ANALYSING URBAN EFFECTS IN BUDAPEST USING THE WRF NUMERICAL WEATHER PREDICTION MODEL

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Abstract. - Analysing Urban Effects in Budapest using the WRF Numerical Weather Prediction Model. Continuously growing cities significantly modify the entire environment through air pollution and modification of land surface, resulting altered energy budget and land-atmosphere exchange processes over built-up areas. These effects mainly appear in cities or metropolitan areas, leading to the Urban Heat Island (UHI) phenomenon, which occurs due to the temperature difference between the built-up areas and their cooler surroundings. The Weather Research and Forecasting (WRF) mesoscale model coupled to multilayer urban canopy parameterisation is used to investigate this phenomenon for Budapest and its surroundings with actual land surface properties. In this paper the basic ideas of our research and the methodology in brief are presented. The simulation is completed for one week in summer 2015 with initial meteorological fields from Global Forecasting System (GFS) outputs, under atmospheric conditions of weak wind and clear sky for the Pannonian Basin. Then, to improve the WRF model and its settings, the calculated skin temperature is compared to the remotely sensed measurements derived from satellites Aqua and Terra, and the temporal and spatial bias values are estimated.

Keywords: urban modelling, Weather Research and Forecasting Model, land use, urban heat island, mesoscale processes

1. INTRODUCTION

The population of Earth is steadily growing, and due to urbanisation it is concentrated in metropolitan areas. This causes several environmental and social problems because more than half of the total population live in cities although these cities cover only about 2% of the global land area (United Nations, 2007). The artificial surface covers significantly modify the surface energy budget through modification of natural lands resulting in altered local wind and temperature patterns because of the presence of buildings. The buildings' three-dimensional extensions affect the incoming radiation, the sky-view factor as well, as the wind field resulting in specific local microclimates of the metropolitan areas. The increased temperature in the central built-up areas and the cooler surroundings of the cities lead to the urban heat island phenomenon, which is widely studied with observations (e.g., *Landsberg,*

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1981; Oke, 1987; Dezső et al., 2005) and numerical models (e.g., *Kimura & Takahashi, 1991; Avissar, 1996; Taha, 1999; Kusaka et al., 2000*).

The resolutions of mesoscale models are usually not appropriate to analyse the urban effects, however, in the last decade some improvement can be recognized toward developing urban schemes and building in into atmospheric models. These submodels calculate the physical effects caused by the presence of the buildings (e.g. *Kusaka et al., 2001, Martilli et al., 2002*). Such urban submodels are used in case of the Weather Research Forecast (WRF) mesoscale modelling system (*Skamarock et al., 2008*). *Chen et al. (2014)* and *Gutiérrez and Gonzalez (2015*) used the WRF model for different metropolitan areas, i.e., Hangzhou City, China and New York, USA, respectively. The WRF simulations require detailed classification of building data for the pre-processing system and the land use category in each urban grid. Therefore, it is necessary to set up the actual, detailed land use data with high resolution for the target area.

Previously, at the Dapertment of Meteorology of Eötvös Loránd University the urban heat island effect for Budapest was mainly examined based on satellite measurements (*Dezső et al., 2012*), however, these data were not used for modelling purposes. The ultimate goals of our current study are (i) to compile a database of the actual land cover for Budapest and its vicinity, and (ii) to develop a methodology to examine the urban processes using the WRF numerical model.

The WRF model and simulations for the urban area

For the simulations the WRF model is used, which is a mesoscale numerical weather prediction system using compressible and non-hydrostatic equations of motion (*Skamarock et al., 2008*). It includes a number of options for various physical processes, i.e., land-surface exchange processes, microphysics, urban surface processes, etc. The prognostic equations are calculated on mesoscale, meanwhile the microscale urban processes are managed via urban parametrisation in the model integration. The model can distinguish three or more urban surface categories within the model target area: low-intensity residential, high-intensity residential, and commercial/industrial. The model includes three types of urban parametrisation.

(1) the bulk urban parametrisation in the Noah scheme (*Chen and Dudhia, 2001*), using variant parameters for the urban surfaces (referred as SLAB model). The roughness-length is 0.8 m to represent the drag effects due to buildings, the albedo is 0.15 to represent the shortwave radiation trapping due to urban canyons, and the volumetric heat capacity and thermal conductivity are also different from the natural surface parameters. Furthermore, it calculates the soil moisture and temperature at four levels under the built-up surfaces.

