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Sensitivity of modeled urban climate to urban canopy parameters over central Europe

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Abstract

Urban areas are characterized by modifications of the local climate, leading to so-called urban meteorology islands (UMIs). A UMI is the result of the 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 Forecasting model and two urban schemes to investigate the sensitivity of urban climate modifications (i.e. UMIs) to changes in characteristics of the urban environment, described in models by so-called urban canopy parameters (UCPs). Our results reveal a high sensitivity of urban-induced changes in all mentioned meteorological variables to alterations in UCPs. Temperatures in urban areas are mainly influenced by changes in urban fraction (UF), 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 by parameters that describe the urban morphology, about 0.1 m s^{-1}. Our study also shows substantial differences between both urban models used, mainly in urban-induced temperatures in winter, with a difference of around 1.5 °C. 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 UF and the increase in roof albedo seem to be the most suitable possibilities to reduce the intensity of urban heat islands in summer; vegetation-covered roofs have a noticeable impact only if they are also irrigated.

1. Introduction

Urban areas represent small and mostly isolated parts of Earth's surface, but with very distinct physical characteristics, which manifest in modifications of the local climate, often called the urbanclimate. 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, for example, boundary layer structure or height (Lin *et al* 2008, Theeuwes *et al* 2015, Karlický *et al* 2018), wind speed (Oke 1987, Grawe *et al* 2013, Droste *et al* 2018), and humidity, cloudiness, precipitation, and convection (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, known as the 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 UHIs, and which will lead to more frequent occurrence of heatwaves and temperature extremes in general in the near future. This could lead to a decrease in the quality of 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 lives in cities, and the percentage is still rising (United Nations, HSP 2022), the

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topic of urban climate plays a crucial role for everyday life. Therefore, it is important to improve overall knowledge about the development of UMIs 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 courses of hardly observed quantities to be shown 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 a resolution to capture most cities. Therefore, limited area models with a horizontal resolution of 10 km or less are used to investigate the impact of urban areas on local climates, coupled with a special parametrization of urban canopy, enabling them to describe the physical processes inside the city. There are several widely used regional model/urban parametrization pairs, for example, COSMO-community land model (CLM; used previously by Trusilova *et al* 2016), regional climate model (RegCM)-CLM (Huszar *et al* 2018, Huszár et al 2018), Global Environmental Multiscale (GEM)-Town Energy Balance (TEB; Martilli *et al* 2002, Oh and Sushama 2021), and the Weather Research and Forecasting (WRF) single layer urban canopy model (SLUCM) or WRF-building environment parametrization (BEP) + building energy model (BEM; Karlický *et al* 2018, Chen *et al* 2021, Sun *et al* 2021).

However, all of these parametrizations of the urban canopy need to set a number of values describing the urban morphology, urban build-up density, physical characteristics of artificial surfaces, or heat released from buildings, known together as urban canopy parameters (UCPs). While they can have a significant impact on a simulation, which is documented by sensitivity studies using SLUCM separately without a regional climate model (e.g. Wang *et al* 2011, Zhao *et al* 2014, Ao and Zhang 2022), UCPs can also differ substantially for specific cities. Several studies have focused on improving model results by updating UCPs for a specific locality (e.g. Shen *et al* 2019, Chen *et al* 2021, Sun *et al* 2021), but there are nearly no studies describing the sensitivity of regional climate model outputs to a specific set of UCPs. Furthermore, many studies investigate the relationship between some specific UCPs and the resulting UMI, e.g. urban fraction (UF; Bassett *et al* 2020), anthropogenic heat (AH; Qian *et al* 2023), building height (BH; Xi *et al* 2021), or roof albedo (RA; Oleson *et al* 2010, Wang *et al* 2022). On the contrary, there is also a study investigating the impact of multiple UCPs on only one variable (Steeneveld *et al* 2018), but the impact on other variables or an overall comparison is missing.

Our study aims to resolve these shortcomings in the sensitivity of model simulations to UCPs as well as the relationship between UCP values and the resulting UMI. More specifically, it aims to (1) evaluate the impact 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 based on the evaluation in a domain covering several large cities and will be considered from a long-term perspective of climatic simulations.

