC forecasts during May 2005.

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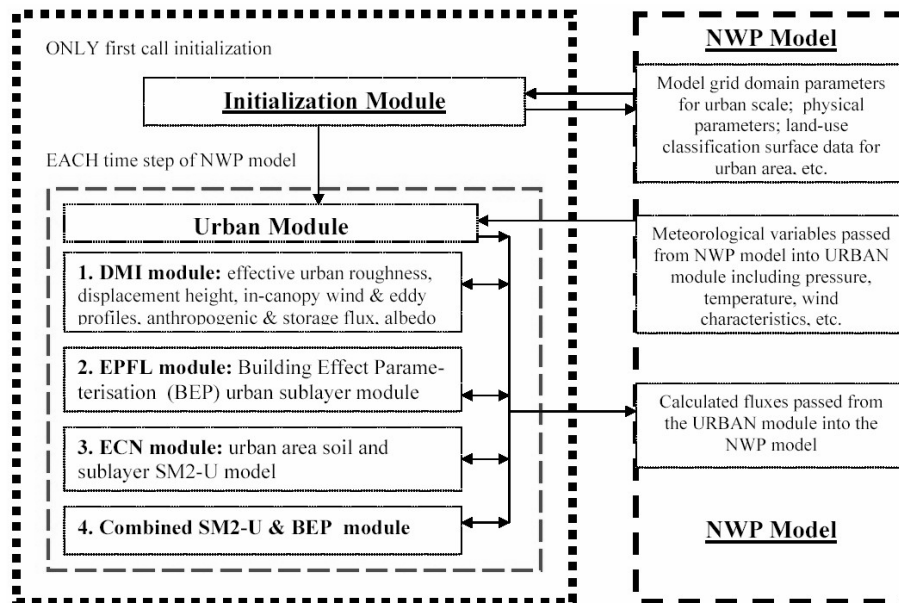
**Fig. 3.** Examples of improved urban land-use classifications prepared for: **(a)** the Copenhagen metropolitan area (shown as a percentage of the urban class representation in each grid-cell of the domain) used in the DMI-HIRLAM simulations; **(b)** the Marseilles metropolitan area (shown as a presence of 9 classes in domain, see Long, 2003) used in simulations of the SUBMESO model urbanized with SM2-U module.

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**Fig. 4.** General scheme of the FUMAPEX urban module for urbanisation of the numerical weather prediction models.

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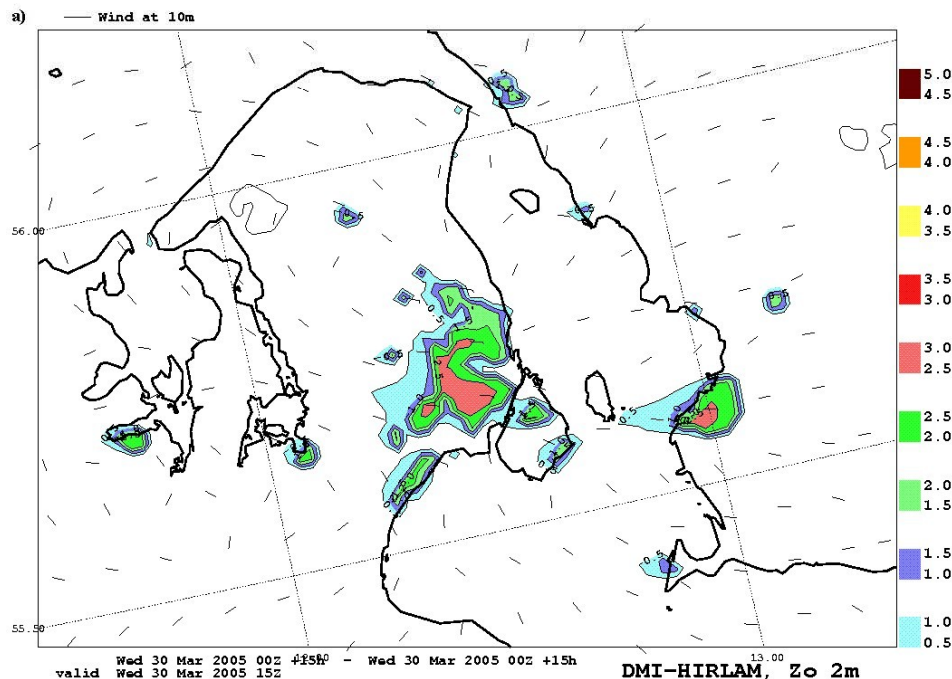
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**Fig. 5.** Sensitivity tests to urban features with the DMI-HIRLAM high resolution model shown as the difference fields (runs without vs. with modifications) for the 10 m wind velocity separately with the inclusion of the **(a)** urban roughness and **(b)** anthropogenic heat flux over the Copenhagen and Malmö metropolitan areas on 30 March 2005.

