Verification of long-term DMI–HIRLAM NWP model runs using urbanization and building effect parameterization modules

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Abstract
In this study, an evaluation of the numerical weather prediction (NWP) model's urbanization based on long-term runs of the DMI–HIRLAM model with and without urbanization modules has been done. Two modules – 1) urban anthropogenic heat flux and roughness and 2) building effect parametrization – have been tested for off-line runs of NWP model. The period studied is from 1 July till 31 August 2004.
Verification results of modules performance are summarized for forecasted diurnal cycle of wind velocity, air temperature and relative humidity fields for all stations and selected urban stations in the Copenhagen metropolitan and surroundings.

1 Introduction

It is known that the boundary layer in the urban areas has a complex structure due to multiple contributions of different parameters, including variability in roughness and fluxes, etc. All these effects can be included to some extend into models. In such areas the meteorological network is sparse (although better than most other places) and measurements at stations do not reflect a characteristic meteorological state as well as fluxes are not directly measured at such stations and within a city itself can have differences between parts may exist. Since measurements cannot reflect the complexity of the urban area the modelling is only way to examine the effects of the urban areas on the meteorological variables.
The goal of our study is to evaluate effects of urbanization of numerical weather prediction (NWP) model on simulating meteorological fields for the overall NWP model performance as well as over the urbanized areas. The specific objectives include the following. At first, to conduct long-term simulations of meteorological fields using NWP model in two modes (control vs. urbanized runs) and for two types of urbanization modules (anthropogenic heat flux and roughness vs. building effect parametrization module). Second, to evaluate effects of urbanization on temporal-spatial structure and variability of simulated meteorological fields. Third, to estimate on a diurnal cycle the differences between control and urbanized runs for meteorological variables of key importance.

2 Methodology

2.1 DMI–HIRLAM NWP Modelling and Meteorological Data

DMI performs daily forecasts of meteorological fields employing the High Resolution Limited Area Model (HIRLAM) model (Undén et al., 2002). The present DMI weather forecasting system (Yang et al., 2005) is based on HIRLAM. It consists of two nested models: DMI–HIRLAM–T15 and –S05. These two models are identical, except for horizontal resolution (15 vs. 5 km) and geographical boundaries of domains. Both versions have 40 layers in vertical. The lateral boundary values are received from ECMWF every 6 hours. The system is run on NEC–SX6 DMI supercomputer and produced model output files are archived on a mass storage system. The current operational DMI forecasting model includes a digital filtering initialization, semi-Lagrangian advection scheme,

and a set of physical parameterizations such as Savijaervi radiation, STRACO condensation, CBR turbulence scheme, and ISBA scheme.
For research purposes, the DMI–HIRLAM–U01/I01 models (resolution of 1.4 km) with domains shown in Figure 1 are employed for testing and verification of the HIRLAM model performance for high resolution (Mahura et al., 2005) and urbanization (Baklanov et al., 2006; Mahura et al., 2006) were done within the FUMAPEX project (Baklanov et al., 2005ab). For these models the preparation of land-use classification based on CORINE dataset (CORINE, 2000) and climate generation files were done at resolution of 1.4 km. Moreover, these on-going research activities are a part the DMI–Enviro–HIRLAM model developments and testing.

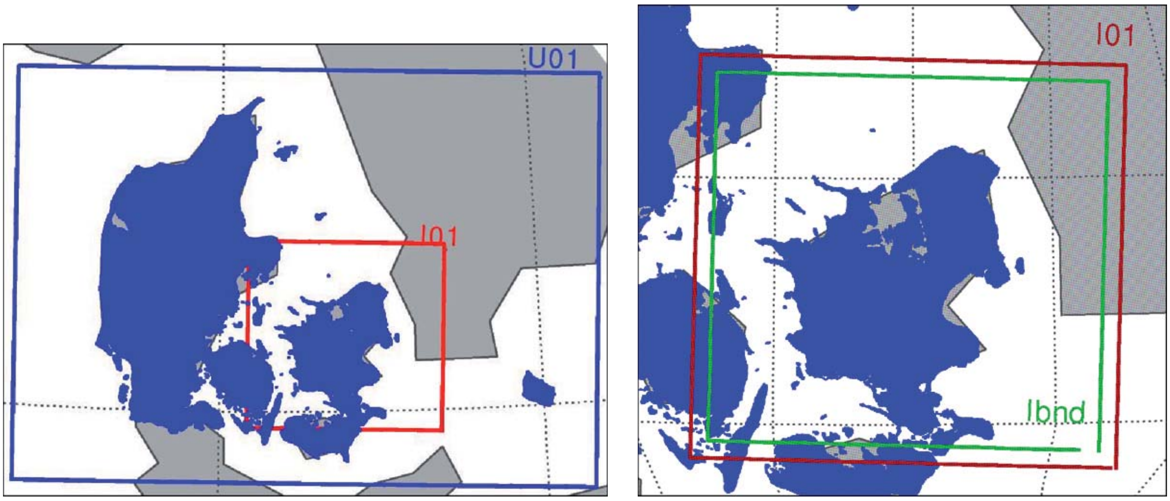


Figure 1. Domains for the DMI–HIRLAM–U01 and –I01 models.