2. Methods

2.1. Model setup

In our study, we used the WRF model (Skamarock *et al* 2008), version 4.3.3. All simulations were performed in the domain that covers central Europe (figure 1), with a horizontal grid spacing of 9 km and including 190 × 166 grid boxes. In the vertical direction, 40 model layers were adopted with the model top at 5000 Pa, with the height of the first model level at 49 m above ground. All simulations were driven by ERA-5 reanalysis (Hersbach *et al* 2020). For static geographic data, the standard WRF input was used, and only land-use information was derived from CORINE Land Cover data, version CORINE Land Cover 2012. The simulation time span was 2015–2019, but due to the high number of simulations performed (see later), in order to reduce the computation amount, only winter and summer months were simulated, which led to a set of separate three-month-long free-running simulations. If we consider that urban-induced effects are of the highest relevance in these two seasons, model meteorology is strictly dependent on boundary conditions given by ERA-5 data, and a short few-day spin-up interval of urban schemes can be neglected in view of the simulation length, there is no significant impairment of the study results by such an approach.

The WRF model parameterizations were the same for all simulations, and were as follows. The Purdue-Lin scheme (Chen and Sun 2002) of micro-physical processes and planetary boundary layer processes were resolved by the Bougeault–Lacarrere scheme (Bougeault and Lacarrere 1989), and convection by the Grell 3D ensemble scheme (Grell 1993). Furthermore, the RRTMG scheme (Iacono *et al* 2008) was used for short-wave and long-wave radiation transfer parameterization, surface physics processes

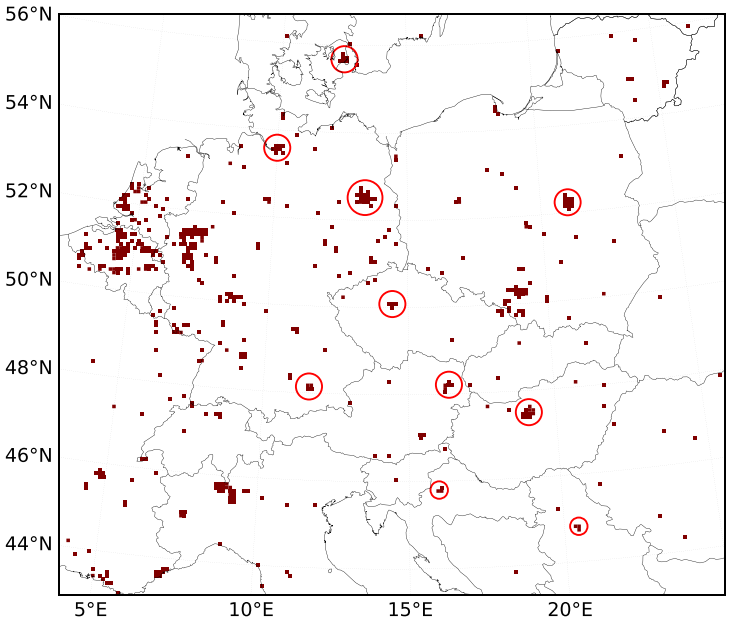

Figure 1. Position of the model domain with grid boxes predominantly covered by urban areas. Large cities used in the evaluation are indicated by a red circle.

were resolved by the unified Noah land surface model (Tewari *et al* 2016), and surface layer mechanisms by the Eta similarity scheme (Janjić 1994).

This combination of parameterization settings was chosen based on our previous study (Karlický *et al* 2020), which employed WRF over the same model domain. For the description of urban surface processes, two schemes were utilized: (1) the SLUCM (Kusaka *et al* 2001), describing the city as a long street canyon in different directions. Single layer urban canopy model (SLUCM) accounts for momentum and thermal interactions between the city and the atmosphere using a single-layer grid, with the assumption of an 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, and AH is not explicitly computed. (2) Building environment parametrization (BEP; Martilli *et al* 2002), a multi-layer urban model, enabling vertical profiles of temperature, momentum, and turbulent kinetic energy in urban areas to be explicitly computed, following the vertical distribution of BHs, momentum, moisture, and energy sources and sinks. BEP is mostly connected with the building energy model (BEM; Salamanca *et al* 2009), which explicitly determinines the energy exchange between buildings and the atmosphere depending 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 sections, this connection will be marked as BEP+BEM parameterization. The resulting ensemble of simulations, which includes choices of urban parameterization and related values of UCPs, is listed in the next section.

