NUMERICAL MODELLING OF THE BUCHAREST URBAN HEAT ISLAND WITH THE WRF-URBAN SYSTEM

A. IRIZA[1], R.C. DUMITRACHE[1], S. ŞTEFAN[2*]

[1]National Meteorological Administration, 97 Bucuresti – Ploiesti str., Bucharest, Romania,
E-mail: amalia.iriza@meteoromania.ro; rodica.dumitrache@meteoromania.ro
[2] University of Bucharest, Faculty of Physics, P.O.BOX MG-11, Magurele, Bucharest, Romania
[*]*Corresponding author*: sabina_stefan@yahoo.com

Received December 12, 2016

Abstract. The main purpose of this study is to assess the ability of the *Weather Research and Forecasting* (WRF) model to capture the Bucharest urban heat island. Simulations with the WRF model run at high resolutions (4.5 km – 1.5 km – 500 m) in different configurations were carried out in order to test the sensitivity to urban parameterization schemes employed by the model. Several cases from March 2014 were selected for this purpose. The model was integrated using initial and lateral boundary conditions from the *European Centre for Medium Range Weather Forecast* (ECMWF) model. Numerical simulations were performed using no urban parameterization scheme, *a single level urban canopy model* (SLUCM) or a *building environment urban parameterization* (BEP). Results from the numerical simulations are analysed in comparison to 2 m temperature measurements from two synoptic stations (urban and peri-urban) in Bucharest. Results suggest a better performance of the WRF modelling system when a complex urban parameterization scheme (BEP) is used.

Key words: Bucharest Urban Heat Island, urban parameterization.

1. INTRODUCTION

The present paper is the second part of a study dedicated to the numerical simulation of the *Bucharest Urban Heat Island* (Bucharest UHI) with the WRF modelling system. The first part of the study was dedicated to the coupling of the WRF model with two land-use data sets and led to the identification of the *Moderate-Resolution Imaging Spectroradiometer* (MODIS) data set as the most accurate for Romanian territory. This second part of the study concentrates on the coupling of the WRF model with or without urban parameterization schemes.

The urban heat island (UHI) effect is defined by the fact that the air in the urban canopy is usually warmer than that in the surrounding countryside [1]. The difference between the warm urban core and the background rural temperature defines the UHI intensity [1]. Extensive reviews on the progress in urban climatology and scale modelling of urban climate have been conducted [2, 3], while urban areas and their effect on local meteorology have been the object of many studies which include the general characteristics of the phenomenon, the identification and characterization of the UHI for different urban areas [4, 5], and the impact on meteorological variables [6, 7].

The necessity to assess the impact of urban areas on local meteorology and the extensive development of *numerical weather prediction* (NWP) models has led to a particular interest in the representation of urban areas in such models, thus creating coupled urban-NWP modelling systems. *Single-layer urban canopy models* (SLUCMs) [8, 9, 10] represent the urban geometry as infinitely long street canyons and take into account different urban surfaces, while estimating surface skin temperature, heat and momentum fluxes. The most complex approaches used for the parameterization of urban areas are the multi-layer urban canopy models such as *Building Environment Parameterization* (BEP) [11] and *Building Energy Model* (BEM) [12]. These parameterizations represent three-dimensional urban surfaces and consider the effects of vertical and horizontal surfaces on potential temperature, momentum and turbulent kinetic energy in the urban canopy layer.

In recent years, the *Weather Research and Forecasting* (WRF) model [13] has been the object of intensified efforts in order to improve the ability of the model to capture and assess different problems in urban areas [14]. Studies performed for various urban regions such as Stuttgart [15], Lisbon [16], Salt Lake City [17], Taipei [18] and Beijing [19] proved the advantages of using the WRF-Urban/Noah coupled system for the study of the UHI phenomenon and its effects on precipitation, boundary layer development, local meteorology, air pollution. Salamanca *et al.* [20] points out the importance of using numerical models such as WRF in order to perform detailed studies over longer periods of time, for different urban areas, in order to analyse the impact of the UHI on cloud formation, planetary boundary layer structure and air quality.

The largest city and capital of Romania, Bucharest is the sixth largest city in the European Union by population within city limits ([21], © European Union, 1995–2014). Situated in the southern part of the country, in the Romanian Plain, Bucharest is considered a Larger Urban Zone and is an important transportation hub and economic center. However, the Bucharest UHI has primarily been the subject of observational research. The behavior of the Bucharest UHI in terms of extension, geometry and magnitude has been described using MODIS thermal data [22, 23]. Studies on the Bucharest UHI were also conducted by Andrei and Stefan [24], who took into account synoptic-scale circulation patterns over South-Eastern

Europe and revealed a strong relationship between the Bucharest UHI, air mass circulations and the impact upon the weather in Bucharest.