2.2 Approach: Urban Anthropogenic Heat Flux and Roughness

The simple urbanization of NWP includes modifications (Baklanov et al., 2005b) of the land surface scheme so-called the Interaction Soil Biosphere Atmosphere (ISBA) scheme originally proposed by Noilhan & Planton (1989) and further up-dated and used in the DMI–HIRLAM model. The changes of the ISBA scheme include modifications of the set of parameters in each grid cell of the modelling domain where the urban class is presented. These modifications include the urban roughness, anthropogenic heat flux and albedo. The urban roughness changes up to a maximum of 2 m for grid cells where the urban class will reach up to 100%. The anthropogenic heat flux (from 10 to 200 W/m^2) is modified similarly to the roughness. Albedo was tested for the summer vs. winter cases – from 0.2–0.4 by factor of two, i.e. when the snow is covering the surface.

2.3 Approach: Building Effect Parameterization

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 (Hamdi & Shayes, 2007). The aim of the urban sub-layer parameterization 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) the vertical and horizontal surfaces (wall, canyon floor and roofs), (ii) the shadowing and radiative trapping effects of the buildings, (iii) the anthropogenic heat fluxes through the building's wall and roof. In this parameterization, the city is 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 (canyon width), but with different heights (with a certain probability to have a building with specific 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.

Note, 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.

2.4 Long-term Model Setup

In our study, the urban related modifications of the ISBA land surface scheme are evaluated. At first, over the grid cells of the model domain where, at least, a small fraction of urban related class was presented, the roughness and anthropogenic heat fluxes were modified to reflect the urban area presence. A combined contribution of these two features into the formation of airflow over the urban areas was incorporated into the land surface scheme. At second, the building effect module was incorporated into the land surface scheme to simulate the urban effects on atmospheric urban flow taking into account a set of main characteristics of the urban environment.

Sensitivity tests and verification of urbanization approaches were performed employing DMI–HIRLAM–U01 and –I01 models without and with urbanization for the Copenhagen metropolitan area and surroundings. The meteorological fields' simulations were driven using boundary conditions of the DMI–HIRLAM–S05 model. These conditions were used as input for simulation of meteorological fields for the urbanized models. Independent runs were done in a short-term mode for specific cases/dates with variable wind conditions and in a long-term mode for the months of July-August 2004. These included: (1) control runs with no modifications in the land surface scheme of lower and higher resolutions – *CTRL;* and (2) modified runs including (a) urban roughness and anthropogenic heat fluxes changes – *AHF+R,* and (b) building effect parameterization approach – *BEP.*

The simulated outputs (+ 24 hour forecast) were evaluated on a diurnal cycle. The diurnal cycle of meteorological variables such as wind velocity (at 10 m), humidity and air temperature (at 2 m), pressure were analyzed comparing outputs of different runs. Moreover, for specific dates 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 vs. run with modified urbanization.

3 Sensitivity tests

3.1 Specific Cases: Typical, Low, High Winds and High Precipitation Conditions

Following the simulation results, it was found that incorporating actual urban features (e.g. roughness and anthropogenic heat flux) modified the structure of the meteorological fields within the surface layer, i.e. wind, temperature, and humidity fields over urban areas.

It was found that, on average, there are some differences between NWP control vs. urbanized runs over the Copenhagen metropolitan area and surroundings. These differences are the following. For typical wind conditions, TWC (an example is shown in Figure 2), the differences for wind at 10 m are less than 0.5 m/s (with a maximum up to 1.5, at midday). For the air temperature at 2 m these are less than 0.25ºC (with a maximum up to 0.5ºC, at nighttime), and for the relative humidity – a few percent (with a maximum up to 5%, at midday).

The differences between runs are more pronounced for the low winds conditions, LWC (an example is shown in Figure 3). For such situations the differences for the wind at 10 m are more than 1 m/s (with a maximum up to 3 m/s, at nighttime). For the air temperature at 2 m these differences are more than 0.5ºC (with a maximum up to 1.5ºC, at nighttime), and for the relative humidity – a few percent (with a maximum up to 7%, at midday).

For the high wind conditions, the differences for wind at 10 m are less than 0.5 m/s (with a maximum up to 1.5 m/s, at midday). For the air temperature at 2 m these differences are less than 0.25ºC (with a maximum up to 0.75ºC, at nighttime). For the high precipitation cases, a clear pattern in differences

of wind velocities was not identified, although for the air temperature differences are less than 0.25ºC, with an unclear flat maximum of less than 1ºC occurring around noon.
Note, the urban roughness affects temperature less than wind speed. Moreover, the anthropogenic heat flux increased the temperature above the urban cells, but with a large variance over metropolitan area depending on the urban fraction in each grid cell. The changes in atmospheric pressure are negligible. For the sensible heat fluxes, the differences are negative at night hours (with a minimum at 05–06 UTCs) and positive during late morning – evening hours (with maxima at midday hours). For the latent heat fluxes, the difference is always positive during the day, except it became negligible (of less than 1 W/m^2) during late evening hours. The maxima are observed at 05–06 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. Simulation results with urban modules showed that the radiation budget does not differ significantly for urban vs. rural regions, 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 storage heat flux is usually higher in urban compared with rural areas. Other factors of importance are the low moisture availability and slightly higher thermal inertia for urban vs. rural environments. The anthropogenic heat flux is a most typical urban energy component and it is absent in rural areas.