(2) A more complex urban parametrisation in WRF is the single-layer urban canopy model (SLUCM), developed by *Kusaka et al.* (2001), *Kusaka and Kimura* (2004). The calculations use infinitely-long street canyons parameterized to represent urban geometry. SLUCM recognizes the three-dimensional extension of the cities resulting in shadowing, radiation trapping, and reflection. The total

sensible heat flux involves the fluxes from roof, wall, roads, and added to the calculated sensible heat flux from Noah LSM. Anthropogenic heat and its diurnal variation are predefined in SLUCM, and incorporated by adding them to the sensible heat flux from the urban canopy layer. The presence of the buildings increases the roughness, therefore this scheme calculates the drag effects with exponential wind profile over the city (Fig. 1, left).

(3) One of the most sophisticated urban canopy models in WRF is the BEP (Building Energy Parametrisation), which allows direct interaction with the planetary boundary layer (*Martilli et al., 2002*). The three dimensional extent of buildings represent sources and sinks of heat, moisture, and momentum. Prognostic turbulent kinetic energy is generated by the effects of vertical (walls) and horizontal (streets and roofs) surfaces of momentum. The BEP keeps the building internal temperatures constant, in contrast to BEM (Building Energy Model), which takes into account the heat generated by buildings and equipments, such as air conditioning, ventilation, and heating at each floor of the building, which depends on the height of the buildings. BEM calculates the radiation passing through windows and the indoor temperature. The incoming shortwave radiation is reflected, shadowed, and trapped depending on the surface properties and their orientations. The BEP model can be used by itself, or coupled to the BEM model, however, *Liao et al.* (*2014*) found that considering temperature, the BEP alone will perform worse than the SLAB model. To take appropriate use of BEP/BEM, high vertical resolution of the urban canopy is needed. In order to increase the resolution in the urban model, several atmospheric model levels are necessary in the urban canopy layer, which requires dense vertical levelling close to the surface.

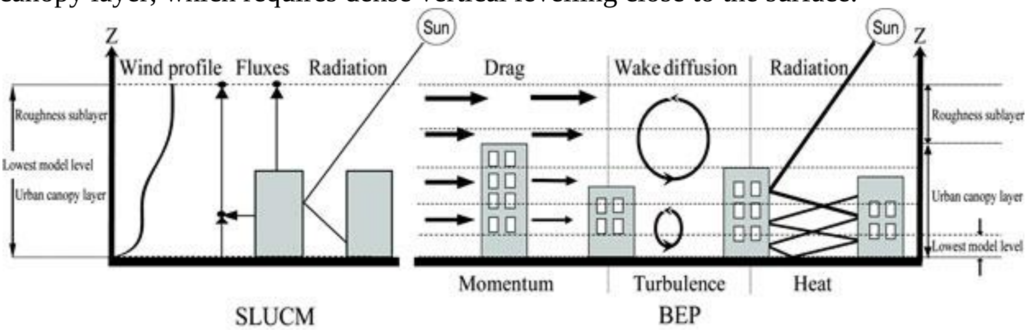

Fig. 1. ***Schematic effects of urban parameterisations in WRF. Left: Single-layer urban canopy model, Right: Building Energy Model (Chen et al., 2010).***

These urban canopy schemes are able to reproduce the urban heat island (UHI) with numerical models, especially the nocturnal UHI. The increased volumetric heat capacity, the decreased sky-view factor, and the added anthropogenic heat over the cities help the simulation of UHI both day and night.

In our simulations four target areas are defined (Fig. 2), the most external (D01) domain covers the whole Pannonian Basin with 10 km horizontal resolution, whereas the innermost domain (D04) covers Budapest and its surroundings with 370 m grid resolution. The other two intermediate embedded domains (horizontal resolution: 3333.33 m and 1111.11 m in case of D02 and D03, respectively) are needed for the dynamical downscaling in order to prevent numerical instabilities. All these outer domains use 44 Eta vertical levels. Because of the high horizontal resolution, the innermost domain contains 87 vertical levels. This vertical refinement is interpolated using the program *ndown* available in WRF for reducing vertical instabilities. In addition, *ndown* creates lateral boundary conditions for the simulations over D04.