2.2. Experimental setup

The sensitivity of model simulations to specific UCP values is determined from differences between the results of simulations with base values of UCPs and simulations with altered values of UCPs. We considered two base simulations with SLUCM and BEP+BEM urban schemes. The specific base values of the UCPs (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 magnitude of these alterations were suggested based on preliminary short-term simulations, showing that the variation of some urban parameters has a considerable impact on results, while the impact of other parameters is negligible. Furthermore, the modifications of the UCP values were also set with regard to WRF model limits (e.g. in the case of BH), physical limits (albedo range, etc.), and a realistic range of values for central European cities (UF or the value of the AH flux). Finally, the total number of altered UCPs and their values was also limited by computational resources. Thus, alterations of BH, building width (BW), street width (SW), UF, and roof albedo were tested within both urban schemes. Moreover, the AH and green roof ratio (GR) were tested within SLUCM simulations. These UCPs were not tested within the

Table 1. Base values of UCPs.

Parameter	Base value	Scheme
Roof (building) width (m)	17.5	both
Road (street) width (m)	17.5	both
UF	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
Roof albedo	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
BH (m)	17.5	SLUCM
AH ($W\,m^{-2}$)	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 air-conditioning (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 A/C systems (K)	298 ($\pm$0.5)	BEP+BEM
Target humidity of A/C systems ($kg\,kg^{-1}$)	0.005 ($\pm$0.005)	BEP+BEM
Peak number of occupants per unit floor area (person m^{-2})	0.01	BEP+BEM
Peak heat generated by equipment ($W\,m^{-2}$)	18.00	BEP+BEM
Street direction degrees from north	0, 90	BEP+BEM
BH (m)	10, 15, 20, 25	BEP+BEM
BH percentage (%)	10, 40, 40, 10	BEP+BEM

BEP+BEM model because AH is calculated internally, thus it is not possible to set manually, and the green roof model offered by BEP+BEM is distinct from that used in SLUCM, manifesting a negligible impact. The specific values of the altered UCPs 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 a selected set of cities, listed in table 3 and also marked in figure 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 (figure 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 a 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 a distance of three grid boxes from the considered urban grid boxes.

For general validation of the model at 2 m air temperature, the E-OBS dataset (Cornes *et al* 2018) version 21.0e was used, containing daily gridded data with a 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 measuring 2 m air temperature inside and around the city were selected to represent the Prague urban area and its rural surroundings (see table 4). 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 the corresponding model grid boxes.

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

Scheme	Run name	Parameter changed	Base	New value
SLUCM	Base	—	—	—
SLUCM	BH12.5	BH (m)	17.5	12.5
SLUCM	BH22.5	BH (m)	17.5	22.5
SLUCM	BW12.5	BW (m)	17.5	12.5
SLUCM	BW22.5	BW (m)	17.5	22.5
SLUCM	SW12.5	SW (m)	17.5	12.5
SLUCM	SW22.5	SW (m)	17.5	22.5
SLUCM	AH20	AH ($W\,m^{-2}$)	35.5	20
SLUCM	AH50	AH ($W\,m^{-2}$)	35.5	50
SLUCM	AH80	AH ($W\,m^{-2}$)	35.5	80
SLUCM	UF0.6	UF	0.8	0.6
SLUCM	UF0.7	UF	0.8	0.7
SLUCM	UF0.9	UF	0.8	0.9
SLUCM	UF1.0	UF	0.8	1.0
SLUCM	RA0.1	RA	0.3	0.1
SLUCM	RA0.5	RA	0.3	0.5
SLUCM	RA1.0	RA	0.3	1.0
SLUCM	GR0.2	GR	0.0	0.2
SLUCM	GR0.5	GR	0.0	0.5
SLUCM	GR1.0	GR	0.0	1.0
SLUCM	GR1.0ir	GR	0.0	1.0 + ir.[a]
BEP+BEM	Base	—	—	—
BEP+BEM	BH12.5	BH (m)	17.5	12.5[b]
BEP+BEM	BH22.5	BH (m)	17.5	22.5[b]
BEP+BEM	BW12.5	BW (m)	17.5	12.5
BEP+BEM	BW22.5	BW (m)	17.5	22.5
BEP+BEM	SW12.5	SW (m)	17.5	12.5
BEP+BEM	SW22.5	SW (m)	17.5	22.5
BEP+BEM	UF0.6	UF	0.8	0.6
BEP+BEM	UF0.7	UF	0.8	0.7
BEP+BEM	UF0.9	UF	0.8	0.9
BEP+BEM	UF1.0	UF	0.8	1.0
BEP+BEM	RA0.1	RA	0.3	0.1
BEP+BEM	RA0.5	RA	0.3	0.5
BEP+BEM	RA1.0	RA	0.3	1.0

[a] ir. means irrigated vegetation.

[b] decreased/increased BH means changes in the overall distribution of BHs in the BEP+BEM scheme.

