https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

Impact of urban canopy parameters on urbanization induced modifications of climate

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Abstract. Urban areas are characterized by modifications of the local climate leading to a so called urban meteorology island (UMI). UMI is the results of different physical properties of surfaces in cities compared to their rural surroundings. In this study we performed a set of multi-year simulations with the Weather Research and Forecast (WRF) model and two urban schemes to investigate the sensitivity of the urban climate modifications (or UMI) on changes in characteristics of the urban environment, described in models by the so-called urban canopy parameters (UCP). Our results reveal a high sensitivity of urban-induced changes in all mentioned meteorological variables to the alterations of UCP. Temperature in urban areas is mainly influenced by changes in urban fraction, roof albedo, green roofs with irrigation and also by anthropogenic heat in winter, with a magnitude around 0.5 °C. On the contrary, urban wind speed is impacted rather by parameters that describe the urban morphology. Our study also shows substantial differences between both urban models used, mainly in urban-induced temperature in winter. The results of the study can also be used as a primary evaluation of different mitigation strategies represented by changes in UCP values. The decrease of urban fraction and the increase of roof albedo seem to be the most suitable possibilities to reduce the intensity of the urban heat island in summer, vegetation-covered roofs have a noticeable impact only if they are also irrigated.

1 Introduction

Urban areas represent a small and mostly isolated parts of Earth's surface, but with very distinct physical characteristics, which manifest in modifications of local climate, often called urban climate. From all these climate modifications, increase in the city temperature was described several decades ago as the first one (Oke and Maxwell, 1975) and was named the urban heat island (UHI). More recently, modifications of other meteorological variables in urban areas have been investigated – boundary layer structure or height (e.g. Lin et al., 2008; Theeuwes et al., 2015; Karlický et al., 2018), wind speed (e.g. Oke, 1987; Grawe et al., 2013; Droste et al., 2018), humidity, cloudiness, precipitation and convection (e.g. Langendijk et al., 2019; Theeuwes et al., 2019; Manola et al., 2020; Oh and Sushama, 2021). A few years ago, a generalization of all these one-variable islands was introduced and called urban meteorology island (UMI; Karlický et al., 2020), which describes overall alterations of meteorological and climatic conditions from their rural counterparts.

Due to climate change, global temperatures are rising, which is amplified in urban areas by the UHI, leading to more frequent occurrence of heatwaves and temperature extremes in general in the near future. This would lead to a decrease in the quality of

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

life in cities during summer and numerous situations with a high potential of health risks. If we consider that nowadays around 57 % of the world's population live in cities and the percentage is still rising (United Nations, HSP, 2022), the topic of urban climate plays a crucial role for everyday life. Therefore, it is important to improve the overall knowledge about the development of urban meteorology island to preserve or rather potentially mitigate negative features connected with urban climate.

Numerical models are suitable tools for studying urban climate features because they enable to show courses of hardly observed quantities and also perform simulations with modified inputs to access potential impacts of future urban development or mitigation strategies. However, global climate or weather forecast models have too coarse resolution to capture most of cities. Therefore, limited area models with a horizontal resolution of 10 km or less are used to investigate the impacts of urban areas on local climate, coupled with a special parametrization of urban canopy, enabling to describe physical processes inside the city. There are several widely used regional model/urban parametrization pairs, e.g. COSMO-CLM used previously by Trusilova et al. (2016), RegCM-CLM (Huszár et al., 2018), GEM-TEB (Oh and Sushama, 2021) and WRF-SLUCM or WRF-BEP+BEM (Karlický et al., 2018; Sun et al., 2021; Chen et al., 2021).

However, all of these parametrizations of the urban canopy need to set a number of values describing the urban morphology, urban builtup density, physical characteristics of artificial surfaces or heat released from buildings, called together as urban canopy parameters (UCP). Although they can have a significant impact on simulation and differ substantially for specific cities and there are several studies focused on improving model results by updating UCP for a specific locality (e.g. Shen et al., 2019; Chen et al., 2021; Sun et al., 2021), there are nearly no studies describing the sensitivity of model output on specific set of UCP. Further, lot of studies investigate the relationship between some specific UCP and the resulting UMI, e.g., urban fraction (Bassett et al., 2020), anthropogenic heat (Qian et al., 2023), building height (Xi et al., 2021) or roof albedo (Oleson et al., 2010; Wang et al., 2022), but the impact of other UCP or overall comparison is missing.

Our study aims to resolve these shortcomings in the sensitivity of model simulations on urban canopy parameters as well as the relationship between UCP values and the resulting UMI. More specifically, it aims to (1) evaluate impacts of changes in individual UCP values on urban-induced changes in meteorological variables in cities and, based on this, also to (2) reveal eventual possibilities for preserving or mitigation of negative consequences connected with UMI development. Both of these goals will be considered in a long-term perspective of climatic simulations.

2 Methods

2.1 Model setup

In our study, we used Weather Research and Forecasting model (WRF; Skamarock et al., 2008) in version 4.3.3. All simulations were performed in the domain that covers central Europe (Fig. 1), with horizontal resolution 9 km and including 190×166 gridboxes. In vertical direction, 40 model layers were adopted with the model top at 5 000 Pa. All simulations were driven by ERA-5 reanalysis (Hersbach et al., 2020). As a static geographic data, standard WRF input was used, only land-use information was derived from CORINE Land Cover data, version CLC 2012. The simulation time-span is 2015–2019, but with regard to the high number of simulations performed (see further) and thus reducing computation amount, only winter and summer months were

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

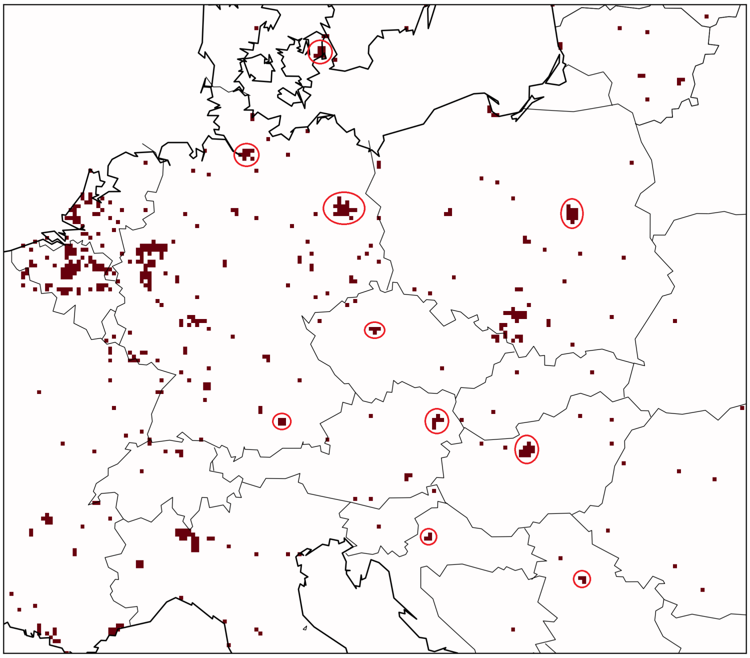

Figure 1. Position of model domain with grid-boxes predominantly covered by urban areas. Large cities used in evaluation circled.

simulated. If we consider that urban-induced effects are of the highest relevance in these two seasons and model meteorology is strictly dependent on boundary conditions given by ERA-5 data, there is no significant impairment of study results by such simplification.