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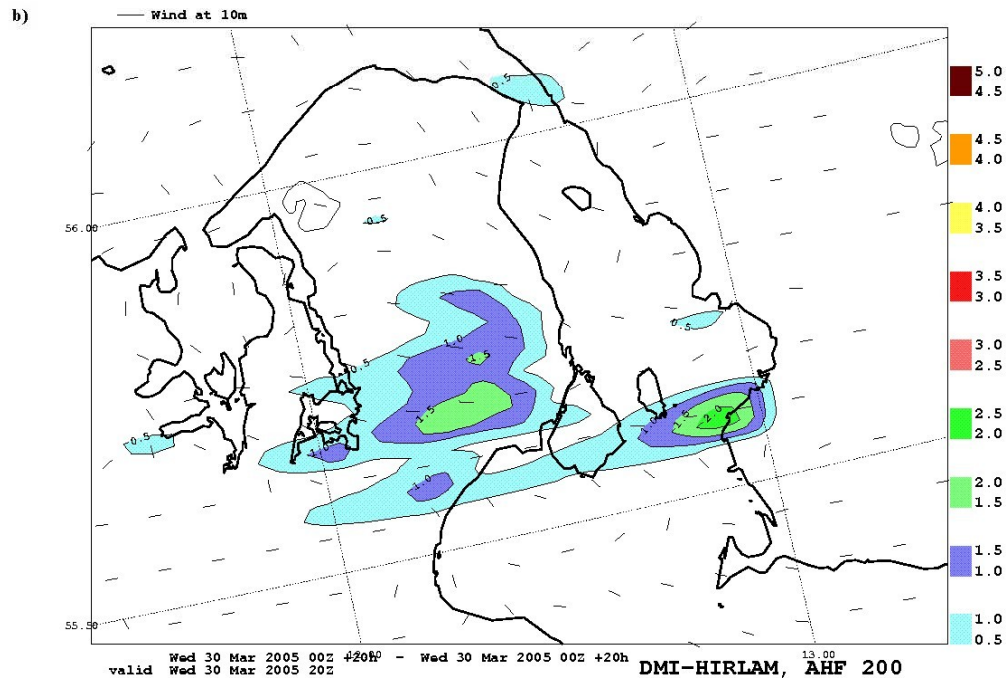