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

City	Population	Latitude	Longitude
Berlin	3645 000	52.52	13.41
Vienna	1897 000	48.21	16.39
Hamburg	1841 000	53.59	9.99
Warsaw	1793 000	52.24	21.02
Budapest	1751 000	47.50	19.08
Munich	1472 000	48.15	11.57
Belgrade	1383 000	44.81	20.46
Prague	1309 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 the year 2019, with the exception of Warsaw (2020) and Zagreb (2014).

3. Results

3.1. Model validation

In this section, only the two base simulations are evaluated against reference data because they are considered the most realistic. Figure 2 shows winter and summer 2 m air temperature biases. Rather negative biases prevail, mainly in winter, up to 2 °C. Differences between simulations with SLUCM and the

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

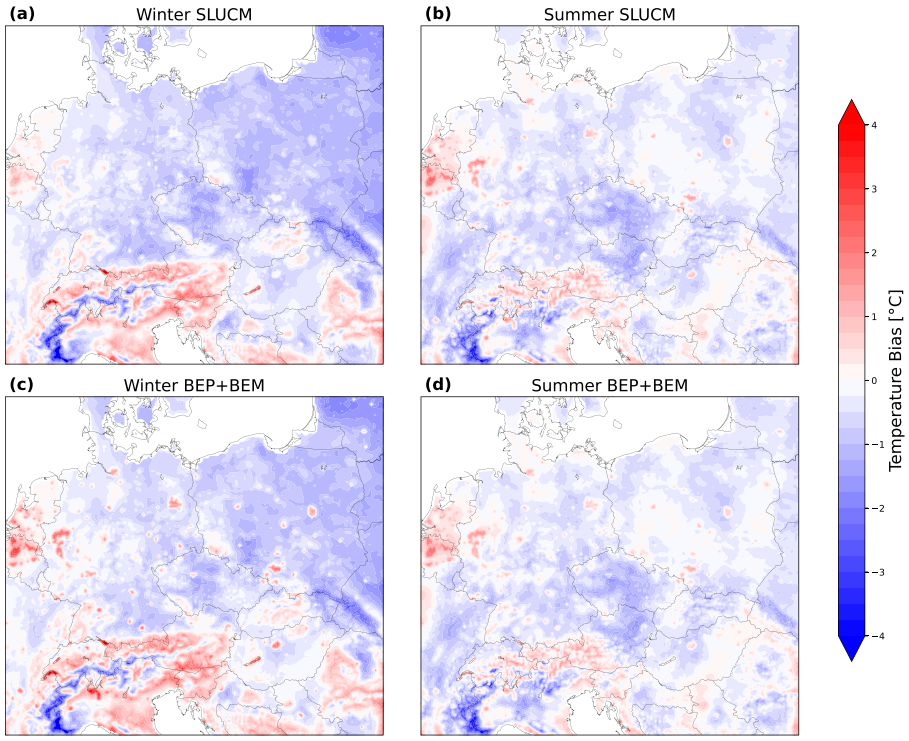

Figure 2. Spatial distribution of winter (DJF) and summer (JJA) biases of 2 m air temperature.

Table 5. Model validation statistics for 2 m air temperature in comparison to E-OBS.

	Winter (DJF)		Summer (JJA)	
	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

BEP+BEM urban model are noticeable only in urban areas, where BEP+BEM significantly increases temperature in the winter season. Overall, biases are below 0.4 °C, and root mean square errors (RMSE) are significantly lower in summer and are almost independent of urban scheme, with spatial correlation close to one in all cases (table 5).

Validation of the urban impact on the 2 m air temperature was performed for Prague based on the stations listed in table 4 and the corresponding model grid boxes. Here, only grid boxes closest to the listed stations were taken for this validation, which is a different approach to the one mentioned in the third paragraph of section 2.2. The resulting daily averaged UHI intensity is determined as the difference between the averages of urban and rural stations/grid boxes, corrected to the same height above sea level. Although such a validation can include some discrepancies due to insufficient representativeness of station data in urban areas, station-based values of the intensity of UHIs are well captured by both model simulations in the summer season (table 6), but in winter there is an overestimation in the BEP+BEM simulation exceeding 1.5 °C.

Table 6. Comparison of modeled and observation-derived UHI intensities in Prague (°C).