In the present study, the performance of the WRF model in capturing the Bucharest UHI was analyzed using various urban parameterization schemes employed by the model. The modelling system and analysis methods are described in Section 2 of this paper, while Section 3 is dedicated to the analysis of the results obtained with the numerical simulations, followed by conclusions in Section 4.

2. MODEL SET-UP AND METHODS

The WRF model with the Advanced Research WRF solver (ARW) dynamical core (version 3.4) was integrated for 6 cases in the spring of 2014 when the observed intensities of the Bucharest UHI varied between -1^{o}C and 8^{o}C. Numerical simulations were performed for the initial dates of 11, 12, 13, 20, 30 and 31 March 2014 (30 hours of forecast), in order to assess the ability of the WRF model to capture the Bucharest UHI observed in this period. The 2 m temperature forecasts from the WRF model were compared to the observations registered at two synoptic stations: station B1 (urban) located in the center of Bucharest (Bucharest-Filaret), and station B2 (peri-urban) located at the periphery (northern limit) of the city (Bucharest-Baneasa).

The WRF model was integrated for three nested domains, with the two-way nesting option and feedback between them (Fig. 1). The domains covered the entire Romanian territory (d01 – 4.5 km – 175 × 127 grid cells, 35 vertical levels), the South part of the country (d02 – 1.5 km – 310 × 169 grid cells, 35 vertical levels) and the Bucharest urban area and surroundings (d03 – 500 m – 403 × 382 grid cells, 35 vertical levels).

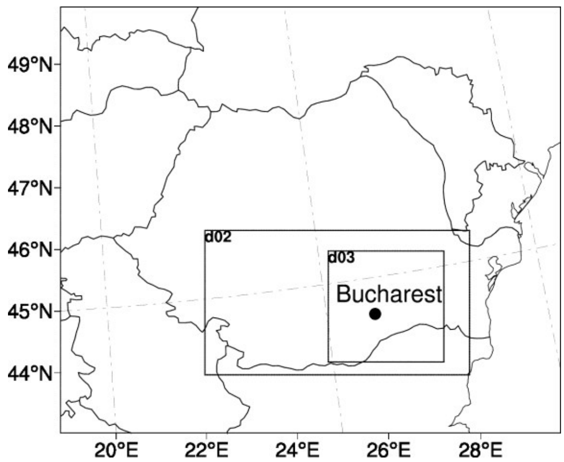

Fig. 1 – WRF integration domains 4.5 km, 1.5 km (d02) and 500 m (d03).

Recent studies [25, 26] have shown that topography data at 3 seconds horizontal resolution from the *Shuttle Radar Topography Mission* (SRTM) database [27] offer the best approximation for the Romanian territory. As a consequence, the WRF model was integrated using this topography data.

Previous studies performed with the WRF model for the Bucharest UHI employed *Consortium for Small-Scale Modelling* (COSMO, [28]) initial and boundary conditions. However, the use of COSMO numerical forecasts does not currently allow the coupling with the more complex urban parameterization schemes available in the WRF model. As a consequence, for this study initial and lateral boundary conditions were obtained from the *European Centre for Medium Range Weather Forecast* (ECMWF, [29]) global model. All numerical experiments were performed with the Thompson microphysics scheme [30], the *Rapid Radiative Transfer Model* (RRTM; [31]) for shortwave radiation and Dudhia scheme for long wave radiation [32], while convection was solved explicitly for the 1.5 km and 500 m integrations. For the planetary boundary layer and land-surface we employed the Mellor-Yamada-Janjic scheme [33] coupled with the Unified Noah land-surface scheme [34].

In accordance with results obtained from previous numerical simulations, MODIS land-use data [35] were employed and the WRF model was integrated using three options for the urban parameterization schemes (Table 1): no urban parameterization scheme (except the bulk parameterization existing in the land-surface option), the *single-layer urban canopy model* – SLUCM [10] or the BEP scheme [11].

Table 1

Description of the numerical experiments performed

Experiment ID	LBC ECMWF	MODIS Land-Use Data	Urban Parameterization		
			NO	UCM	BEP
WRF+NO	x	x	x		
WRF+UCM	x	x		x	
WRF+BEP	x	x			x

Similar to the study regarding the influence of land-use data on the forecast of the Bucharest UHI with the WRF model, the analysis of the results was performed using several methods. The UHI intensity defined as 2 m temperature differences between stations B1 and B2 (urban – peri-urban) was computed (observations and model equivalents) for each configuration (Table 1), for each individual day. The frequencies of urban-peri-urban temperature differences in one degree temperature intervals for each hour were calculated for all cases in order to study the diurnal cycle of the UHI intensity. Mean frequencies were computed for the entire period, for four the intensity classes, following [36]: class 0 – urban cold island ($\Delta T \leq 0.0$ °C); class I – normal UHI (0.0 °C < $\Delta T \leq 3.0$ °C); class II – medium UHI (3.0 °C < $\Delta T \leq 6.0$ °C) and class III – high (intense) UHI (6.0 °< ΔT).