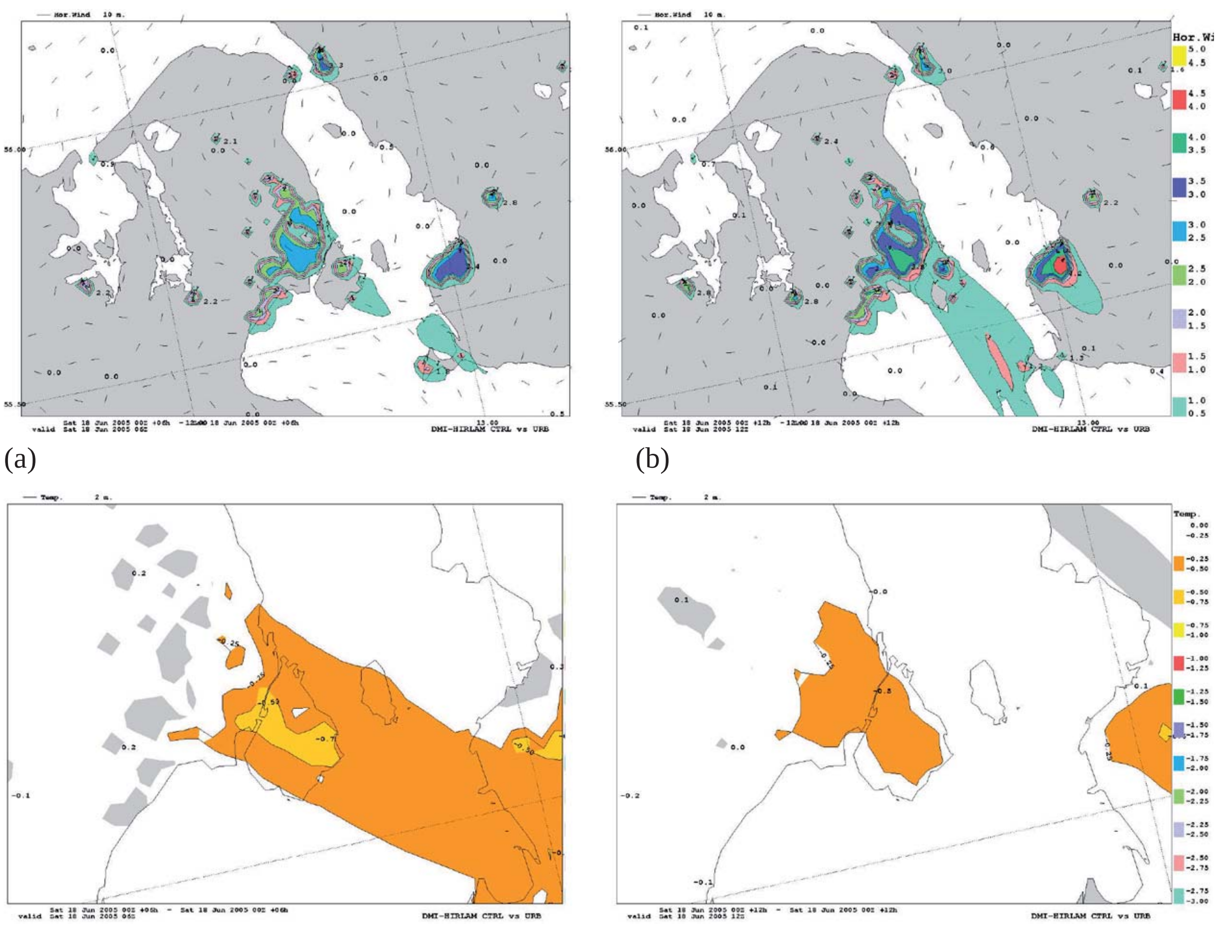
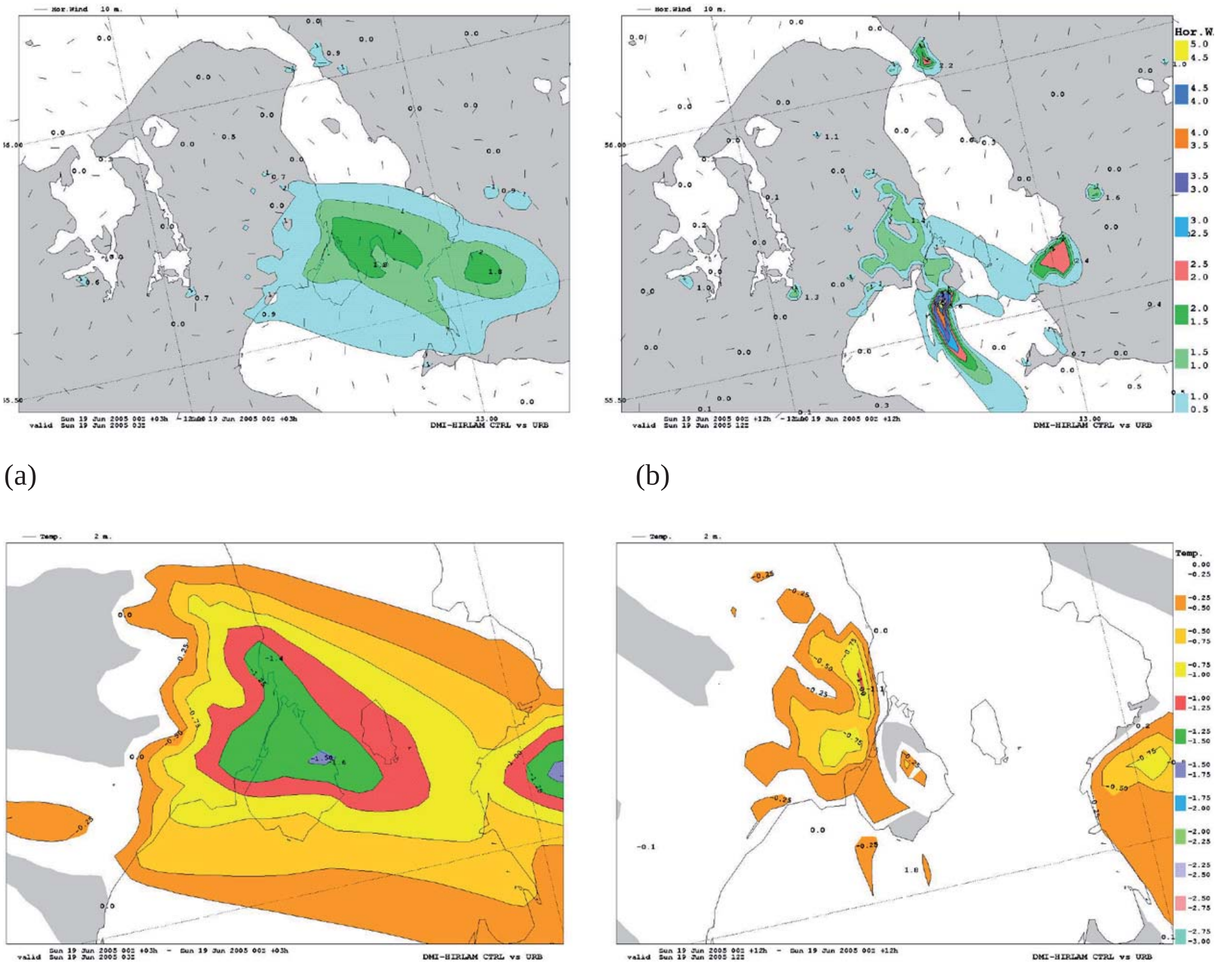