The choice of WRF model parameterizations was the same for all simulations, and it is the following. Purdue Lin scheme (Chen and Sun, 2002) of micro-physical processes, planetary boundary layer processes are resolved by the Bougeault–Lacarrere (BouLac) scheme (Bougeault and Lacarrere, 1989), convection by the Grell 3D Ensemble scheme (Grell, 1993). Furthermore, the RRTMG scheme (Iacono et al., 2008) is used for short-wave and long-wave radiation transfer parameterization, surface physics processes are resolved by the Unified Noah Land Surface Model (Tewari et al., 2016) and surface layer mechanisms by the Eta Similarity scheme (Janjić, 1994).

For the description of urban surface processes, two schemes were utilized: (1) Single Layer Urban Canopy Model (SLUCM; Kusaka et al., 2001), describing the city as a long street canyon in different directions. SLUCM accounts for momentum and thermal interactions between the city and the atmosphere using a single-layer grid, with the assumption of exponential profile of wind speed. It takes into account phenomena such as shadowing, reflections and trapping of radiation and canopy flows, but there is no direct interaction with higher model layers as well as anthropogenic heat is not explicitly computed. (2) Building Environment Parametrization (BEP; Martilli et al., 2002), a multi-layer urban model, enabling to compute vertical profiles of temperature, momentum and turbulent kinetic energy in urban areas explicitly, following the vertical distribution of building heights, momentum, moisture and energy sources and sinks. BEP is mostly connected with the Building Energy Model (BEM;

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

Salamanca et al., 2009), explicitly determining the energy exchange between buildings and atmosphere in dependence on indoor and outdoor temperature, inward and outward radiation fluxes, the production of heat from machines, the density of inhabitants, and the need for heating or air conditioning. In the next chapters, this connection will be marked as BEP+BEM parameterization. The resulting ensemble of simulations that include choices of urban parameterization and related values of UCP are listed in the next section.

2.2 Experimental setup

The sensitivity of model simulations on specific urban canopy parameters is determined from differences between results of simulations with base values of UCP and simulations with altered values of UCP. We considered two base simulations, with SLUCM and BEP+BEM urban schemes. The specific base values of UCP (see Table 1) are the same as those used by Karlický et al. (2018), corresponding to typical urban morphology in central Europe, which is similar to this study.

The choice of specific urban parameters worthy of altering their values and the specific alteration of these values were suggested based on preliminary short-term simulations, showing that the alteration of some urban parameters has a considerable impact on results, while the impact of other parameters is negligible. Further, altered values of chosen UCP are set with regard to their potential realism, limits and possibilities given by urban models. Finally, the total number of altered UCP and their values is also limited by computational resources. Thus, alterations of building height, building width, street width, urban fraction and surface albedo of roof are tested within both urban schemes. Moreover, anthropogenic heat and green roof ratio by SLUCM. The specific values of the altered UCP and the overall simulation ensemble are listed in Table 2.

The magnitude of urban-induced effects on various meteorological variables and their potential perturbations given by alteration of UCP values is determined for selected set of cities, listed in Table 3 and also marked in Fig. 1. All chosen cities consist of several neighboring grid-boxes defined as urban land-use in the model, while most of their surroundings are covered by non-urban land use types (Fig. 1), which enables investigation of urban-induced effects. Specific values of urban-induced effect magnitudes or UMI intensities are subtractions between urban and rural values of meteorological variables, where urban marks the average value within all urban grid-boxes for given city (with the exception of urban grid-boxes with only one adjacent urban grid-box), while rural means the average value within a rectangular ring of grid-boxes around the city in the distance of three grid-boxes from considered urban grid-boxes.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

Table 1. Base values of urban canopy parameters.

Parameter	Base value	Scheme
Roof (Building) Width (m)	17.5	both
Road (Street) Width (m)	17.5	both
Urban Fraction	0.8	both
Heat Capacity of Roof ($J\,m^{-3}K^{-1}$)	0.776×10^6	both
Heat Capacity of Building Wall ($J\,m^{-3}K^{-1}$)	1.02×10^6	both
Heat Capacity of Ground (Road) ($J\,m^{-3}K^{-1}$)	1.7×10^6	both
Thermal Conductivity of Roof ($J\,m^{-3}K^{-1}$)	0.8	both
Thermal Conductivity of Building Wall ($J\,m^{-3}K^{-1}$)	1.28	both
Thermal Conductivity of Ground (Road) ($J\,m^{-3}K^{-1}$)	0.6	both
Surface Albedo of Roof	0.3	both
Surface Albedo of Building Wall	0.27	both
Surface Albedo of Ground (Road)	0.16	both
Surface Emissivity of Roof	0.7	both
Surface Emissivity of Building Wall	0.88	both
Surface Emissivity of Ground (Road)	0.92	both
Building Height (m)	17.5	SLUCM
Anthropogenic Heat ($W\,m^{-2}$)	35.5	SLUCM
Thickness of Each Roof Layer (m)	0.05	SLUCM
Thickness of Each Building Wall Layer (m)	0.05	SLUCM
Thickness of Each Ground (Road) Layer (m)	0.05/0.25/0.50/0.75	SLUCM
Roughness length for momentum over roof (m)	0.01	BEP+BEM
Coefficient of performance of the A/C systems	3.5	BEP+BEM
Coverage area fraction of windows in the walls of the building	0.2	BEP+BEM
Thermal efficiency of heat exchanger	0.75	BEP+BEM
Target temperature of the A/C systems (K)	298 (±0.5)	BEP+BEM
Target humidity of the A/C systems ($kg\,kg^{-1}$)	0.005 (±0.005)	BEP+BEM
Peak number of occupants per unit floor area person (m^{-2})	0.01	BEP+BEM
Peak heat generated by equipment ($W\,m^{-2}$)	18.00	BEP+BEM
Street direction degrees from north	0, 90	BEP+BEM
Building heights (m)	10, 15, 20, 25	BEP+BEM
Building heights' percentage (%)	10, 40, 40, 10	BEP+BEM

Table 3. List of cities examined, with their population and coordinates.