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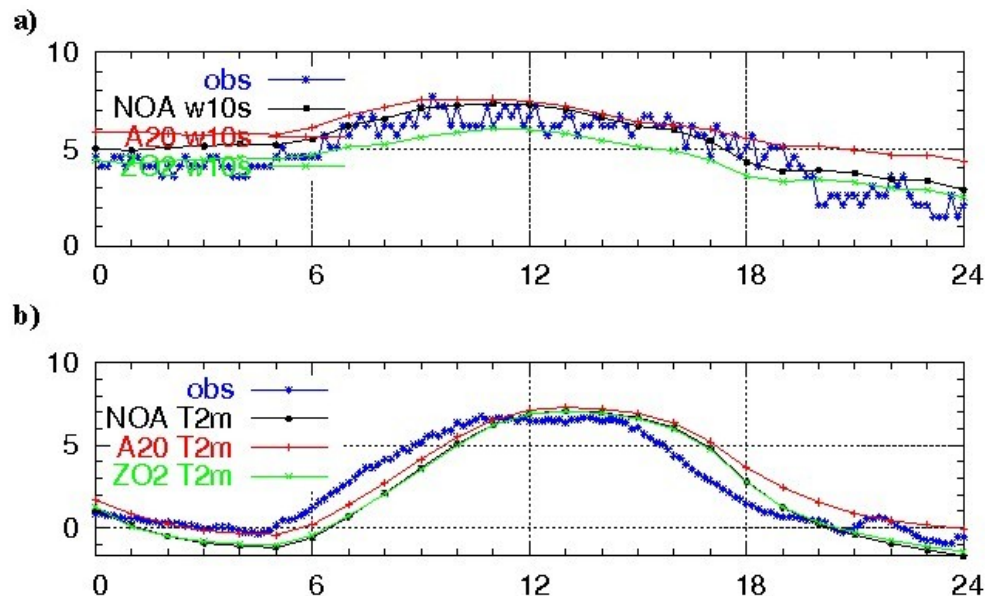
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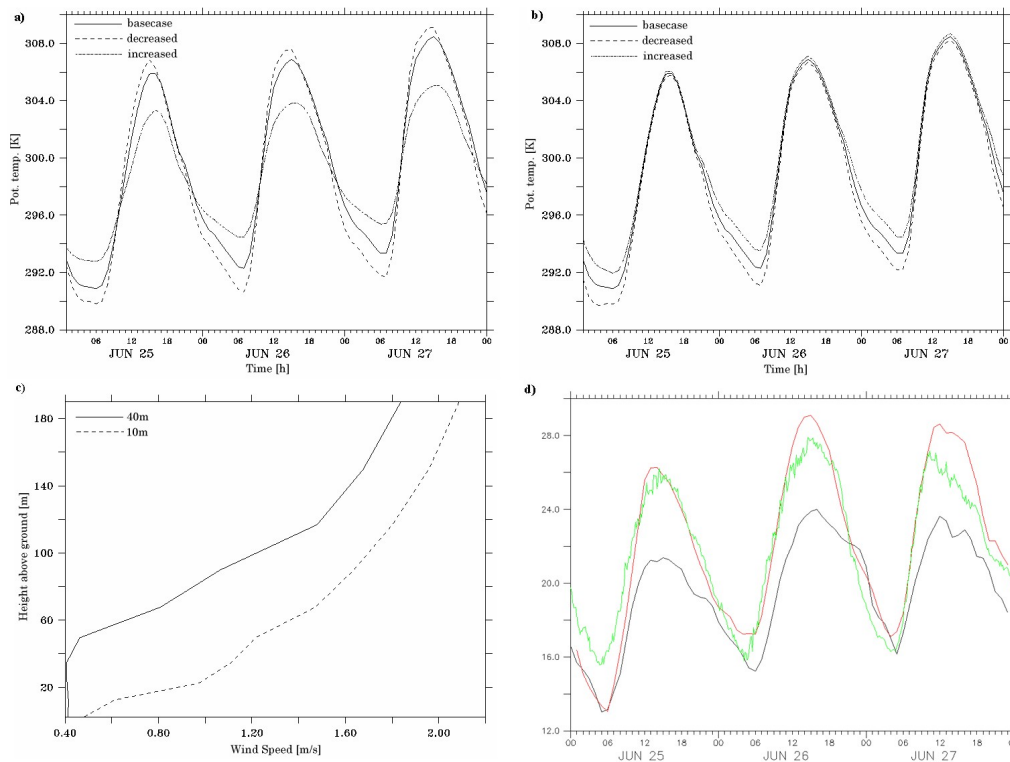
**Fig. 6.** Diurnal cycle (30 March 2005) of wind velocity at 10 m (w10s, in m/s; top panel) and air temperature at 2 m (T2m, in °C; lower panel) based on the DMI-HIRLAM high resolution control run (NOA), modified runs with added anthropogenic heat flux (max  $200 \text{ W/m}^2$ ) (A20) and urban roughness (max. 2 m) (Z02) vs. observational data (obs) at Værløse urban station ( $55.8^\circ \text{ N}$ ,  $12.3^\circ \text{ E}$ ) located in central Copenhagen.

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**Fig. 7.** Sensitivity and verifications results for the BEP module: **(a)** Potential temperature (in K) evolution during 25–27 June 2002 inside the urban canopy for three different street heat capacities: 1.4 (basecase), 14 (decreased), and 0.14 (increased)  $\text{MJm}^{-3} \text{K}^{-1}$ ; **(b)** Potential temperature (in K) evolution during 25–27 June 2002 inside the urban canopy for three different building indoor temperatures: 20 (basecase), 17 (decreased), and 23 (increased)  $^{\circ}\text{C}$ ; **(c)** Simulated wind velocity profiles for building heights of 10 and 40 m; **(d)** Air temperature evolution (in  $^{\circ}\text{C}$ ) during 25–27 June 2002: measured (green line), simulated by LM model (blue line), and recalculated with BEP module (red line).