Figure 2: Typical Wind Conditions (TWC) Case: difference plots (between outputs of the DMI–HIRLAM vs. DMI–HIRLAM +Urb) – for the (a, b) wind velocity at 10 m and (c, d) air temperature at 2 m at (a, c) 06 UTC and (b, d) 12 UTC on 18 June 2005.



(a) (b)

(c) (d)

Figure 3: Low Wind Conditions (LWC) Case: difference plots (between outputs of the DMI–HIRLAM vs. DMI–HIRLAM+Urb) for the (a, b) wind velocity at 10 m and (c, d) air temperature at 2 m at (a, c) 03 UTC and (b, d) 12 UTC on 19 June 2005.

3.2 Variation Between BEP and Urban AHF+R Runs

The variation between the two urban modules runs is shown (on example of the models runs on 1 August 2004) for temperature and wind velocity in Figure 4ab vs. 4cd, respectively. As seen, the adding of urban anthropogenic heat flux in combination with roughness (Figure 4a) substantially changes the spatial distribution of the temperature field within the urban area itself, as well as an influence is extended further windward. The maximum is more than 2°C compared with a value of slightly higher than 1°C (Figure 4b) when the BEP module is used for parameterization. Moreover, an extension of influenced area is almost twice smaller in the latter case. It is more localized over the urban area and it shows less influence on the surrounding areas. This can be partially explained by consideration of the momentum part and does not include anthropogenic heat flux in the BEP module even though the AHF+R includes both effects although at a simple level.

Similarly, for wind velocity the differences between two urban modules runs are shown in Figure 4cd. As seen, simultaneous adding of both factors – AHF and roughness – creates a more complex structure of the wind field (Figure 4c). The maximum of difference is observed over the urban area and it is comparable for both modules, i.e. 1.5 m/s vs. 1.43 m/s, although it is divided spatially into two parts for the AHF+R module. Moreover, the field is more extended in the NE-SW directions for the latter compared with the BEP module.