The normalization proposed by Oke [37] was used to study of the typical course of temperature differences during the day. In order to reduce the influence of individual characteristics of each day, each value was averaged and normalized to 1, following Eq. 1.

$$(\Delta T - \Delta T_{min})/(\Delta T_{max} - \Delta T_{min}), \quad (1)$$

where ΔT is the mean hourly difference between urban and peri-urban 2 m temperatures, ΔT_{min} and ΔT_{max} are the minimum and maximum differences in hourly urban and peri-urban temperatures at 2 m (over all cases). The analysis of the mean daily course of the UHI intensity (observations and model equivalents) was performed using isotherms for temperature differences between B1 and B2. The normalized UHI and the isotherms for temperature differences were analysed for periods of 30 hours, starting from 00 UTC until 06 UTC the next day, in order to capture the evolution of the phenomenon in the first hours of the morning.

3. RESULTS

3.1. FREQUENCY OF HOURLY TEMPERATURE DIFFERENCES

The frequency of class 0 differences is underestimated by the model in all the configurations used for the present numerical experiments (Table 2). Moreover, WRF-4.5 km+NO and WRF-4.5 km+BEP do not forecast such events at all, while observations show an 18.40% frequency of such differences. For this class, the best results (lowest underestimation of the number of events) are given by the WRF+UCM model at all horizontal resolutions (underestimation of approx. 11.46%, Table 2).

In all three model configurations, at all spatial resolutions, the model strongly overestimates the frequency of class I intensities, forecasting over twice as much events compared to the observed ones. Better results for this class are obtained with the WRF+BEP configuration, which estimates frequencies of up to 62.15%, while the other configurations estimate frequencies around 90% and above. For class II, all configurations strongly underestimate the frequency of differences within this range compared to observations, with the exception of WRF+BEP. In this last configuration, the model has a similar behaviour as for the previous class, overestimating the frequency of class II intensities compared to observations with up to 22.91%. Good results for this class are obtained with the WRF+NO configuration which is the closest to the observed frequency in this case at all horizontal resolutions. The class III intensity Bucharest UHI has the lowest observed frequency (7.98%) and is only captured by the WRF+BEP configuration at all three spatial resolutions, but frequencies are underestimated compared to observations.

Table 2

Frequency of the hourly urban-rural temperature differences (%)

Observations / Numerical simulations	Frequency (%)			
	class 0 $\Delta T \leq 0.0^oC$	class I $0.0^oC < \Delta T \leq 3.0^oC$	class II $3.0^oC < \Delta T \leq 6.0^oC$	class III $\Delta T > 6.0^oC$
Observations	**18.40**	**53.13**	**20.49**	**7.98**
WRF-4.5 km+NO	0.00	92.36	7.64	0.00
WRF-4.5 km+UCM	9.37	90.28	0.35	0.00
WRF-4.5 km+BEP	0.00	**56.25**	**43.40**	**0.35**
WRF-1.5 km+NO	0.35	89.93	9.72	0.00
WRF-1.5 km+UCM	6.94	91.67	1.69	0.00
WRF-1.5 km+BEP	**1.03**	**56.95**	**40.28**	**1.74**
WRF-500 m+NO	0.35	87.85	11.80	0.00
WRF-500 m+UCM	8.68	87.85	3.47	0.00
WRF-500 m+BEP	**0.35**	**62.15**	**36.11**	**1.39**

It can be noticed that, for a specific configuration, the model maintains a similar behaviour for all three horizontal resolutions. For configurations WRF+NO and WRF+UCM, the model strongly overestimates the number of class I differences and underestimates (or does not capture at all) the differences in the other intensity classes. On the other hand, WRF+BEP slightly overestimates the frequency of temperature differences situated in classes I and II and underestimates (or does not capture at all for WRF-4.5 km+BEP) the minimum and maximum values (class 0 or class III intensities). Moreover, WRF-1.5 km+BEP and WRF-500 m+BEP are the only configurations in which the model forecasts values in all 4 classes, similar to the observations.

3.2. NORMALIZED HOURLY VARIATION OF THE BUCHAREST UHI INTENSITY

The analysis of the normalized course for the simulated Bucharest UHI intensity shows that the WRF+NO and WRF+UCM (Fig. 2) simulations display a similar behaviour at all three horizontal resolutions. Both these configurations place the highest thermal contrasts during the afternoon (around 15 UTC, approx. 17 local time), in contrast with the observations. The behaviour of the model in these configurations is opposed to the observations, with an underestimation of the UHI intensity during night-time and morning and the overestimation of the intensity during daytime. Although WRF+UCM captures the fast decay in the intensity of the Bucharest UHI during early morning (after 03 UTC), the highest magnitude of the phenomenon is simulated after 12 UTC, when the model forecasts the fastest growth and decay in intensity. However, none of these two configurations reproduce the normalized course of the Bucharest UHI. Moreover, the increase of the horizontal resolution of the model for these two configurations does not bring a quantifiable improvement in capturing the daily course of the UHI. The similar behaviour of these two simulations is probably due to the less complex representation of the urban geometry in the UCM parameterization scheme.