City	Population	Latitude	Longitude
Berlin	3 645 000	52.52	13.41
Vienna	1 897 000	48.21	16.39
Hamburg	1 841 000	53.59	9.99
Warsaw	1 793 000	52.24	21.02
Budapest	1 751 000	47.50	19.08
Munich	1 472 000	48.15	11.57
Belgrade	1 383 000	44.81	20.46
Prague	1 309 000	50.08	14.44
Zagreb	790 000	45.80	15.98
Copenhagen	627 000	55.68	12.50

Population data taken from https://data.un.org/ for year 2019, with the exception of Warsaw (2020) and Zagreb (2014).

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

Table 2. List of model simulations with values of altered UCP.

Scheme	Run name	Parameter changed	Base	New value
SLUCM	BASE	–	–	–
SLUCM	BH12.5	Building height (m)	17.5	12.5
SLUCM	BH22.5	Building height (m)	17.5	22.5
SLUCM	BW12.5	Building width (m)	17.5	12.5
SLUCM	BW22.5	Building width (m)	17.5	22.5
SLUCM	SW12.5	Street width (m)	17.5	12.5
SLUCM	SW22.5	Street width (m)	17.5	22.5
SLUCM	AH20	Anthropogenic heat ($W\,m^{-2}$)	35.5	20
SLUCM	AH50	Anthropogenic heat ($W\,m^{-2}$)	35.5	50
SLUCM	AH80	Anthropogenic heat ($W\,m^{-2}$)	35.5	80
SLUCM	UF0.6	Urban fraction	0.8	0.6
SLUCM	UF0.7	Urban fraction	0.8	0.7
SLUCM	UF0.9	Urban fraction	0.8	0.9
SLUCM	UF1.0	Urban fraction	0.8	1.0
SLUCM	RA0.1	Surface albedo of roof	0.3	0.1
SLUCM	RA0.5	Surface albedo of roof	0.3	0.1
SLUCM	RA1.0	Surface albedo of roof	0.3	0.1
SLUCM	GR0.2	Green Roof Ratio	0.0	0.2
SLUCM	GR0.5	Green Roof Ratio	0.0	0.5
SLUCM	GR1.0	Green Roof Ratio	0.0	1.0
SLUCM	GR1.0ir	Green Roof Ratio	0.0	1.0 + ir.*
BEP+BEM	BASE	–	–	–
BEP+BEM	BH12.5	Building height (m)	17.5	12.5**
BEP+BEM	BH22.5	Building height (m)	17.5	22.5**
BEP+BEM	BW12.5	Building width (m)	17.5	12.5
BEP+BEM	BW22.5	Building width (m)	17.5	22.5
BEP+BEM	SW12.5	Street width (m)	17.5	12.5
BEP+BEM	SW22.5	Street width (m)	17.5	22.5
BEP+BEM	UF0.6	Urban fraction	0.8	0.6
BEP+BEM	UF0.7	Urban fraction	0.8	0.7
BEP+BEM	UF0.9	Urban fraction	0.8	0.9
BEP+BEM	UF1.0	Urban fraction	0.8	1.0
BEP+BEM	RA0.1	Surface albedo of roof	0.3	0.1
BEP+BEM	RA0.5	Surface albedo of roof	0.3	0.5
BEP+BEM	RA1.0	Surface albedo of roof	0.3	1.0

* ir. means irrigated vegetation ** decreased/increased Building height means changes in overall distribution of Building heights in BEP+BEM scheme

For general validation of model temperature, E-OBS dataset (Cornes et al., 2018) v. 21.0e is used, containing daily gridded data with horizontal resolution of 0.1°, close to the model resolution. In addition, station data provided by the Czech Hydro-Meteorological Institute (CHMI) were used to validate the UHI intensity in Prague. More specifically, three stations inside the city and three stations in the surroundings were selected (see Table 4) to be corresponding to the model urban area and the rural ring. A correction was performed using a standard temperature moist adiabatic gradient of $0.65 \times 10^{-2}\,K\,m^{-1}$ for preventing the difference between the heights above sea level of the stations and model grid-boxes.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

Table 4. List of stations used for Prague UHI intensity validation.

Urban area		Rural ring	
Station	Height (m)	Station	Height (m)
Karlov	261	Dobřichovice	205
Klementinum	191	Tuháň	161
Libuš	302	Neumětely	315

3 Results

3.1 Model validation

In this chapter, only both BASE simulations are evaluated against reference data, because they are considered as the most realistic ones. Fig. 2 shows winter and summer temperature biases. Rather negative biases prevail, mainly in winter, up to 2 °C. Differences between simulations with SLUCM and BEP+BEM urban model are noticeable only in urban areas, where BEP+BEM significantly increases temperature in the winter season. In the overall view, biases are till 0.4 °C, root mean square errors are significantly lower in summer and almost independent on urban scheme, spatial correlation close to one in all cases (Table 5).

Table 5. Model validation statistics against E-OBS.

	Winter		Summer	
	SLUCM	BEP+BEM	SLUCM	BEP+BEM
BIAS (°C)	−0.40	−0.28	−0.23	−0.22
RMSE (°C)	0.910	0.906	0.681	0.688
Correlation	0.950	0.947	0.967	0.968

Validation of urban impact on temperature was performed for Prague based on the stations listed in Table 4 and the corresponding model grid-boxes. The resulting UHI intensity is determined as a difference between averages of urban and rural stations/grid-boxes, firstly corrected on the same height above see level. The station-based values of the intensity of the UHI are well captured by both model simulations in the summer season (Table 6), but in winter there is an overestimation of simulation with BEP+BEM model with a magnitude above 1.5 °C.

Table 6. Comparison of UHI intensities in Prague (°C).