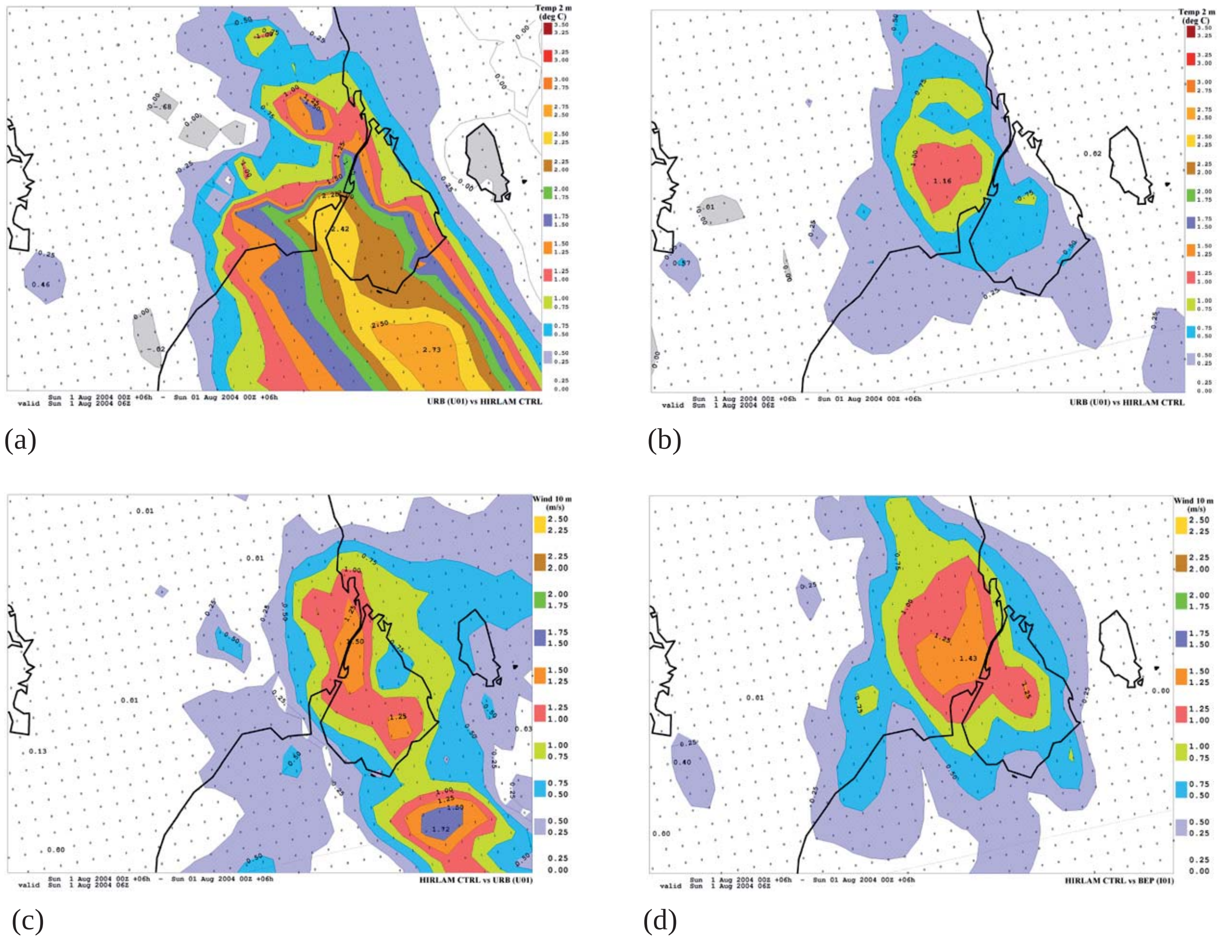


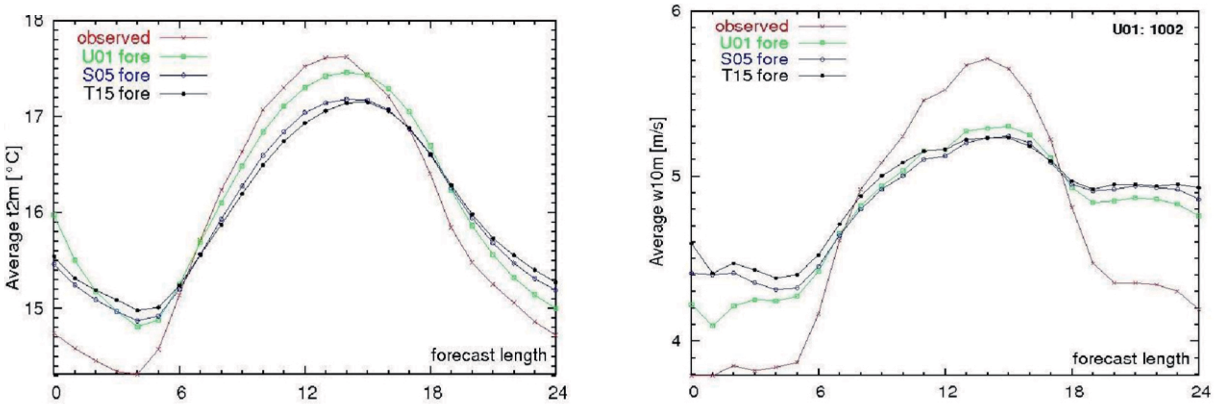
Figure 4: Difference plots (between outputs of the DMI–HIRLAM control and urbanized runs using (a,c) AHF+R and (b,d) BEP modules – modifications of the ISBA land-surface scheme) for the (a,b) air temperature at 2 m and (c,d) wind velocity at 10 m on 1st August 2004 at 06 UTC.