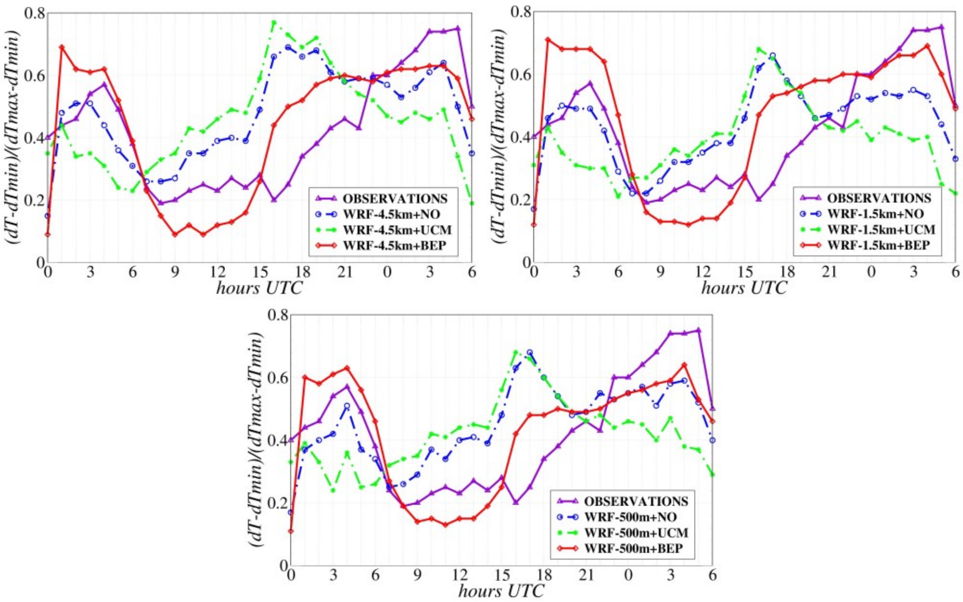

Fig. 2 – Normalized hourly variation of the Bucharest UHI (for all days): observations (purple) and WRF+NO (blue), WRF+UCM (green), WRF+BEP (red) integrated at 4.5 km (top, left), 1.5 km (top, right) and 500 m (bottom) horizontal resolution.

The strongest impact on the forecast of the WRF model can be obtained by employing the BEP urban parameterization scheme. Compared to the previous configurations, WRF+BEP (Fig. 2) brings an important improvement in the ability of the model to capture the normalized course of the UHI intensity at all three horizontal resolutions, due to the complex description of the urban geometry.

Although the values for the normalized simulated UHI intensity are slightly underestimated compared to the observations, WRF+BEP (especially WRF-500 m+BEP) displays a better ability to capture the diurnal cycle of the UHI. For all three horizontal resolutions, the model captures the fast decay of the thermal differences in the morning (until 11 UTC), the maximum intensity during night time and the fast decay and minimum intensity during the day. Also, the WRF+BEP model shows a slight advance in forecasting the steep growth of the thermal contrasts in the afternoon compared to the observations, while diminishing the growth of the UHI intensity for the evening period. In this last configuration, the model also captures the more stable behaviour of the phenomenon displayed during the day. For this configuration, the values of the normalized UHI intensity are close to the observed ones for most of the analysed period. The model integrated in this configuration at 1.5 km and 500 m also captures the magnitude of the phenomenon and the maximum UHI intensity during the night for the second part of the analysed period, due to the positive influence of the horizontal resolution and better description of the topography.

The WRF+BEP model generally reproduces the normalized course of the Bucharest UHI intensity at all three spatial resolutions; moreover, WRF-500 m+BEP captures better the smaller variations of the thermal contrasts displayed especially during daytime. In accordance with the results presented in the previous section, this also suggests a positive influence from the increased resolution and better description of the topography. Thus, the WRF+BEP model approximates better the periods with fast growth or decay of the thermal contrasts compared to the previous numerical simulations, offering a better representation for the normalized course of the Bucharest UHI intensity.

3.3. ISOTHERMS OF THE TEMPERATURE DIFFERENCES

The isotherms of the observed urban-peri-urban temperature differences (Fig. 3) indicate mostly class I and class II UHI intensities, with higher intensities for 13 March. The strong variations in the intensity of the UHI during the entire day can be the result of the fast change in air circulation specific to the spring season.