	SLUCM	BEP+BEM	Observation
Winter (DJF)	1.24	2.73	1.15
Summer (JJA)	1.83	1.63	1.67

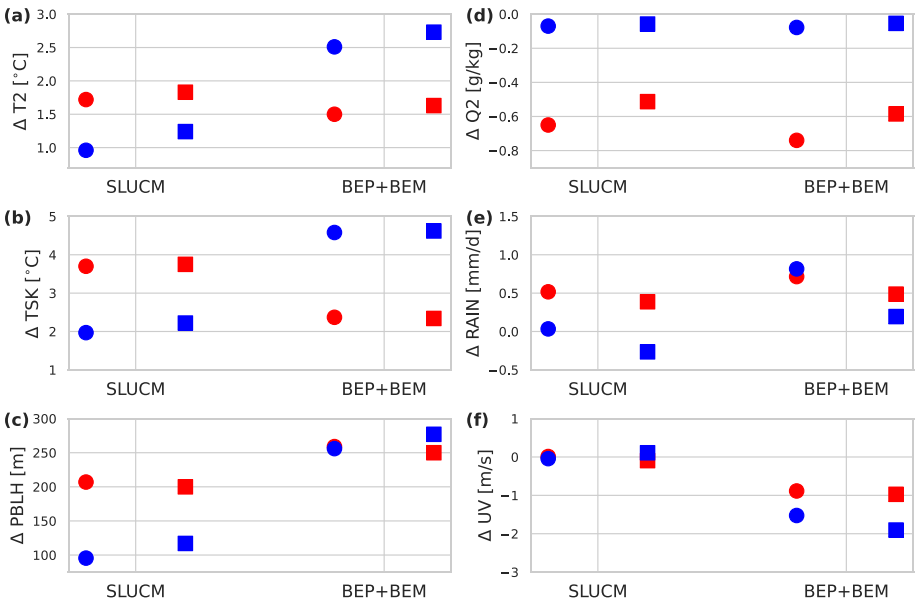

Figure 3. Differences between urban and rural areas in selected meteorological variables: 2 m air temperature (a) surface temperature (b) PBLH (c) 2 m air specific humidity (d) daily precipitation (e) and first model layer wind speed (f). Red indicates the summer season (JJA), and blue indicates winter (DJF). Circles denote average values for all selected European cities, and square symbols denote the Prague urban area.

3.2. Urban-induced effects and their changes

In this section, urban-induced effects are derived from differences between urban grid boxes and the rural ring for each city, as stated in detail in the third paragraph of section 2.2. First, we demonstrate the effects of urban areas and thus UMI behavior in both base simulations. Figure 3 shows urban-induced effects on several meteorological variables, separated by seasons, urban model, and covering all cities versus Prague only. The impact of urban areas on air temperature is 1.5 °C–2 °C in summer; for winter, the models agree less: the impact in winter is less in the case of SLUCM but higher in the case of BEP+BEM. Surface temperature exhibits a similar feature, but the magnitudes are higher (2 °C–4 °C). The planetary boundary layer height (PBLH) is also significantly affected by urban areas, being more than 200 m higher in cities in the summer, but again with a model discrepancy for the winter season. Specific humidity is significantly reduced in urban areas in summer, around 0.7 g kg^{-1}, but in winter, there is only a low decrease up to 0.1 g kg^{-1}. Summer daily precipitation is increased in urban areas, with the magnitude around 0.5 mm d^{-1}, which corresponds to approximately 50 mm per season, which means an increase of roughly 20%. In winter, the models do not correspond (opposite effects), and there is also a high difference between European cities and Prague. In this study, we consider wind speed in the first model layer instead of the standard 10 m wind speed, which exhibits incorrect values in the SLUCM simulations. The impact on the first model layer wind speed depends mainly on the urban model; SLUCM has nearly zero effect, but BEP+BEM indicates a decrease up to 2 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.

In the following paragraphs, we investigate the impact of UCP variation on the alteration of urban-induced changes of meteorological variables or on specific components of UMIs, respectively. First, figure 4 shows the impact of the altered UCPs on the urban modification of 2 m air temperature. The values vary significantly with altered UCPs; namely, AH, UF, and RA have 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 UCPs 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