4 Verification for Copenhagen metropolitan area

Evaluation of the HIRLAM NWP models (–S05, –U01, and –I01) performance has been done through analysis of meteorological parameters for the diurnal variations of the average air temperature, wind velocity, and their bias/rms for 00 and 12 UTC forecasts; the hit rates (with ±2ºC and ±2 m/s) of the same temperature and wind as well as their bias/rms for 12 and 24 hour forecasts (valid at 00 and 12 UTC). This evaluation was done for the overall performance of the models but with a focus on six urban/suburban meteorological stations located in the Copenhagen metropolitan area and surroundings. All these were estimated for two selected summer months – July and August of 2004.

4.1 Forecasted Diurnal Cycle: Air Temperature, Wind Velocity and Relative Humidity

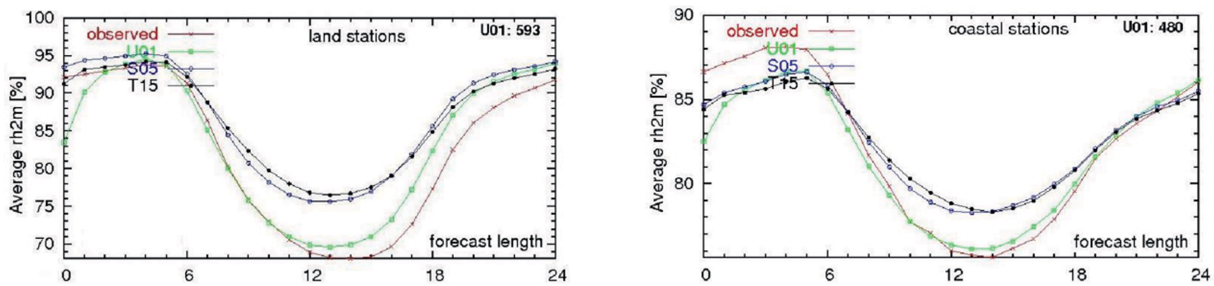
The diurnal variability for 00 UTC forecasts for the temperature and wind is shown in Figure 5ab. As seen, the higher resolution urbanized model has good predictive skills compared with two models (S05 and T15) of lower resolution. On average, the air temperature is well predicted during 06–16 and 19–24 hours compared with other models. For all models the wind velocity is overpredicted during the evening and night hours, and it is underpredicted during the daytime. For the urbanized version, during late evening and night hours (18–06 hours) a better predictability is observed for wind velocity, and moreover, it is also has better prediction during 13–17 hours, compared with the two other models.



(a) (b)

Figure 5: Diurnal variability for 00 UTC forecasts for the average a) air temperature at 2 m and b) wind velocity at 10 m for the Danish stations during August 2004 as a function of the forecast length based on the DMI–HIRLAM–T15, –S05 and –U01+(AHF+R) model runs vs. observations.

Analysis of the diurnal variability for the relative humidity showed comparable results for all models during night and evening hours, but the urbanized model had a better predictability during daytime (Figure 6ab). For the land stations, it is well predicted during 06–14 hours and during 15–20 hours it is better predicted compared with the other models. For the coastal stations, it is well predicted during 08–20 hours. As seen from Figure 6 there is a shift of 2 hours in accuracy of the relative humidity prediction which might be due to non-included heat storage flux.



(a) (b)

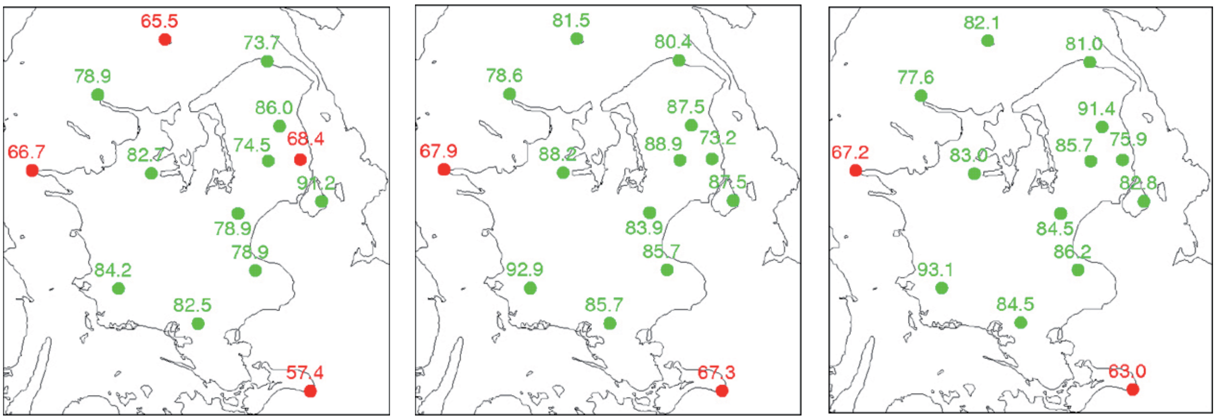
Figure 6: Diurnal variability for 00 UTC forecasts for the relative humidity at 2 m for the Danish a) land stations and b) coastal stations during August 2004 as a function of the forecast length based on the DMI–HIRLAM–T15, –S05 and –U01+(AHF+R) model runs vs. observations.