	SLUCM	BEP+BEM	Stations
Winter	1.24	2.73	1.15
Summer	1.83	1.63	1.67

3.2 Urban-induced effects and their changes

First, we demonstrate effects of urban areas in both base simulations. Fig. 3 shows urban-induced effects on several meteorological variables, separated by seasons, urban model and covering all cities vs. Prague only. The impact of urban areas on

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

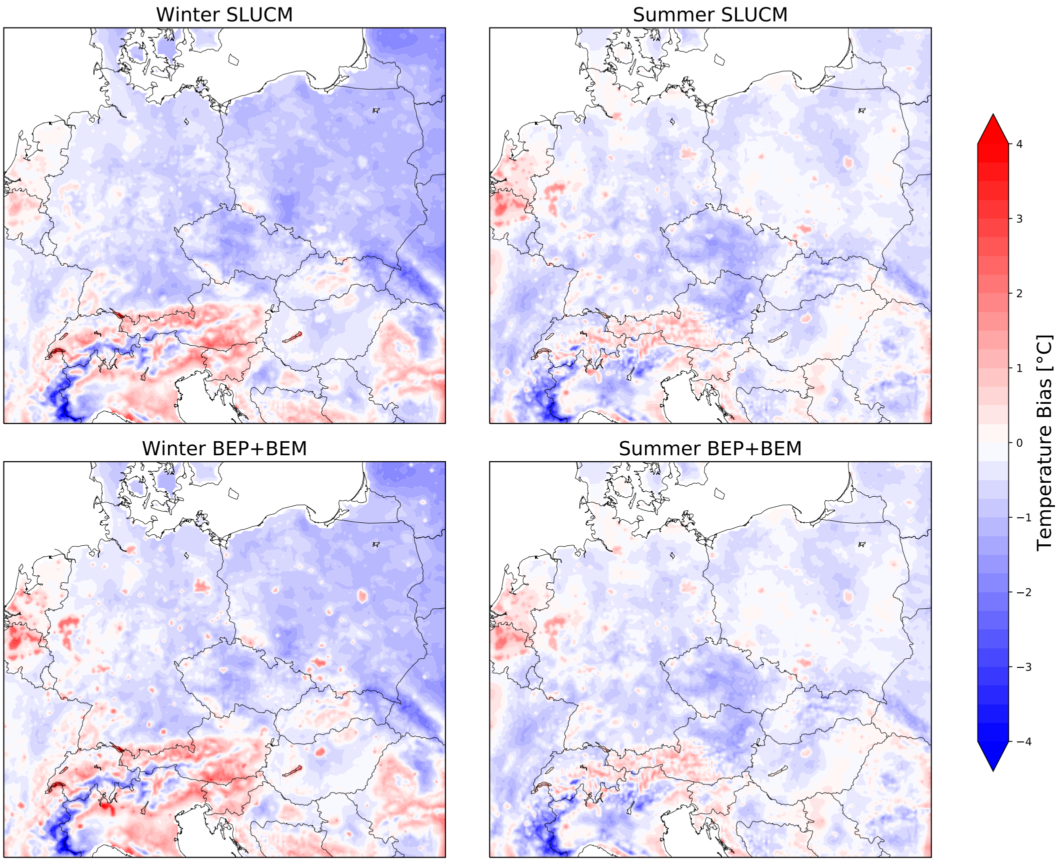

Figure 2. Spatial distribution of winter and summer temperature biases.

air temperature is 1.5–2 °C in summer, in winter the models agree less – the impact in winter is less in case of SLUCM but higher in case of BEP+BEM. Surface temperature exhibits a similar feature, but the magnitudes are higher (2–4 °C). Planetary boundary layer height (PBLH) is also significantly affected by urban areas, to be more than 200 m higher in cities in summer, but again with model discrepancy for the winter season. Specific humidity is significantly reduced in urban areas in summer, around 0.7 g/kg, but in winter, there is only a low decrease up to 0.1 g/kg. Summer daily precipitation is increased in urban areas, with the magnitude around 0.5 mm/d, which corresponds to approximately 50 mm per season, which means an increase of roughly 20 %. In winter, models do not correspond (opposite effects), and there is also a high difference between European cities and Prague. The impact on wind speed depends mainly on the urban model; SLUCM performs nearly zero effect but BEP+BEM indicates decrease up to 2 $\mathrm{m\,s^{-1}}$. With the exception of daily precipitation and partly specific humidity, we can conclude that urban-induced effects are similar if we take all selected cities or Prague only. Therefore, we will further discuss urban effects only in the case of the average within all selected cities.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

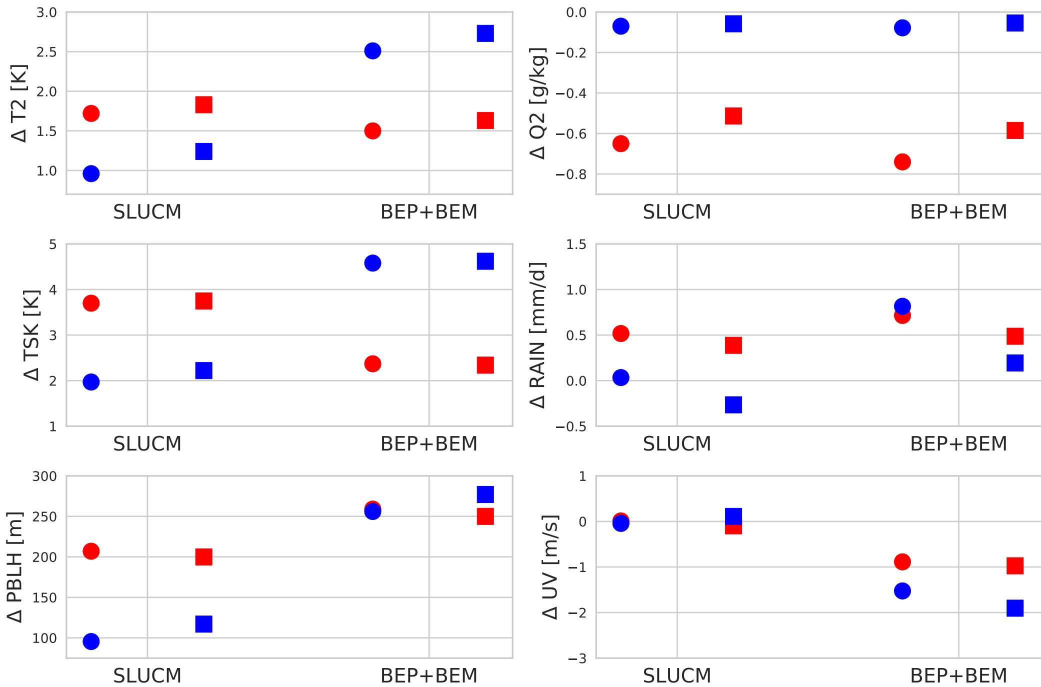

Figure 3. Differences between urban and rural areas in selected meteorological variables (2 m air temperature, surface temperature, planetary boundary layer height, 2 m air specific humidity, daily precipitation and first model layer wind speed). Red color summer season, blue color marks winter. Circles denote averages values for all selected European cities, square symbols for Prague urban area.