Comparative analysis of the results from all numerical simulations (Figs. 4–6) suggests that class 0 intensities are not very well represented in any of the configurations. The model generally overestimates the values forecasted for the period when the observed differences are negative. Slightly better results in this case seem to be obtained from the WRF+UCM configuration. Increasing the spatial resolution of the model usually leads to an improvement of the amplitude for the interval of temperature differences as well as the values themselves, independently from the urban parameterization employed by the model.

The results presented in Fig. 4–6 generally indicate an increase of the simulated UHI intensities forecasted with WRF+NO (Fig. 4), WRF+UCM (Fig. 5) and WRF+BEP (Fig. 6). The isotherms computed for WRF+NO, WRF+UCM and WRF+BEP suggest that the general tendency of the model is that of underestimating the maximum and high intensity values of the Bucharest UHI and overestimating the minimum and low intensity values of the phenomenon.

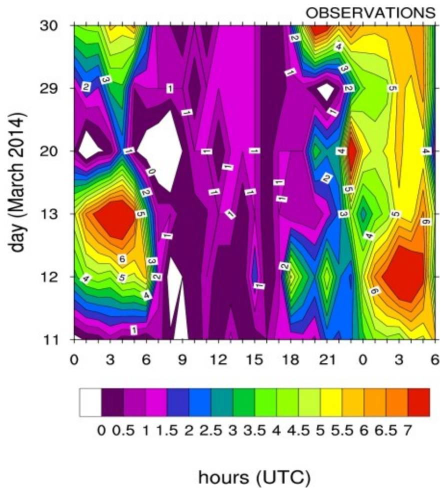

Fig. 3 – Isotherms of 2 m temperature differences between the urban and peri-urban station – observations.

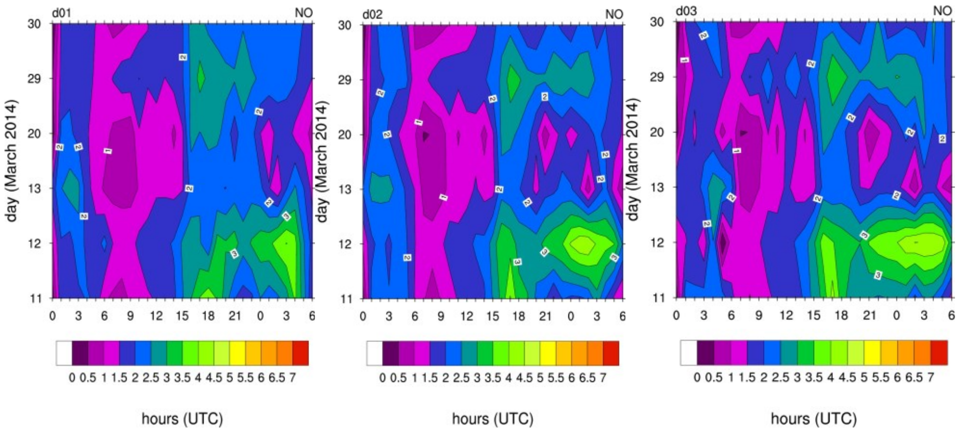

Fig. 4 – Isotherms of 2 m temperature differences between the urban and peri-urban station, WRF+NO: 4.5 km (left), 1.5 km (middle), 500 m (right).

The WRF+NO, WRF+BEP, WRF-1.5 km+UCM and WRF-500 m+UCM configurations offer a good representation for class I UHI intensity and satisfactory results for class II, in contrast to WRF-4.5 km+UCM, which does not capture these intensities. Class III intensities of the Bucharest UHI are only captured by the WRF+BEP configuration. WRF+NO underestimates the intensity for the period when the phenomenon had a high magnitude, with slightly better results from WRF-500 m+NO. The model in this configuration partially captures the periodicity of class III intensities of the Bucharest UHI for the second part of the analyzed period. The amplitude of the UHI is underestimated and the high intensities are further apart in time compared to the observations. WRF+NO captures the daily evolution of the Bucharest UHI for the entire period, with higher intensities in the first and last days of the analyzed interval and lower ones in the middle. However, the evolution of the UHI is staggered in time compared to the observations.

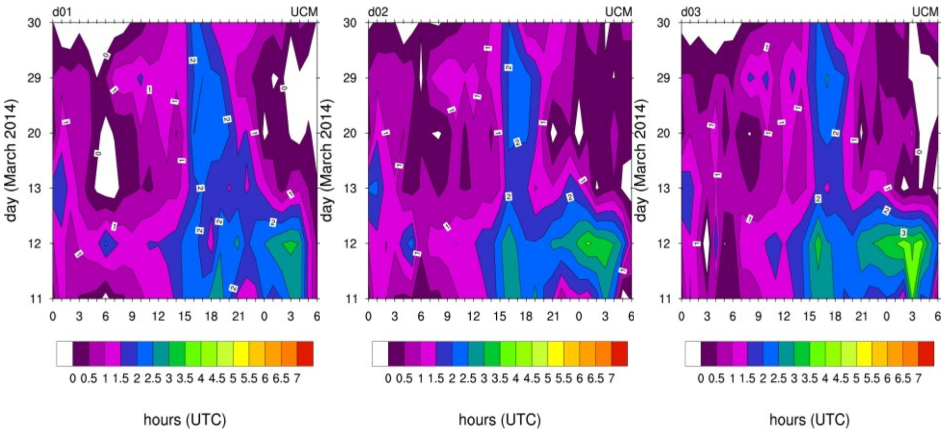

Fig. 5 – Isotherms of 2 m temperature differences between the urban and peri-urban station, WRF+UCM: 4.5 km (left), 1.5 km (middle), 500 m (right).