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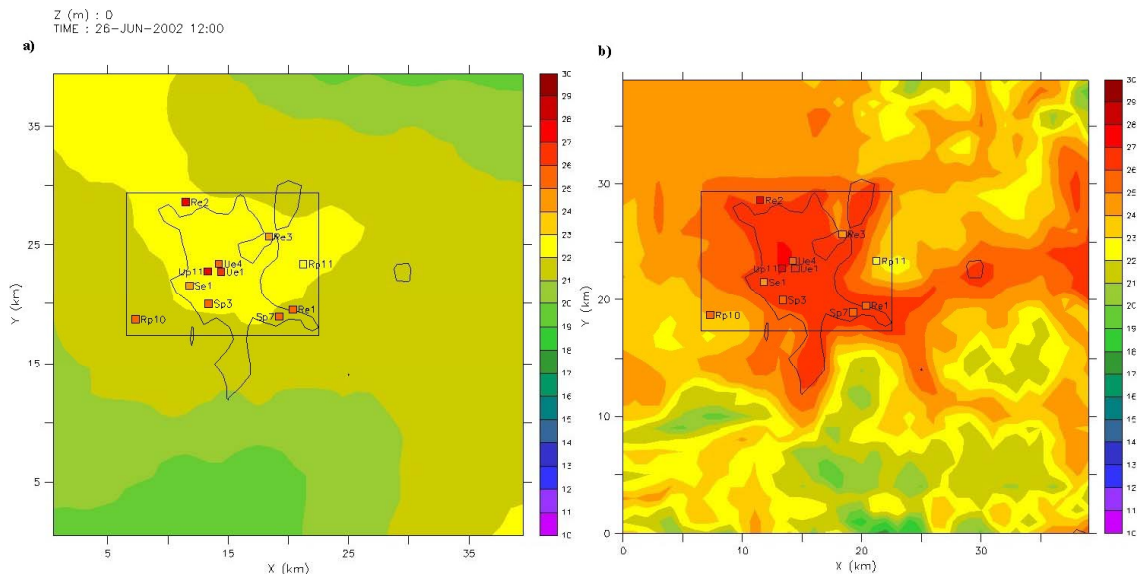
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**Fig. 8.** Temperature fields over the Basel area at ground level at noon on 26 June 2002: **(a)** recalculated with BEP module and **(b)** interpolated from LM model (black line indicates the city boundaries; squares show the measured temperature at several sites).

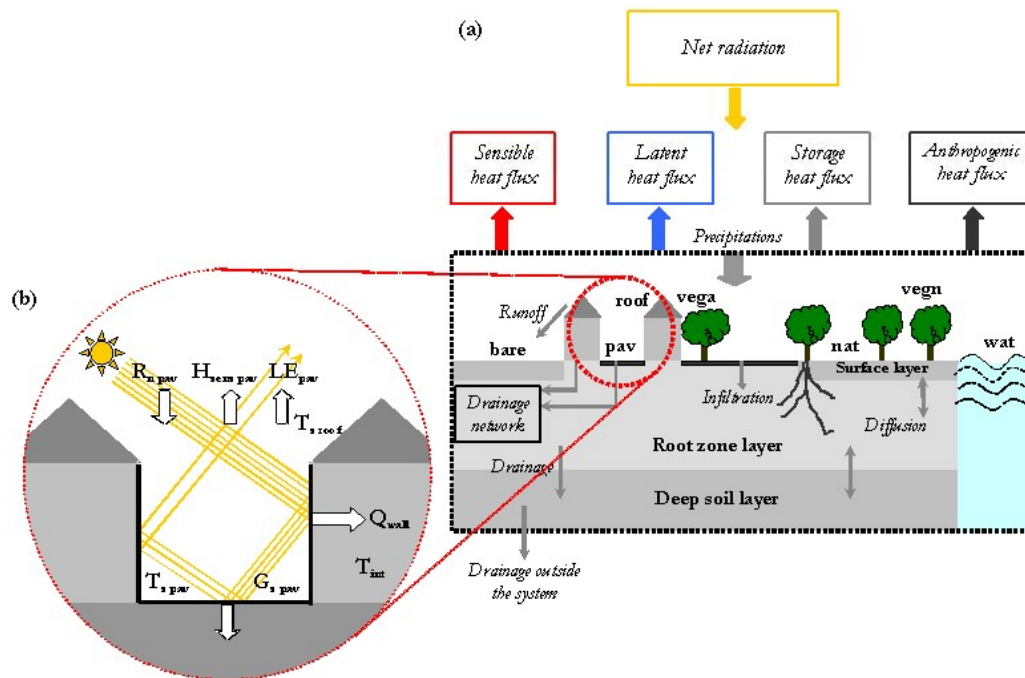
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**Fig. 9.** Scheme of the SM2-U energy and water budget models: **(a)** with 7 surface types (bare soil without vegetation – “bare”; soil located between vegetation elements – “nat”; vegetation cover – “vegn”; building roofs – “roof”; paved surfaces without vegetation – “pav”; vegetation elements over a paved surface – “vega”; water surfaces – “wat”) and 3 soil layers. **(b)** Energy budget of paved surfaces.