In the following paragraphs, we investigate the impact of UCP variation on alteration of urban-induced changes of meteorological variables, or on specific components of UMI, respectively. First, Fig. 4 shows the impact of the altered UCP on the urban modification of 2 m air temperature. The values varies significantly with altered UCP, namely anthropogenic heat, urban fraction and roof albedo has a strong impact on the resulting temperature change in summer. The magnitudes are higher within the SLUCM model, where differences between simulations with both extreme values of UCP are up to 1 °C. In BEP+BEM simulations, differences are lower, around 0.5 °C. On the other hand, parameters that describe the geometry of the urban canopy (building height and street width) have a more significant impact than in the case of SLUCM. In view of summer UHI mitigation, urban fraction decrease, roof albedo increase and irrigated green roofs have the highest potential in terms of SLUCM indicating temperature decrease about 0.5 °C in all cases compared to base simulations. In terms of BEP+BEM, urban fraction and roof albedo have a little less impact, 0.2 and 0.4 °C. The impact of altered UCP on urban modification of surface temperature exhibits similar features (not shown), but specific magnitudes are roughly twice greater (up to 2 °C in case of extreme values of UCP).

The impact of UCP alteration on boundary layer height (Fig. 5) has a similar pattern as in case of air temperature, again, anthropogenic heat, urban fraction and roof albedo influence the most the summer PBLH difference in SLUCM simulations,

https://doi.org/10.5194/egusphere-2025-388
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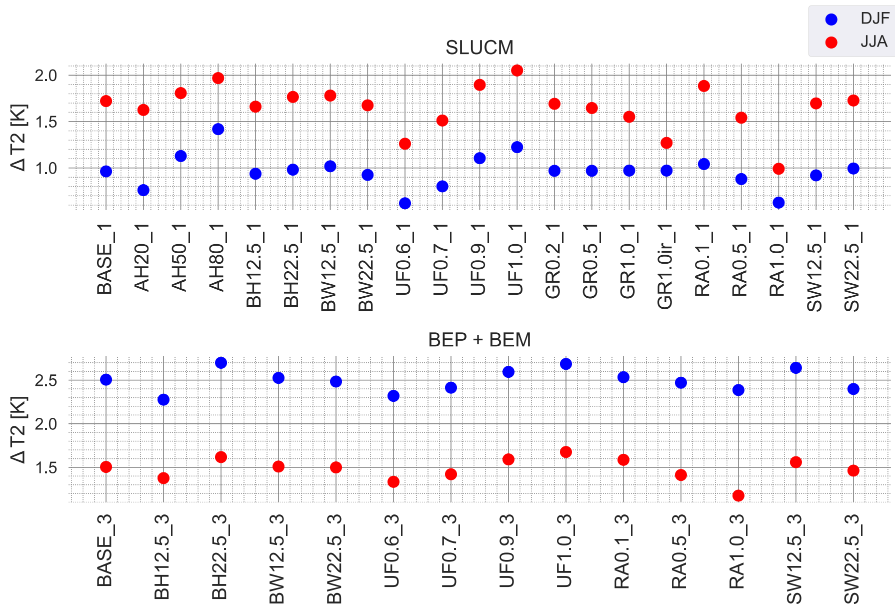

Figure 4. Urban effect on 2 m air temperature in dependence on values of UCP.

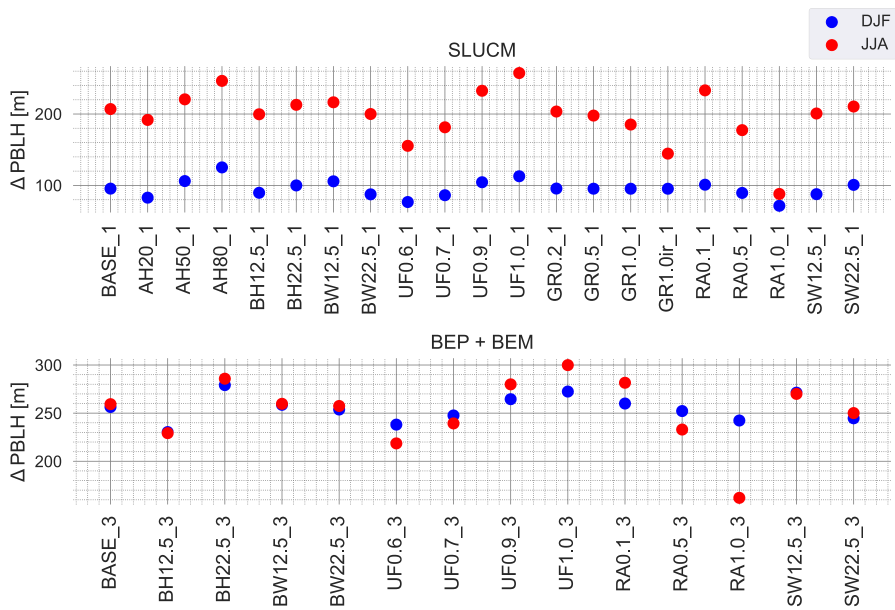

Figure 5. Urban effect on planetary boundary layer height in dependence on different values of UCP.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

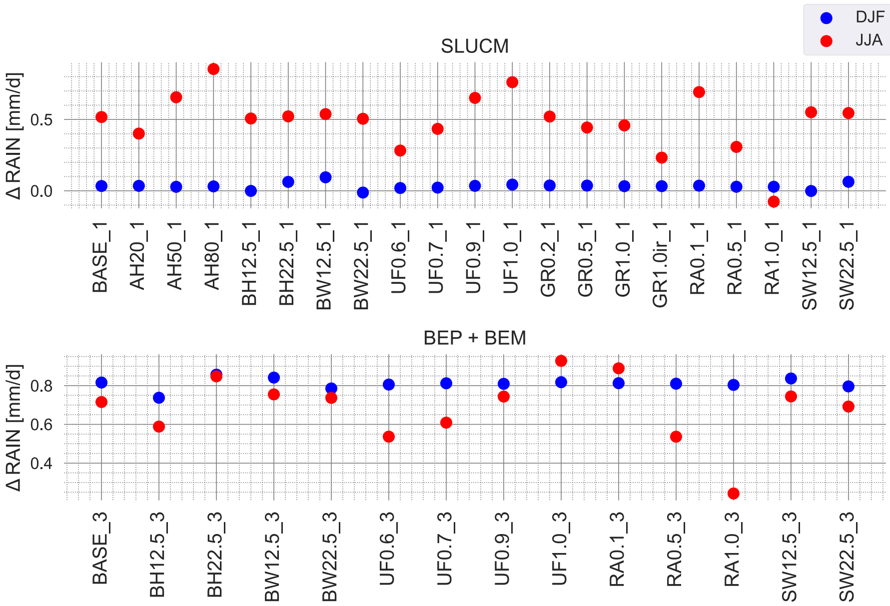

Figure 6. Urban effect on daily precipitation in dependence on values of UCP.

about 50–100 m. In case of BEP+BEM simulations, urban street geometry also affects the results, higher buildings or thinner streets make urban PBLH a few tenths of meters higher. In winter, changes in urban PBLH are generally much lower, with similar features.