As previously mentioned, the WRF+UCM configuration (especially at 4.5 km and 500 m horizontal resolution) captures the low intensities of the Bucharest UHI, but does not place them correctly in time and slightly overestimates them. For this configuration, the class II and III intensities of the Bucharest UHI observed in all cases are strongly underestimated, especially for the second part of the month.

The WRF+BEP model displays a similar behaviour at all 3 spatial resolutions; if the horizontal resolution is increased, the isotherms follow the observations more closely (Fig. 6). The model captures the large amplitude of the interval for the values and the high variations during 11 March 2014 00 UTC – 13 March 2014 03 UTC, especially at the 500 m spatial resolution. In this configuration, the model captures better the periodicity of the class III intensities for the phenomenon compared to the previous numerical experiments. WRF+BEP also gives a satisfactory estimate of the intervals with low intensities of the phenomenon, but these are more restricted compared to the observations. The WRF+BEP configuration captures the evolution and diurnal cycle of the Bucharest UHI for the analyzed period, with higher intensities for 11^{th}– 12^{th} March and 29^{th}–31^{st} March and usually lower intensities in the remaining period. The temperature differences of around 6 ^{o}C captured by the WRF+BEP configuration compared to maximum differences of up to 5 ^{o}C forecasted by the other configurations bring the results of the WRF+BEP closer to the observations compared to all other numerical experiments presented in this paper. It can be noticed that the WRF+BEP in general and the WRF-500 m+BEP in particular capture the highest intensities of the Bucharest UHI during the morning (until 06 UTC), although the values are underestimated compared to the observations.

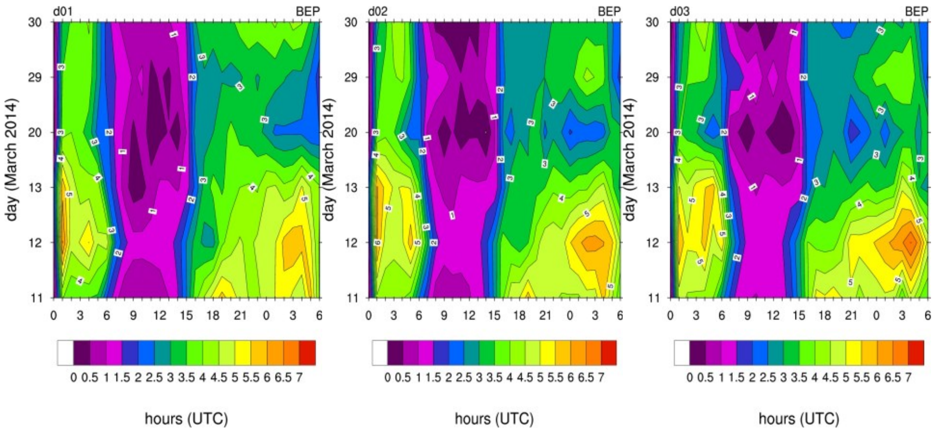

Fig. 6 – Isotherms of 2 m temperature differences between the urban and peri-urban station, WRF+BEP: 4.5 km (left), 1.5 km (middle), 500 m (right).

4. CONCLUSIONS

This study was dedicated to the numerical simulation of the Bucharest UHI using the WRF model integrated at high resolutions using different urban parameterization schemes. The numerical simulations were performed using initial and lateral boundary conditions from the ECMWF global model.

The results from the numerical experiments presented in this study show noticeable differences in the intensity and expansion of the Bucharest UHI forecasted by the WRF model, depending on the urban parameterization scheme employed by the model. The ability of the WRF model to capture the Bucharest UHI improves with the increase of the horizontal resolution of the model.

The WRF model integrated without any parameterization scheme (WRF+NO) does not offer a better estimation of the Bucharest UHI compared to the other two numerical simulations performed in this study. Coupling of the WRF model with the UCM scheme does not bring considerable improvements to the forecast of the Bucharest UHI compared to the previous WRF+NO configuration, at any of the horizontal resolutions employed.

The model using the complex BEP urban parameterization scheme forecasts a more extensive and intense UHI compared to the one forecasted by the other configurations employed in this study, at all horizontal resolutions.