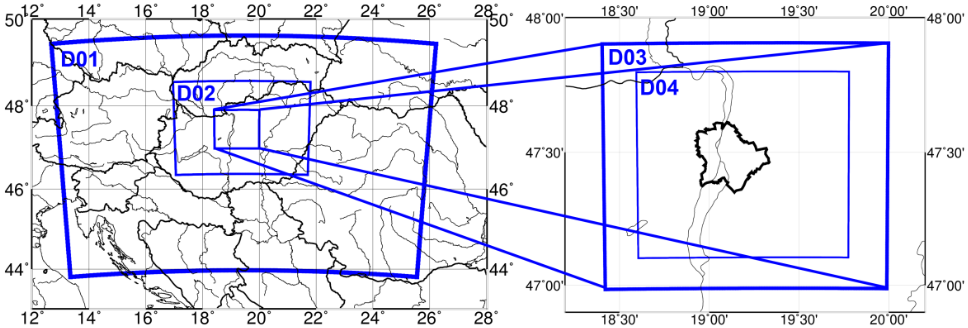

Fig. 2. ***WRF simulation domains over Hungary and around Budapest. Horizontal resolutions are as follows: 10 km (D01), 3.33 km (D02), 1.11 km (D03), 0.37 km (D04).***

In the simulations the BEP+BEM is used with the unmodified predefined urban parameters (Table 1) for the three urban categories included in the model. *Wang et al.* (*2011*) analysed the uncertainty of these parameters, and concluded that the geometry of cities is one of the most important parameter, while for instance the indoor temperature has less impact on the calculations.

Table 1. ***Some of the urban parameters and their value used for BEP+BEM in the WRF model.***

Parameters	Commercial/ Industrial	Low-intensity residential	High-intensity residential
Heat capacity of roof/walls [J m^{-3} K^{-1}]	1.0E6		
Heat capacity of ground [J m^{-3} K^{-1}]	1.4E6		
Thermal conductivity of building wall/roof [J m^{-1} s^{-1}K^{-1}]	0.67		
Thermal conductivity of ground [J m^{-1} s^{-1}K^{-1}]	0.4004		
Albedo of walls/roof/ground [-]	0.20		
Surface emissivity of roof/walls [-]	0.90		
Surface emissivity of the ground [-]	0.95		
Coverage area fraction of windows in the walls of the building [-]	0.2		
Peak heat generated by equipment [W m^{-2}]	36.00	20.00	16.00

To prevent numerical instabilities in the simulations, adaptive time steps are used, therefore, the maximum value of Courant-Friedrich-Lewy criteria were set up to 0.8 in the three external domain. The calculated time steps are approximately 90 s for D01, 15 s for D02, 4-5 s for D03, and 2 s for D04. To reduce the instabilities in the upper atmosphere due to the gravity waves, vertical damping is used.

2. DATA

Surface data

Before starting the simulations the detailed and actual surface has to be set up for the model domain. The WRF originally includes the USGS (United States Geological Survey) database, which contains only one urban category, and the extent of Budapest is quite inadequate (Fig. 3, left). In order to create a new detailed surface cover input with high resolution, the CORINE 2000 (Coordination of Information on the Environment) and OpenStreetMap[2] (OSM) database are used. The OSM is an open-sourced, free, editable map of the world, which includes buildings, roads, water bodies, land use categories, and much more information.