The variation of precipitation in dependence on UCP values (Fig. 6) is noticeable only in the summer season. Significant differences (more than 0.2 mm/d) occur when anthropogenic heat, urban fraction and roof albedo are altered in the SLUCM simulation, together with including irrigated green roofs. Similarly in BEP+BEM simulations, which are also influenced by building height (precipitation increase) and partly by street width (precipitation decrease). In case of specific humidity variation, there are nearly no changes in winter and only noticeable impacts in summer season are performed by alteration of the urban fraction and switching on the irrigation (not shown).

In case of impact of UCP alteration on urban wind speed (Fig. 7), a different pattern occurs compared to previous cases. Now, the wind speed is mainly influenced by parameters describing urban canopy geometry – building height, building width and street width. As expected, higher and thinner buildings decrease urban wind speed within both urban models around 0.1 $\mathrm{m\,s^{-1}}$. In case of street width, both models indicate opposite results. Partly, urban wind speed is also negatively influenced by the increase in the urban fraction. The winter and summer characteristics are almost similar, but the reactivity is a bit stronger in winter.

As the urban-induced effect on temperature (UHI) is the most important component of UMI in view of human living impact, we will study the magnitude of the UHI intensity also in diurnal courses in dependence of different values of urban fraction,

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

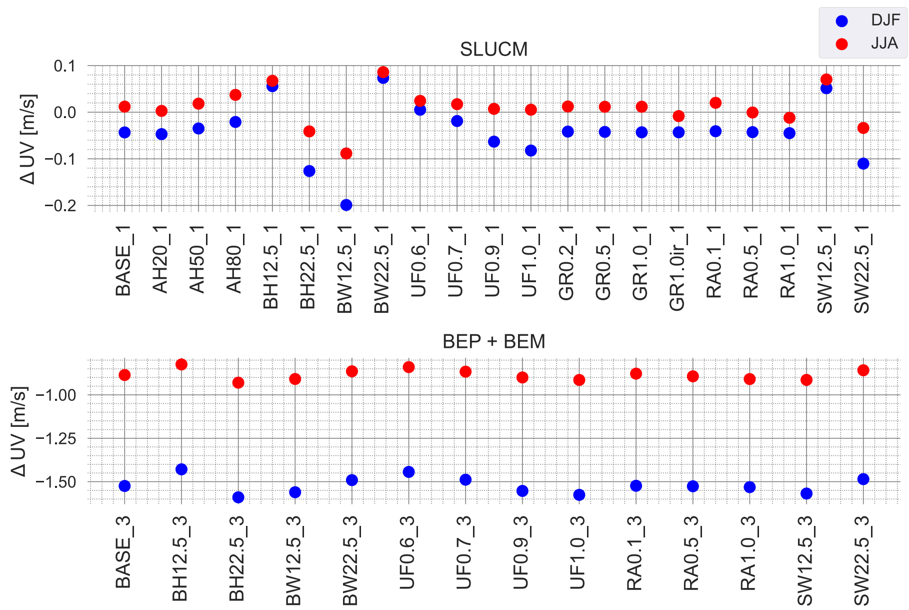

Figure 7. Urban effect on wind speed in dependence on values of UCP.

green roof ratio and roof albedo. Fig. 8 shows daily cycle of the intensity of UHI for different values of urban fraction (UF). In addition to the well-known fact that UHI is weakest during morning hours and strongest in evening and at night, we can see that the dependence is also strongest in evening and at night. In particular, SLUCM simulations indicate high UHI differences in summer, when change of UF from base value 0.8 to 0.6 cause UHI intensity reduction by 1 °C at night. On the other hand, BEP+BEM simulations exhibit lower variation of UHI intensity, only app. 0.2 °C difference between base and lowest value of UF at night, similarly to that in the winter season.

Daily cycle of UHI intensity in dependence on green roof ratio and irrigation is screened in Fig. 9. We can see that this reactivity is weaker than in case of urban fraction – maximizing of green fraction leads to UHI intensity reduction of 0.4 °C at midnight, during daytime there is even increase of the intensity. Irrigation influences UHI only in morning and afternoon hours, decreasing temperatures about 0.5 °C, but not at night. In winter, there is almost no effect of the ratio of green roofs and irrigation.

Variation of UHI intensity in dependence on roof albedo is shown in Fig. 10. Increased albedo influences urban temperature rather in daytime hours, the decrease is around 1 °C in case of maximal albedo against base value in summer. Nighttime UHI is not affected so much in this case; there is a difference between SLUCM and BEP+BEM simulation. In winter, again, daytime temperatures are mainly affected, but with a lower magnitude.

https://doi.org/10.5194/egusphere-2025-388
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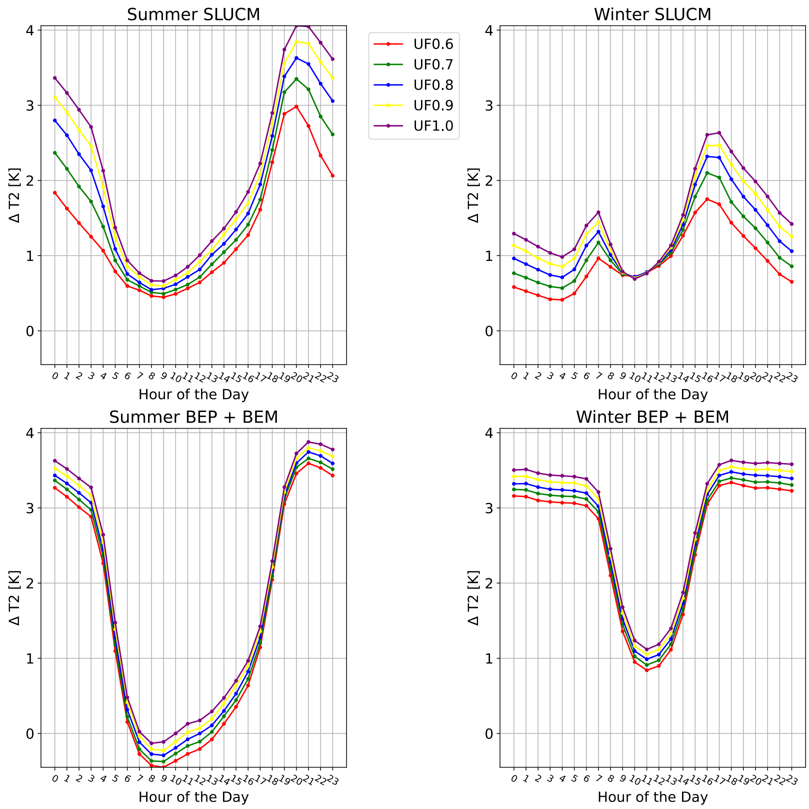

Figure 8. Diurnal cycle of UHI intensity in dependence on urban fraction.