4.2 Forecast Hit Rates: Air Temperature and Wind Velocity

The hit rates (with ±2 m/s) of the wind velocity at 10 m for 24 hour forecasts for two DMI–HIRLAM models –S05 and –I01 (for latter, the control and urbanized runs) are shown on example of August 2004 in Figure 7. As seen the higher hit rates are observed for urbanized runs over the Copenhagen metropolitan area. A summary of the overall hit rates for both the wind velocity and temperature are given in Table 1 for the period studied. For wind velocity, the overall hit rates are slightly higher (around 1%) or comparable for urbanized vs. control runs, and these show better skills for compared with a lower resolution model of –S05, which is not the case for temperature. Although similar to wind velocity there are differences for urban vs. control runs, the hit rate for temperature prediction is higher for the –S05 model. It is related to the shortcoming of the approach that the BEP module used for the DMI–HIRLAM–I01 runs modifies only the momentum part and not the thermal one.

Table 1. Hit rates for the air temperature at 2 meters and wind velocity at 10 meters for the urbanized (AHF+R and BEP) vs. CTRL runs of the NWP DMI–HIRLAM (–U01 and –I01) models during the months of July and August 2004.

Month	July 2004				August 2004			
Model	*I01*	*I01*	*U01*	*U01*	*I01*	*I01*	*U01*	*U01*
Run	*CTRL*	*BEP*	*CTRL*	*AHF+R*	*CTRL*	*BEP*	*CTRL*	*AHF+R*
Forecast	Hit Rate (±2ºC) Air Temperature at 2 m							
12 h	66.3	67.0	79.6	79.7	72.9	74.1	70.3	69.6
24 h	64.9	65.6	76.8	77.2	71.9	72.8	70.9	70.5
	Hit Rate (±2 m/s) Wind at 10 meters							
12 h	82.4	83.6	84.0	83.9	83.8	84.4	81.7	81.7
24 h	78.8	79.5	79.5	79.5	81.4	81.0	80.0	80.0



(a) (b) (c)

Figure 7: Hit rate (±2 m/s, in %) of wind velocity at 10 m for 24 hour forecasts (valid at 00 and 12 UTC) for DMI–HIRLAM models a) –S05, b) I01–CTRL and c) I01+BEP runs during August 2004.

4.3 Forecasts at Urban and Suburban Stations Employing BEP Module

Analysis of the diurnal cycle variability at selected urban stations has been done for modifications of the urban anthropogenic heat flux and roughness (AHF+R) for the DMI–HIRLAM–U01 model runs (FUMAPEX, 2004; Baklanov et al., 2005b). It was found that for wind velocity the run including AHF reflected better an occurrence of local maximum than the run using roughness (which alternatively better fitted the occurrence of local minimum). For temperature, the modified run with AHF run fitted better to urban observations compared with suburban stations. Inclusion of both factors was considered to be essential. Moreover, it was found that inclusion of the storage heat flux (using objective hysteresis model of Grimmond et al., 1991) can correct a time shift of temperature field observed on a diurnal cycle.

The results of the BEP module testing showed the following. At first, for the air temperature, pressure, and wind direction were modeled in all runs with practically with no differences between the control and modified runs. Concerning the wind velocity, for 6 selected urban stations of the Copenhagen metropolitan area (as shown in Figure 9a), on a diurnal cycle, the wind velocity is better predicted with the urbanized model –I01 compared with non-urbanized model –S05, except the prediction skills are comparable during 12–18 UTCs. Differences between the control and urbanized (with BEP) runs of the –I01 model are not so large (Figure 9b), although note that the urbanized run showed slightly better results during the late morning – early evening hours (i.e. 07–18 UTCs).