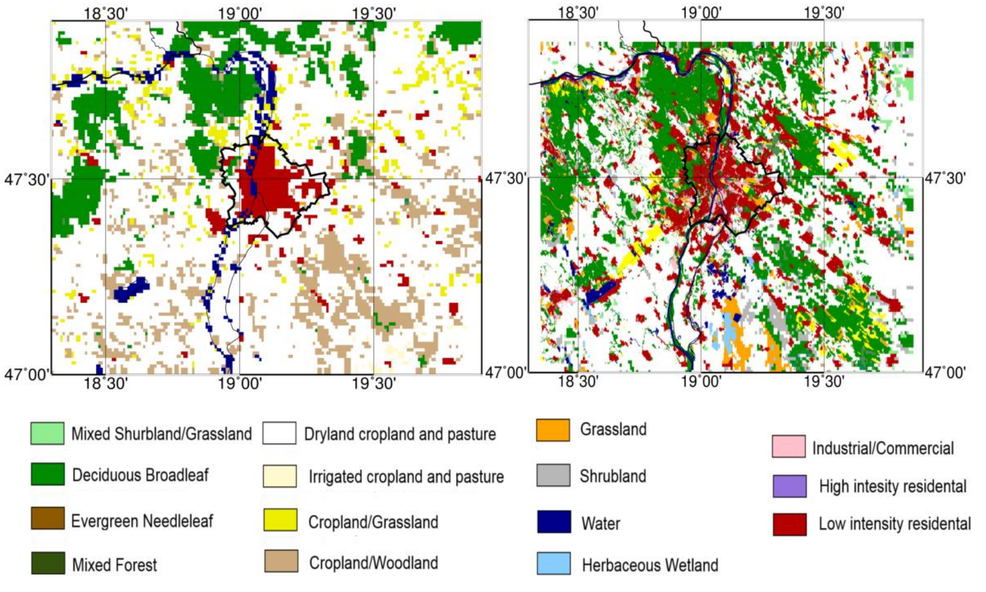

Fig. 3. ***Land use distribution over the model domain in D04, left: from USGS database, right: newly created from OSM and CORINE 2000.***

The available information is converted with the free, cartographic software QGIS resulting in the binary surface files needed for the WRF pre-processing system. Fig. 3 compares the original and the newly created land use distribution made from the OSM and CORINE 2000 with approximately 100 m horizontal resolution and three urban categories. Due to the innermost domain's fine resolution, redefinition of

[2] OpenStreetMap: https://www.openstreetmap.org/

topography is also needed. The source of high resolution topography is the SRTM (Shuttle Radar Topography Mission) database with 90 m horizontal resolution. The static boundary conditions of soil compiled from DKSIS database (Digital Kreybig Soil Information System) (*Pásztor et al., 2010*; *Göndöcs et al., 2015*).

To refine the calculations it is possible to set up the individual urban geometry for each city with several parameters, e.g., mean building height, standard deviation of building height, area-weighted mean building height, building surface to plan area ratio, frontal area index, plan area fraction, etc. For these main parameters, the binary files are created on the base of the OSM database using the net of the streets, the urban types and the specific buildings, such as 10-storey buildings or the densely built downtown of Budapest. Fig. 4 shows the calculated height and deviation of the buildings at Budapest and its surroundings. The railways, the downtown, and the areas covered by vegetation (city parks, cemeteries, etc.) are all clearly visible.

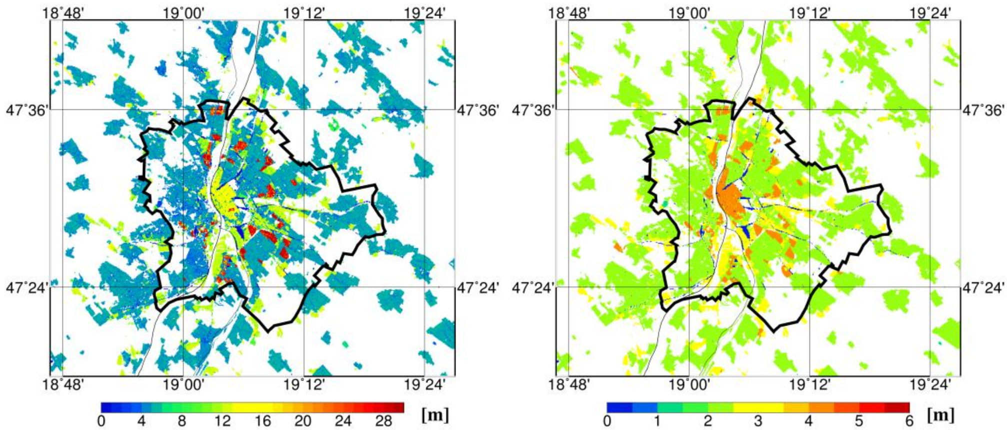

Fig. 4. ***Calculated urban parameters specifically for Budapest over the model domain area D04. Left: building height [m], right: building standard deviation [m]***

Meteorological data

UHI can be recognized the most clearly at atmospheric conditions of clear sky and calm wind, therefore for the test runs such a summer week of 02–07 July 2015 has been selected when mainly the whole Pannonian Basin was under anticyclone conditions. On the very last day of the simulation week, a strong cold front arrived to Hungary with heavy thunderstorm, rain, and strong wind. The initial meteorological fields for WRF are derived from the GFS (Global Forecast System) Analysis database with 0.25° horizontal resolution. Quite large bias values can be recognized in the calculated fields over cities probably caused by the coarse resolution of GFS, in which Budapest is not represented appropriately.