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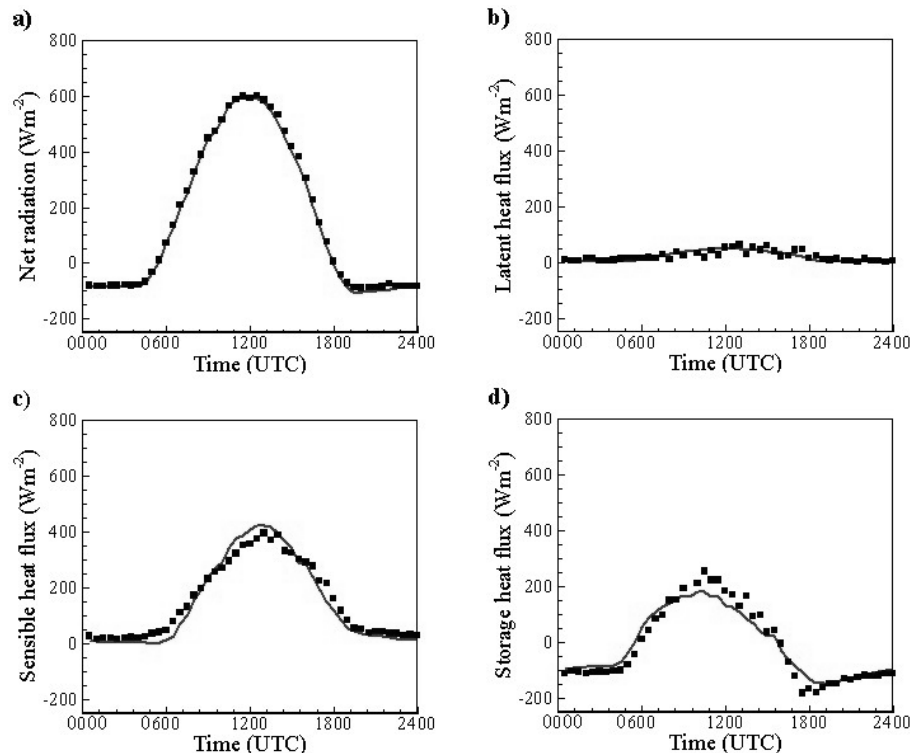
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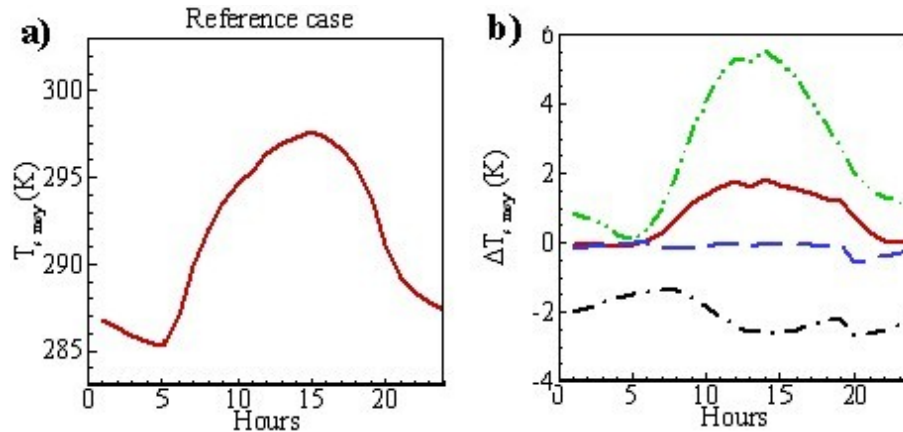
**Fig. 10.** Average diurnal cycle for observed (dotted line) vs. simulated (solid line) net radiation (a), latent heat flux (b), sensible heat flux (c), and storage heat flux (d) for the site located in Marseilles city centre during the UBL-ESCOMPTE experimental campaign of June–July 2001.

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**Fig. 11.** Influence of surface layout on the Rezé suburban settlement mean surface temperature: **(a)** surface temperature diurnal cycle in the reference simulation averaged over July 1996; **(b)** difference with the reference simulation for a dry year: with no layout change (solid line), with 1-h vegetation watering in the evening (dash line), with grassy ground for roads and parking lots (dash-dot line), with natural grounds covered with pavement (dash-dot-dot line).

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