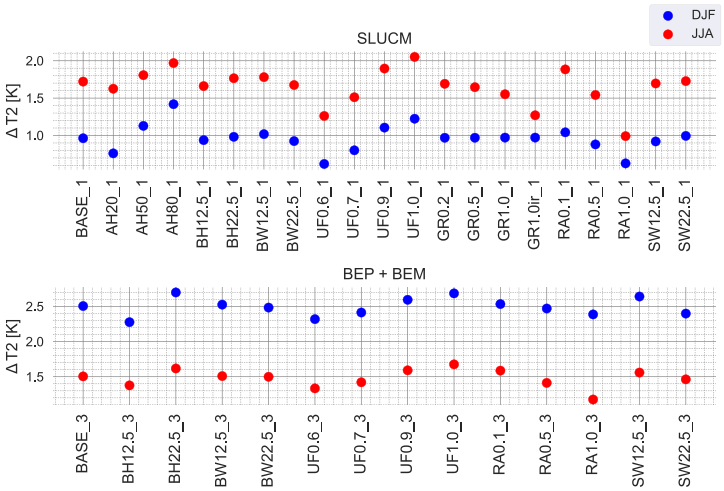

Figure 4. Dependence of urban alteration of 2 m air temperature on the values of UCPs. Displayed values represent averages within all selected European cities.

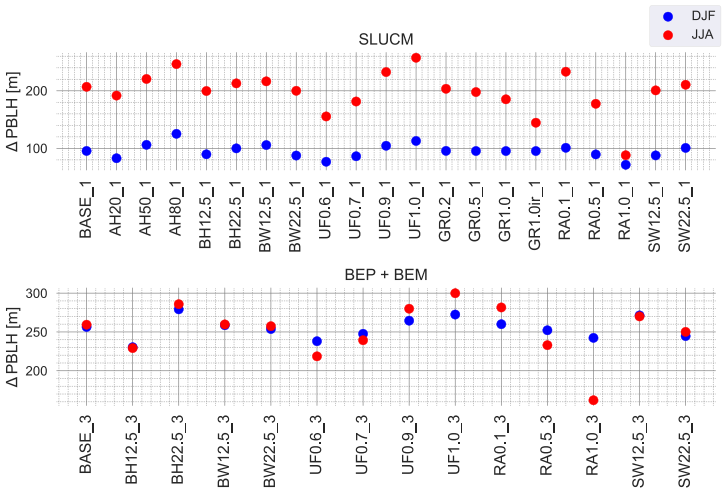

Figure 5. Dependence of the urban effect on PBLH on different values of UCPs. Displayed values represent averages within all selected European cities.

urban canopy (BH and SW) have a more significant impact than in the case of SLUCM. In view of summer UHI mitigation, UF decrease, RA increase, and irrigated green roofs have the highest potential in terms of SLUCM, indicating a temperature decrease of about 0.5 °C in all cases compared to base simulations. In terms of BEP+BEM, UF and RA have a little less impact, 0.2 °C and 0.4 °C. The impact of altered UCPs on urban modification of surface temperature exhibits similar features (not shown), but specific magnitudes are roughly twice greater (up to 2 °C in the case of extreme values of UCPs).

Having examined the temperature effects, we now turn to urban PBLH alteration as a function of UCP values. The increase of boundary layer height in cities (figure 5) is most influenced in SLUCM simulations by variations of AH, UF, and RA. An increased amount of AH, greater UF, or lower RA make the urban boundary layer higher by about 50–100 m in the summer season. In the case of BEP+BEM simulations, the urban street geometry also affects the results: higher buildings or thinner streets make the urban PBLH a few tenths of meters higher. In winter, changes in the urban PBLH are generally much lower in both models, with similar features.

Moving to precipitation impacts, we can conclude that modifications of urban precipitation in dependence on UCPs are noticeable only in the summer season (figure 6) are noticeable only in the summer season. Expressive differences (more than 0.2 mm d^{-1}) occur when AH, UF, and RA are altered in the SLUCM simulation, together with including irrigated green roofs. This is similar in BEP+BEM simulations, which are also influenced by BH (precipitation increase) and partly by SW (precipitation decrease). In the case of specific humidity variations, similar to precipitation, there are nearly no changes

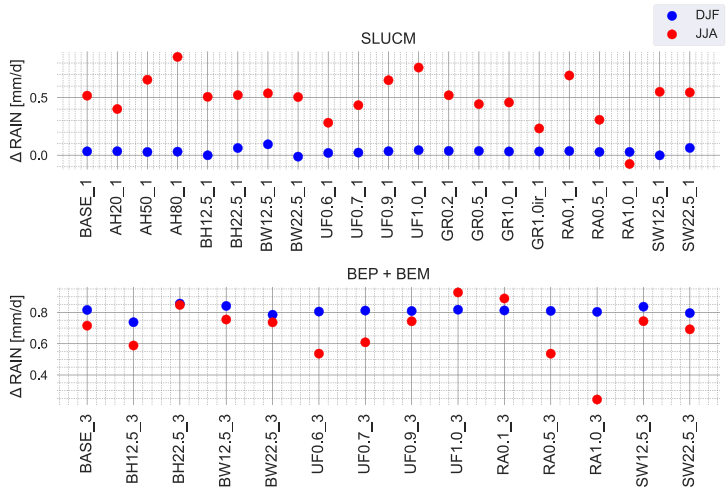

Figure 6. Dependence of the urban effect on daily precipitation on values of UCPs. Displayed values represent averages within all selected European cities.