3. RESULTS AND CONCLUSIONS

For the characteristics of the UHI intensity the air temperature at standard 2 m height can be used, or alternatively, the surface skin temperature can also be used, which defines SUHI (Surface Urban Heat Island) intensity. In this study, we used this latter type of intensity in order to evaluate – and later verify – the urban processes in the WRF simulations. From the simulations, results for D03 are presented here. First, the calculated SUHI intensity is evaluated. Urban area is defined as the gridpoints where (i) the altitude does not exceed 200 m, (ii) the surface is not covered by waterbodies, and (iii) the surface is covered by artificial material within the city boundaries of Budapest. The surrounding rural area includes irrigated and dryland cropland and pastures, forests, shrub- and grasslands, and excludes rivers, lakes, and smaller settlements in the vicinity of Budapest (Fig. 3).

Distributions of hourly values of the one week simulation are shown in Fig. 5, more specifically, the maximum, the minimum, the median, the upper and lower quartile values are indicated at each hour of the day in the form of a Box-Whisker diagram. The diurnal variation of averaged SUHI intensity includes a minimum before sunrise (at 05 UTC) and a maximum in the evening after sunset (19 UTC). The inter-day variation of SUHI intensity significantly increased at 16 UTC due to the passing cold front, which strongly decreased the SUHI intensity on the last day of the simulation resulting in very small intensity values. After the front passed the area the spread slowly decreased back by the end of the day. Compared to satellite measurements available for the target area (e.g., *Dezső et al., 2012*) the simulated SUHI intensity is smaller by about 1.5 °C both during the day and the night. One of the reasons for this difference is that the GFS data used for model initialisation includes surface temperature values lower than the satellite measurements. As an example of spatial distribution of skin temperature, the daily average value is presented for 6 July in Fig. 5 (right). All build-up areas in Budapest can be identified because of the higher temperature values. The highest values are around 32 °C, most of which are inside the city contour indicating Budapest. Furthermore, the cooler regions to the northwest of the city can be recognized, which are mountains nearby (i.e., Pilis, Gerecse).

The preliminary results presented in this paper justify that the constructed WRF model is able to appropriately represent the UHI effect although the simulated SUHI intensity values are below the satellite measurements. Our further aim is to improve the model parameters and settings within WRF. For this purpose we are planning to (i) compare the calculated skin temperature from WRF simulations to satellite measurements derived from Aqua and Terra, and (ii) estimate the temporal and spatial bias values in great details for the D03 domain using ~1 km spatial resolution.

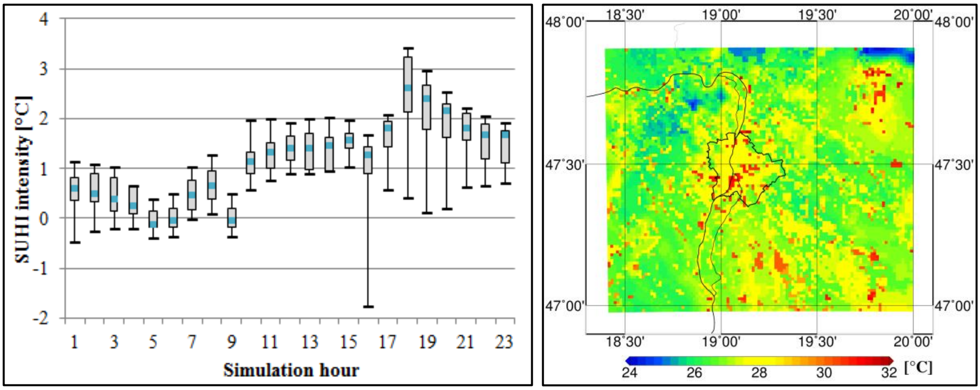

Fig. 5. ***Summary of SUHI intensity results for the D03 domain. Left: Distribution of SUHI intensities averaged for each hour throughout the simulation days: median is displayed with blue squares, maximum and minimum values are indicated by the thick black lines at the end of the vertical thin lines, upper and lower quartile values are indicated by the grey columns. Right: the daily average skin temperature on 6 July 2015 over the model domain D03.***

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