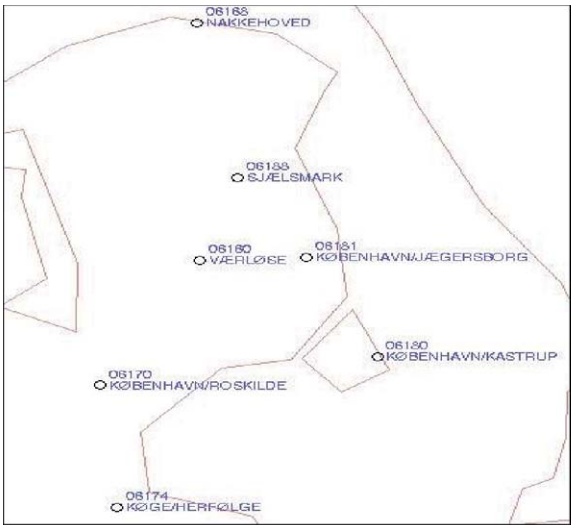
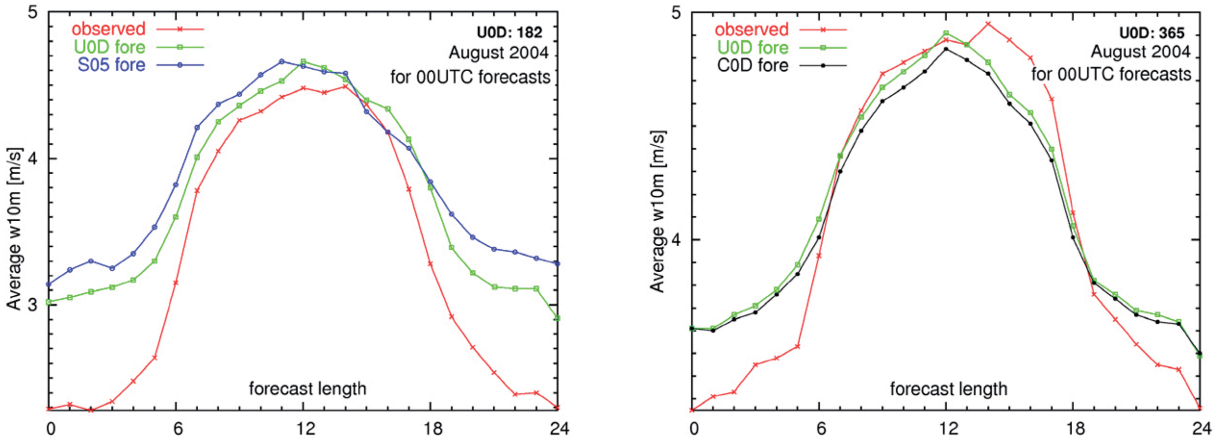
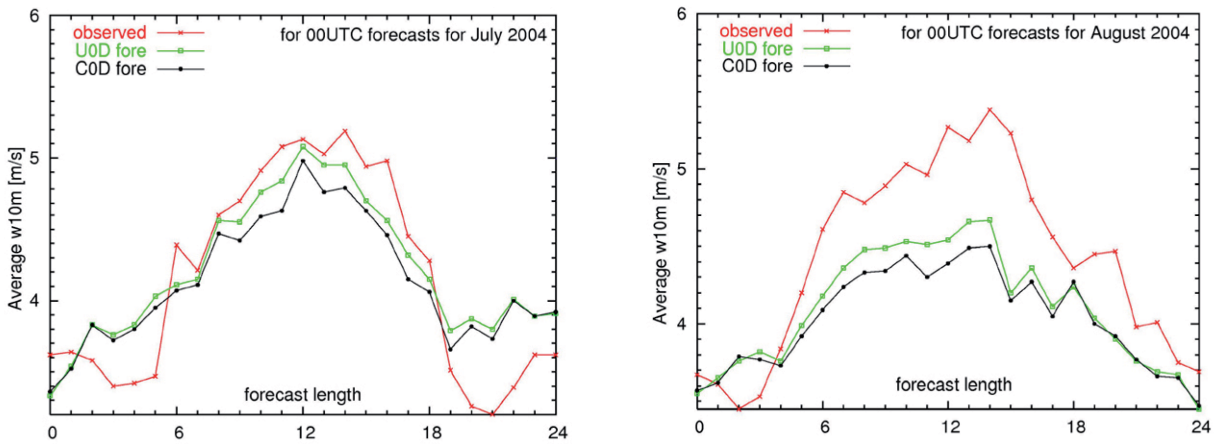


Figure 8: Urban/suburban stations in the Copenhagen metropolitan area.



(a) (b)

Figure 9: Diurnal variability for 00 UTC forecasts for the average wind velocity at 10 m for the a) 6 urban vs. a) all stations during August 2005 as a function of the forecast length based on the DMI–HIRLAM–S05, –I01+BEP and –I01–CTRL model runs vs. observations.



(a) (b)

Figure 10. Diurnal variability for 00 UTC forecasts for the average wind velocity at 10 m for the urban station N–6180 in the Copenhagen metropolitan area during month of (a) July and (b) August of 2004 as function of the forecast length based on the DMI–HIRLAM–I01+BEP and –I01–CTRL model runs vs. observations.

As an example, the diurnal variability of wind velocity is shown for one of the stations (N–6180) located in the Copenhagen (Figure 10). As seen, the differences are small, but the urbanized version showed a slightly better predictive skill during daytime. For the rural sites such differences are even smaller, i.e. practically negligible.

5 Conclusions

The urbanization of DMI–HIRLAM model with modified roughness, anthropogenic heat fluxes and building effects allowed showing effects over urbanized areas.

In our study, we have found that, on average, the differences between NWP control vs. urbanized runs were the following over the Copenhagen metropolitan area and surroundings. For typical wind conditions, the differences for: 1) wind at 10 m is less than 0.5 m/s (with a maximum up to 1.5, at midday); 2) air temperature at 2 m is less than 0.25ºC (with a maximum up to 0.5ºC, at nighttime); and 3) relative humidity is a few percent (with a maximum up to 5, at midday). For the low wind conditions, the differences for: 1) wind at 10 m is more than 1 m/s (with a maximum up to 3 m/s, at nighttime); 2) air temperature at 2 m is more than 0.5ºC (with a maximum up to 1.5ºC, at nighttime); 3) relative humidity is a few percent (with a maximum up to 7%, at midday).

Moreover, the long-term runs with the DMI–HIRLAM–U01/I01 high resolution urbanized models showed a slight improvement for the overall NWP model performance, but this improvement is more visible over the urbanized areas. Note, these two 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. It is obvious that these developments in 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).

Further analyses of long-term simulated meteorological fields, performances, CPU usage, and other capabilities are planned also for the urban module called the Soil Model for Sub-Meso scales Urbanized version (SM2–U) which is based on the full force-restore soil submodel for urban areas (Dupont, 2001; Dupont et al., 2007ab).

6 Acknowledgements

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