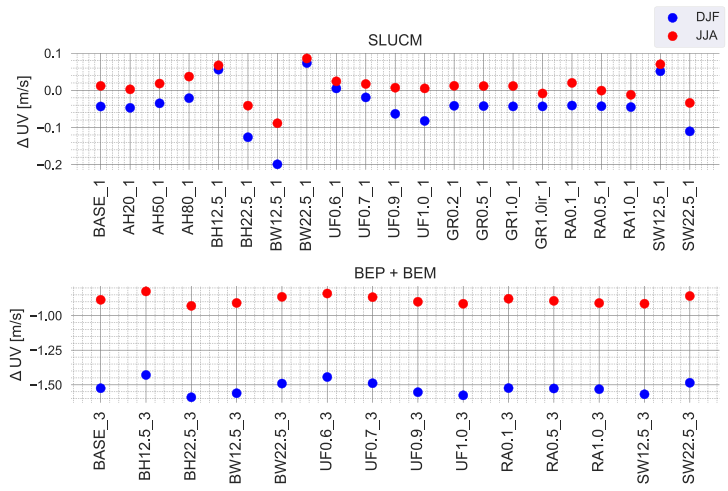

Figure 7. Dependence of the urban effect on first model layer wind speed on values of UCPs. Displayed values represent averages within all selected European cities.

in winter, and only noticeable impacts in the summer season are performed by alteration of the UF and switching on irrigation (not shown).

On the other hand, in the case of the impact of UCP alteration on urban wind speed in the first model layer (figure 7), a different pattern occurs compared to previous cases. The wind speed is mainly influenced by the parameters describing urban canopy geometry—BH, BW, and SW. As expected, higher and thinner buildings decrease urban wind speed within both urban models around 0.1 m s^{-1}. In the case of SW, both models indicate opposite results. Urban wind speed is also partly negatively influenced by the increase in UF. The winter and summer characteristics are almost similar, but the reactivity is a bit stronger in winter.

Having discussed the impact of UCP variation on UMI behavior for seasonal averages, we now investigate in more detail the urban-induced effect on 2 m air temperature (UHI), because it is a very important component of UMIs in view of human living impacts. Specifically, we will study the dependence of the magnitude of UHI intensity on different values of UF, GR, and RA in diurnal courses.. Figure 8 shows the daily cycle of the intensity of UHIs for different values of UF. In addition to the well-known fact that UHIs are weakest during the morning hours and strongest in the evening and at night, we can see that the dependence is also strongest in the evening and at night. In particular, SLUCM simulations indicate high UHI differences in summer, when a change of UF from a base value of 0.8 to 0.6 causes a UHI intensity reduction by 1 °C at night. On the other hand, BEP+BEM simulations exhibit a