All configurations of the WRF model used in this study capture class I Bucharest UHI intensities, but the frequency of hourly differences is overestimated compared to observations. The model integrated in the present configurations underestimates the frequency of class 0 intensities. Moreover, all configurations except WRF+BEP strongly underestimate the frequency for class II intensities.

Class III intensities of the Bucharest UHI are only captured by the WRF+BEP configuration of the model, which slightly underestimates them compared to the observations. The WRF-1.5 km+BEP and WRF-500 m+BEP configurations are the only ones which estimate urban-peri-urban differences in all four intensity classes, due to the complex parameterization of the urban surfaces coupled with the high resolution of the model.

The use of a finer resolution (4.5 km to 1.5 km to 500 m) highlights the differences between different configurations employed by the model. However, for the same configuration, the model displays a similar behavior at different resolutions. While the best results are offered by the 500 m horizontal resolution, a good simulation of the Bucharest UHI is also provided by the 1.5 km resolution, which can be a satisfactory compromise between computational time and the resolution necessary to capture the daily variability of the Bucharest UHI.

The WRF+BEP configuration in general and the WRF-500 m+BEP in particular offers the best estimate for the spatial and temporal distribution of the Bucharest UHI, the amplitude of the urban-peri-urban temperature differences and the intensity of the phenomenon from the configurations analyzed. The use of the BEP urban parameterization scheme shows the strongest positive impact in the forecast of the Bucharest UHI using the WRF numerical model, due to the more complex representation of the city geometry.

In conclusion, we consider that the WRF+BEP configuration is the optimal one for the numerical modelling of the Bucharest UHI from the configurations presented in this study.

REFERENCES

1. T.R. Oke, *Boundary Layer Climates*, Routledge, London (1987).
2. A.J. Arnfield, Two decades of urban climate research: a review of turbulence, exchanges of energy and water and the urban heat island, *Int. J. Climatol*, **23**, 1-26 (2003).
3. M. Kanda, Progress in the scale modeling of urban climate: Review, *Theor. Appl. Climatol*, **84**, 23-33 (2005).
4. K. Klysik, K. Fortuniac, Observed UHI intensity in Lodz – definition and typical values, Fifth International Conference on Urban Climate, 1-5 September 2003, Lodz, Poland (2003).
5. J. Zhou, Y. Chen, J. Wang, W. Zhan, Maximum Nighttime Urban Heat Island (UHI) Intensity Simulation by Integrating Remotely Sensed Data and Meteorological Observations, *IEEE J. Sel. Topics Appl. Earth Observ.*, **4**, 138-146 (2010).
6. F. Fujibe, H. Togawa, M. Sakata, Long-term change and spatial anomaly of warm season afternoon precipitation in Tokyo, *Scientific Online Letters on the Atmosphere*, **5**, 17-20 (2009).
7. J.B. Basara, H.G.L. Basara, B.G. Illston, K.C. Crawford, The Impact of the Urban Heat Island during an Intense Heat Wave in Oklahoma City, *Adv. Meteorol.* 2010 (2010).
8. V. Masson, A physically-based scheme for the urban energy budget in atmospheric models, *Bound.-Layer Meteor.*, **94**, 357-397 (2000).