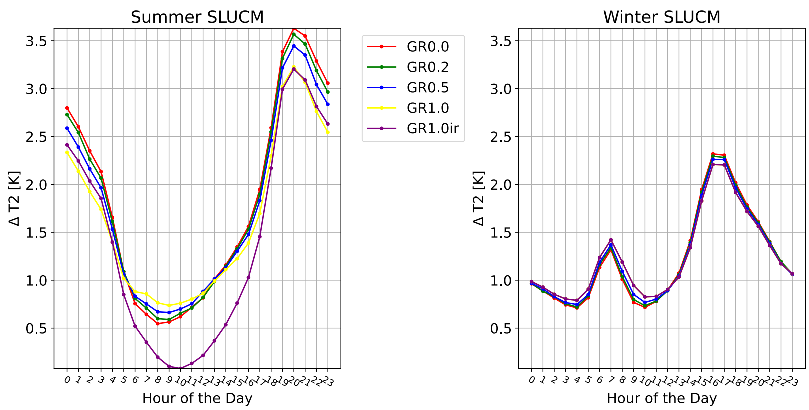

Figure 9. Diurnal cycle of UHI intensity in dependence on green roof ratio.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

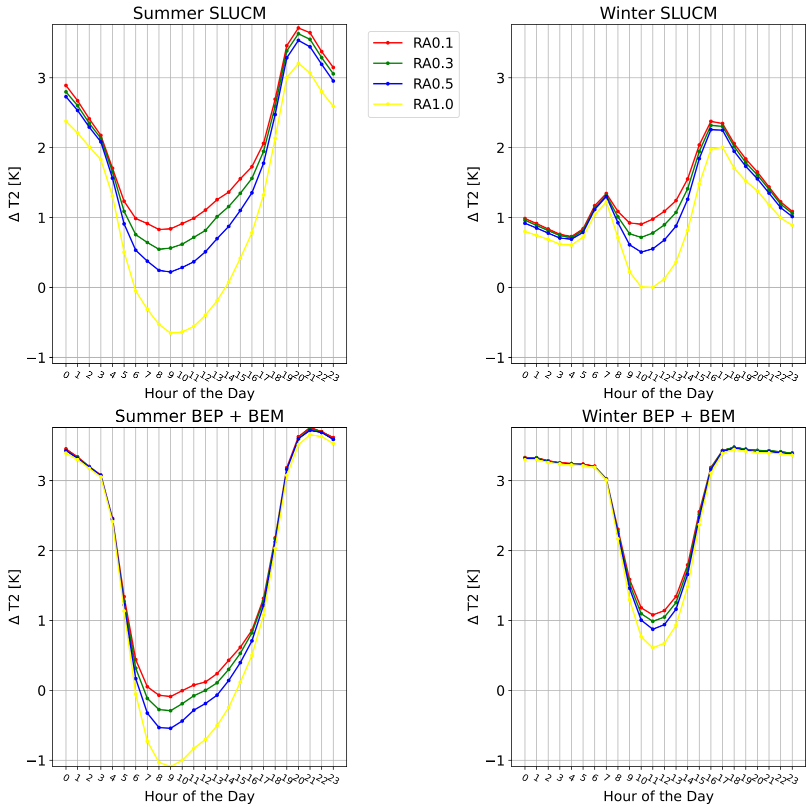

Figure 10. Diurnal cycle of UHI intensity in dependence on roof albedo.

4 Discussion

Low negative overall temperature biases in both base simulations against E-OBS data (Table 5) do not influence urban-induced effects much and both simulations exhibit very similar behavior except urban areas (Fig. 2). The high winter overestimation of the UHI intensity by the BEP+BEM simulation is probably caused by an incorrect description of heat fluxes from buildings (or explicit anthropogenic heat calculation) and was also noticed in previous studies (Liao et al., 2014; Karlický et al., 2018), with a similar magnitude.

Similarly to air temperature, both models indicate a high difference also in the urban-induced effect on surface temperature (Fig. 3). The winter difference has the same reason as in the case of air temperature, partly also the summer one, because SLUCM assumes constant anthropogenic heat independent to outdoor conditions, thus in summer it can be overestimated, manifesting more in surface temperature than in air temperature due to greater mixing in the summer season. The difference of PBLH increase in urban areas between SLUCM and BEP+BEM simulations in winter (Fig. 3) is caused by direct interaction of BEP+BEM urban scheme with model layers, which is not a case of SLUCM. Similar overestimation of BEP+BEM was found also in previous studies (Karlický et al., 2018; Ribeiro et al., 2021). The decrease of specific humidity in cities in summer can be

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

well explained by impervious materials and rain-water drainage in cities, the same feature was found by Karlický et al. (2020), Langendijk et al. (2019) states annual mean urban-rural difference as 0.5 g/kg, which is corresponding to our values. There is a noticeable weakening of this effect for Prague in comparison to all selected cities, which can be assigned to a smaller size and more oceanic climate of Prague than average of the selected cities. A partly similar feature can be seen in the case of urban-induced effect on daily precipitation. The value of the increase of daily precipitation in summer in urban areas (0.5 mm/d) is well in line with the observation study of Manola et al. (2020), who indicated summer precipitation increase in Amsterdam of about 40 mm. The same study shows winter precipitation increase of 20 mm, which is less than indicated by BEP+BEM simulation for all European cities, but more than indicated by SLUCM simulation and BEP+BEM for Prague. The reduction of wind speed in city areas given by BEP+BEM simulation is corresponding to Karlický et al. (2018), who described wind speed reduction in vertical profile including first model layer. In case of SLUCM simulation, almost zero effect contrasts with results of other studies (e.g. Droste et al., 2018), however, Karlický et al. (2020) indicated a very high sensitivity of urban wind speed reduction on boundary-layer scheme, the one used in our study performed the decrease in 10 m only about 0.3 $\mathrm{m\,s^{-1}}$, which is not as far from our results, if we consider that the urban impact is expected to be lower in the first model layer than in 10 m.