9. H. Kusaka, H. Kondo H, Y. Kikegawa, F. Kimura, A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models, *Bound.-Layer Meteorol*, **101**, 329-358 (2001).
10. H. Kusaka, F. Kimura, Coupling a single-layer urban canopy model with a simple atmospheric mode: Impact on urban heat island simulation for an idealized case, *J. Meteor. Soc. Japan*, **82**, 67-80 (2004).
11. A. Martilli, A. Clapier, M.W. Rotach, An urban surface exchange parameterization for mesoscale models, *Bound.-Layer Meteor*., **104**, 261-304 (2002).
12. F. Salamanca, A. Krpo, A. Martilli, A. Clapier, A new building energy model coupled with an urban canopy parameterization for urban climate simulations – part II. Validation with one dimension off-line simulations, *Theor. Appl. Climatol*., **99**, 331-344 (2010).
13. W. Wang, C. Bruyere, M. Duda, J. Dudhia, D. Gill, H.C. Lin, J. Michalakes, S. Rizvi, X. Zhang, *A description of the Advanced Research WRF version 3*, Technical report (2012).
14. F. Chen, H. Kusaka, R. Bornstein, J. Ching, C.S.B. Grimmond, S. Grossman-Clarke, T. Loridan, K.W. Manning, A. Martilli, S. Miao, D. Sailor, F. Salamanca, H. Taha, M. Tewari, X. Wang, A.A. Wyszogrodzkia, C. Zhang, The integrated WRF-urban modelling system: development, evaluation and applications to urban environmental problems, *Int. J. Climatol.*, **31**, 273-288 (2011).
15. J. Fallmann, S. Emeis, P. Suppan, Modeling of the Urban Heat Island using WRF comparing different urban parameterization schemes, Proceedings of the 8th International Conference on Urban Climate (ICUC-8), 6-10 August 2012, Dublin, Ireland (2012).
16. J. Teixeira, T. Luna, A.C. Carvahlo, A. Rocha, WRF sensitivity to Urban canopy schemes: A Lisabon Case Study, *EMS Annual Meeting Abstracts* – 12th EMS / 9th ECAC, 9, 10-14 September 2012, Lodz, Poland (2012).
17. T. Nehrkorn, J. Henderson, M. Leidner, M. Ellis, A. Maher, J. Eluskiewicz, Modelling the urban circulation in the Salt Lake City area using the WRF urban canopy parameterization. 91st American Meteorological Society Annual Meeting, 22-27 January 2011, Seattle, WA, 838 (2011).
18. C.Y. Lin, F. Chen, W.C. Chen, S.C. Liu, Urban Heat Island and its Impact on Boundary Layer Development and Precipitation over Northern Taiwan, The seventh International Conference on Urban Climate (ICUC-7), 29 June – 3 July 2009, Yokohama, Japan (2009).
19. S. Miao, F.Chen, M.A. LeMone, M. Tewari, Q. Li, Y. Wang, An Observational and Modelling Study of Characteristics of Urban Heat Island and Boundary Layer Structures in Beijing, *Bound.-Layer Meteor*., **48**, 484-501 (2009).
20. F. Salamanca, A. Martilli, M. Tewari, F. Chen, A Study of the Urban Boundary Layer Using Different Urban Parameterizations and High-Resolution Urban Canopy Parameters with WRF, *J. Appl. Meteor. and Climatol*., **50**, 1107-1128 (2011).
21. ESTAT, Eurostat, European Union, http://epp.eurostat.ec.europa.eu/portal (2014).
22. S. Cheval, A. Dumitrescu, The July urban heat island of Bucharest as derived from MODIS images, *Theor. Appl. Climatol*. **96**, 145-153 (2009).
23. S. Cheval, A. Dumitrescu, A. Bell, The urban heat island of Bucharest during the extreme high temperatures of July 2007, *Theor. Appl. Climatol*, **99,** 391-401 (2009).
24. S. Andrei, S. Stefan, Influence of Air Circulations upon Bucharest's Urban Heat Island. *EMS Annual Meeting Abstracts* – 11th EMS / 10th ECAM. EMS2011-389, 12-16 September 2011, Berlin, Germany (2011).
25. A. Lupascu, A. Iriza, R.C. Dumitrache, Using a high resolution topographic data set and analysis of the impact on the forecast of meteorological, *Rom Rep. Phys.*, **67**, 653-664 (2015).
26. A. Iriza, R.C. Dumitrache, A. Lupascu, The influence of topography characteristics on the numerical weather forecast with the WRF model in cases of severe weather, *Rom. Rep. Phys*., **67**, 1128-1137 (2015).
27. CGIAR-CSI, Consortium for Spatial Information, http://srtm.csi.cgiar.org/ (2013).

28. U. Schaettler, G. Domms, C. Schraff, *A Description of the Nonhydrostatic Regional COSMO-Model Part VII: Users Guide*, Technical report, Offenbach, Germany, 200 (2013).
29. ECMWF, European Centre for Medium-Range Weather Forecasts. http://www.ecmwf.int/ (2014).
30. G. Thompson, R.M. Rasmussen, K. Manning, Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis, *Mon. Wea. Rev.*, **132**, 519-542 (2004).
31. E.J. Mlawer, S.A. Clough, Shortwave and longwave radiation enhancements in the rapid radiative transfer model, Proceedings of the Seventh Atmospheric Radiation Measurement Science team Meeting ARM-CONF, 3-7 March 1997, San Antonio, Texas, pp. 409-413 (1997).
32. J. Dudhia, Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model, *J. Atmos. Sci*., **46**, 3077-3107 (1989).
33. Z. Janjic, *Nonsingular Implementation of the Mellor-Yamada Level 2.5 Scheme in the NCEP Meso mode*, NCEP Technical Report 437 (2002).
34. F. Chen, J. Dudhia, Coupling and advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity, *Mon. Wea. Rev.*, **129**, 569-585 (2001).
35. NASA, MODIS Land, http://modis-land.gsfc.nasa.gov (2014).
36. S. Andrei, Study of the urban heat island for the Bucharest metropolitan area impact on local meteorological phenomena (in Romanian-Studiul insulei de caldura urbana a zonei metropolitane Bucuresti asupra fenomenelor meteorologice locale), *PhD thesis*, Univ. of Bucharest (2012).
37. T.R. Oke, An algorithmic scheme to estimate hourly heat island magnitude, Proc. 2nd Symp Urban Env., 2-6 November, Albuquergue, USA, 80-83 (1998).