Now we are going to discuss changes of urban-induced effects in dependence on UCP. Let us start with air temperature and its sensitivity to UCP alterations (Fig. 4). The high sensitivity of an increase in urban temperature to anthropogenic heat can be confirmed by Qian et al. (2023), who estimated anthropogenic heat in Chinese cities and found a positive relationship with the intensity of UHI. The impact of the urban fraction (UF) was previously estimated experimentally by Bassett et al. (2020), following his conclusions the difference between extreme values of UF would be 0.3 °C, which is close to results of BEP+BEM simulations (0.4 °C), but not to SLUCM simulations (0.8 °C). The influence of roof albedo (RA) was previously investigated as a part of potential mitigation strategies, Oleson et al. (2010) modeled the impact of RA increase from 0.32 to 0.9 globally with UHI intensity reduction of 0.5 °C in summer, Wang et al. (2022) studied the effects of RA with the SLUCM model for Berlin increasing RA from 0.163 to 0.850 with temperature decrease almost 1 °C during daytime and 0.5 °C ar night, which is close to our results (Fig. 10). Similarly, the effect of green roofs (GR) was evaluated for mitigation purposes, but a noticeable effect in summer is achieved only if green roofs are also irrigated. Green roofs alone cause UHI intensity reduction only of 0.2 °C, which is less than indicated by Wang et al. (2022), but also this study reveals the importance of irrigation for additional reduction of urban temperature. Although the impact of building height is not very significant in comparison to other UCP mentioned previously, the trend showing that higher buildings mean more intensive UHI is the same as described by Xi et al. (2021).

The similar pattern of impact of UCP alteration on urban PBLH (Fig. 5) and daily precipitation in summer (Fig. 6) as in the case of UHI intensity is possible to explain by enhanced convection above urban areas, caused by higher surface and air temperature. Enhanced convection leads to greater mixing, higher PBLH and more frequent presence of convective precipitation (Theeuwes et al., 2019). On the other hand, the impact on the urban wind speed by UCP alteration (Fig. 7) has a very distinct pattern: parameters describing the urban morphology play a major role, UCP influencing convection (AH, UF and RA) have only a minor effect rather in summer.

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

In the case of diurnal profiles of UHI intensity in dependence on UF, GR and RA alteration, it is clearly visible that UF significantly influences nighttime urban temperatures (summer urban temperature decrease up to 1.5 °C, Fig. 8), RA influences rather daytime temperatures (with a similar magnitude around noon, Fig. 10), the same is correct for impact of fully covered and irrigated green roofs (with a magnitude about 0.5 °C, Fig. 9). This feature is physically determined by a less amount of heat stored in the ground and released during night in the case of decreased UF (artificial surfaces have a high conductivity and heat capacity, thus well store the heat), reduction of absorbed solar radiation during daytime in case of high RA and reduction of sensible heat release during daytime due to increase of latent heat consumption in case of irrigated green roofs. Daily cycles with similar features including causal cycles of radiation and thermal balance members are shown in the study of Wang et al. (2022).

Overall, we can conclude that specific values of UCP influence urban modification of all considered variables, models are significantly sensitive to their alterations, therefore our study confirms and generalizes conclusions from previous studies (Shen et al., 2019; Chen et al., 2021; Sun et al., 2021) about the need to correctly set UCP values in regional climate models.

We can also use previously discussed results in order to reveal suitable mitigation strategies for reduction of negative aspects of urban-induced changes of meteorological variables or UMI. As the most negative component of UMI in view of human-living conditions is the summer urban heat island, we have to track its intensity in dependence on the alteration of UCP values. In this sense, the decrease of urban fraction (adding of green areas or parks into cities in practice) and roof albedo increase (use of high-reflective or cool roofs) have the highest impact. The corresponding potential UHI intensity decrease would be 0.5 °C under UF change from 0.8 to 0.6 and 0.7 °C under RA increase from 0.3 to 1.0 following SLUCM simulations. The combination of these two strategies would benefit in whole-day decrease of temperature, because they realize in different parts of day (Fig. 8 and Fig. 10). The introduction of green roofs seems to have a similar effect only with irrigation, without irrigation the effects decrease to 0.2°C. A decrease of anthropogenic heat release influence the intensity of UHI rather in the winter season, changes in urban morphology parameters do not influence urban temperature in a considerable rate. This statement is in line with the study by Shen et al. (2019), who concluded that the urban fraction affects the temperature in urban areas more than the urban morphology, which impacts rather urban wind speed.

5 Conclusions

We presented the results of a series of simulations with the WRF model focused on the sensitivity of the model results on the values of urban canopy parameters used in two urban models (SLUCM and BEP-BEM). The simulations were performed on the European domain with horizontal resolution of 9 km, for time period 2015–2019, when only summer and winter seasons were simulated. Urban-induced effects were evaluated in terms of differences between centers and surroundings of ten selected large cities within the domain. The validation of model temperatures was performed by E-OBS and station data from Czech Hydro-Meteorological Institute.

Validation and comparison between simulations with the SLUCM and BEP+BEM urban models showed significant differences in some aspects of results, based on distinct structure of both urban models. In particular, BEP+BEM tends to largely

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

overestimate the winter urban air temperature. Urban surface temperatures, boundary layer height and daily precipitation are also higher within BEP+BEM simulations compared to SLUCM simulations in winter. On the other hand, the wind speed in cities is reduced more in BEP+BEM simulations in both considered seasons.

Our study reveals a high sensitivity of urban-induced effects in all mentioned meteorological variables on changes in values of urban canopy parameters. The intensity of UHI is mainly influenced by changes in urban fraction, roof albedo, green roofs with irrigation and also by anthropogenic heat in winter, with a magnitude around 0.5 °C from the base setup in all cases. BEP+BEM urban model seems to be a little less sensitive than SLUCM in this regard. Similarly, surface temperature, boundary-layer height and summer precipitation exhibit sensitivity on the same urban canopy parameters, but urban wind speed is influenced rather by parameters describing the urban morphology. The presented high sensitivity of results on UCP confirms previous studies in concluding the need for a correct setting of UCP in regional climate simulations.

In view of potential mitigation strategies, our results show that decreasing urban fraction and increasing roof albedo appear to be the most efficient strategies to reduce the intensity of UHI in summer, they are more efficient than vegetation-covered roofs, which have a noticeable impact only if they are also irrigated. While a decrease in urban fraction can reduce nighttime temperatures by 1 °C, an increase in roof albedo can reduce daytime temperatures by the same value.

Code and data availability. The source code of the WRF model is publicly available. Resulting data from the simulation performed can be obtained upon request to the authors.

Author contributions. PH created the basic concept, JK proposed the methodology, JB performed model simulations, post-processed results and analyzed results with a contribution of JK. JK wrote the manuscript and PH revised it.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work has been supported by the Technology Agency of the Czech Republic (TACR, grant no. SS02030031) and by the Ministry of Education, Youth and Sport (grant no. CZ.02.01.01/00/22_008/0004605). The authors further acknowledge the E-OBS dataset and the data providers in the ECA&D project, the ERA-Interim reanalysis provided by the European Centre for Medium-Range Weather Forecasts and station data provided by the Czech Hydro-Meteorological Institute (CHMI).

https://doi.org/10.5194/egusphere-2025-388
Preprint. Discussion started: 10 February 2025

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