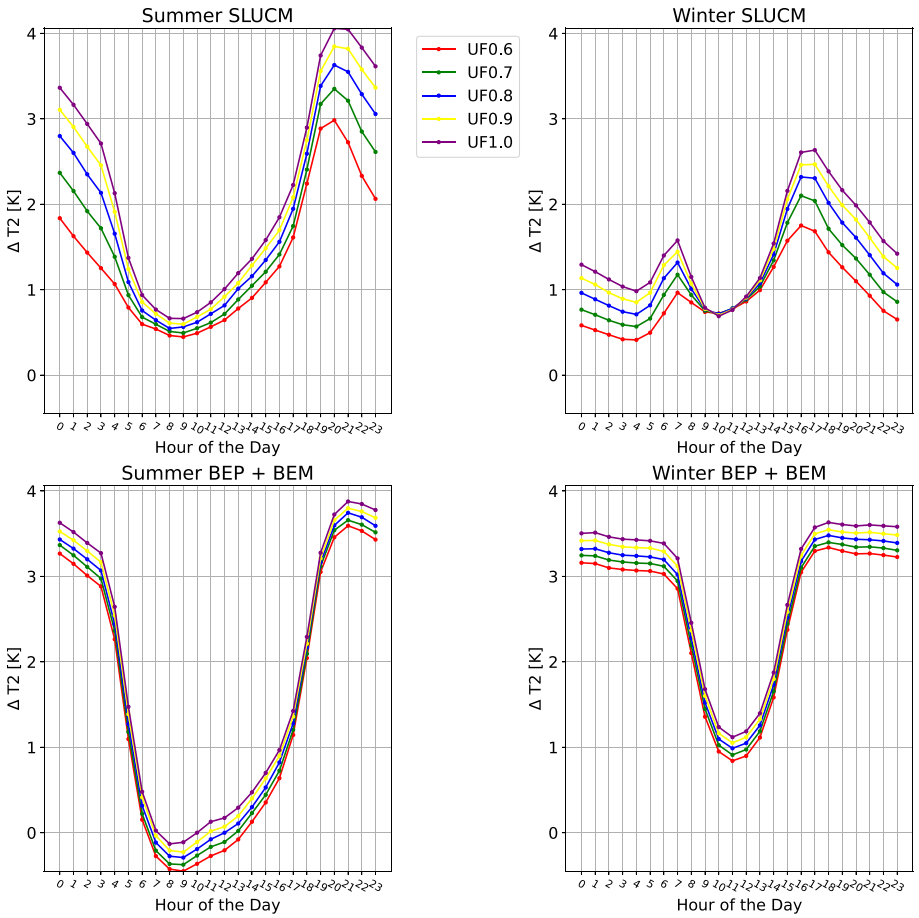

Figure 8. Dependence of the diurnal cycle of modeled UHI intensity on UF. Displayed values represent averages within all selected European cities; the time axis is in coordinated universal time (UTC).

lower variation of UHI intensity, with only approximately 0.2 °C difference between the base and lowest value of UF at night, similar to that in the winter season. Another feature of the BEP+BEM simulations is the generation of negative UHI intensity from early morning to midday, which was previously observed and explained by Theeuwes *et al* (2015) as the urban cool island.

Moving to the green roof impact, the dependence of the daily cycle of UHI intensity on GR and irrigation is shown in figure 9. We can see that this reactivity is weaker than in the case of UF: maximizing the green fraction leads to a UHI intensity reduction of 0.4 °C at midnight, while during the daytime there is even an increase of the intensity. Irrigation influences UHIs only in the morning and afternoon hours, decreasing temperatures by about 0.5 °C, but not at night. In winter, there is almost no effect of GR and irrigation.

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

4. Discussion

We start the discussion section by commenting on model temperature validation. A low negative overall temperature bias in both base simulations against E-OBS data (table 5) was encountered, but this does not influence urban-induced effects much, and both simulations exhibit very similar behavior except in urban areas (figure 2). Although the model parametrization settings are chosen based on a validation performed over the same domain by Karlický *et al* (2020), negative biases seem to be slightly stronger than in this reference study, which could be caused by a newer version of the model. Similar prevailing negative temperature biases were also indicated by Huszar *et al* (2020), who studied the central European region for a similar time period over the same domain and with the same resolution. Looking at the

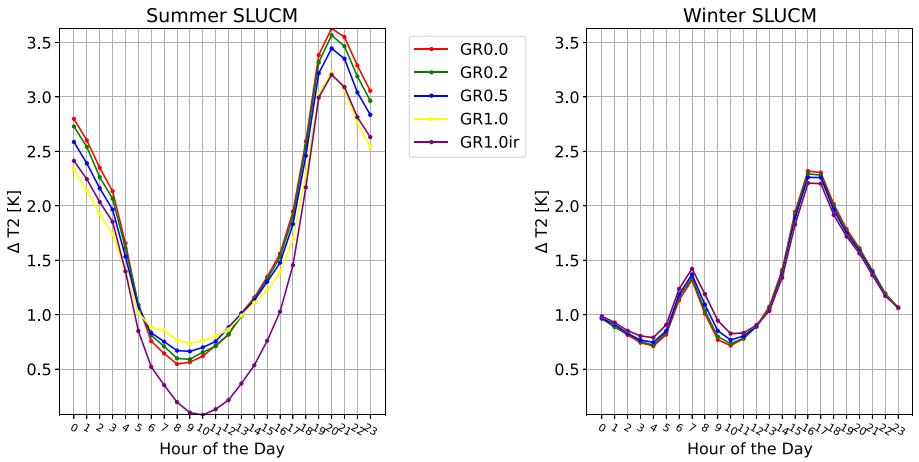

Figure 9. Dependence of the diurnal cycle of modeled UHI intensity on GR. Displayed values represent averages within all selected European cities; the time axis is in UTC.

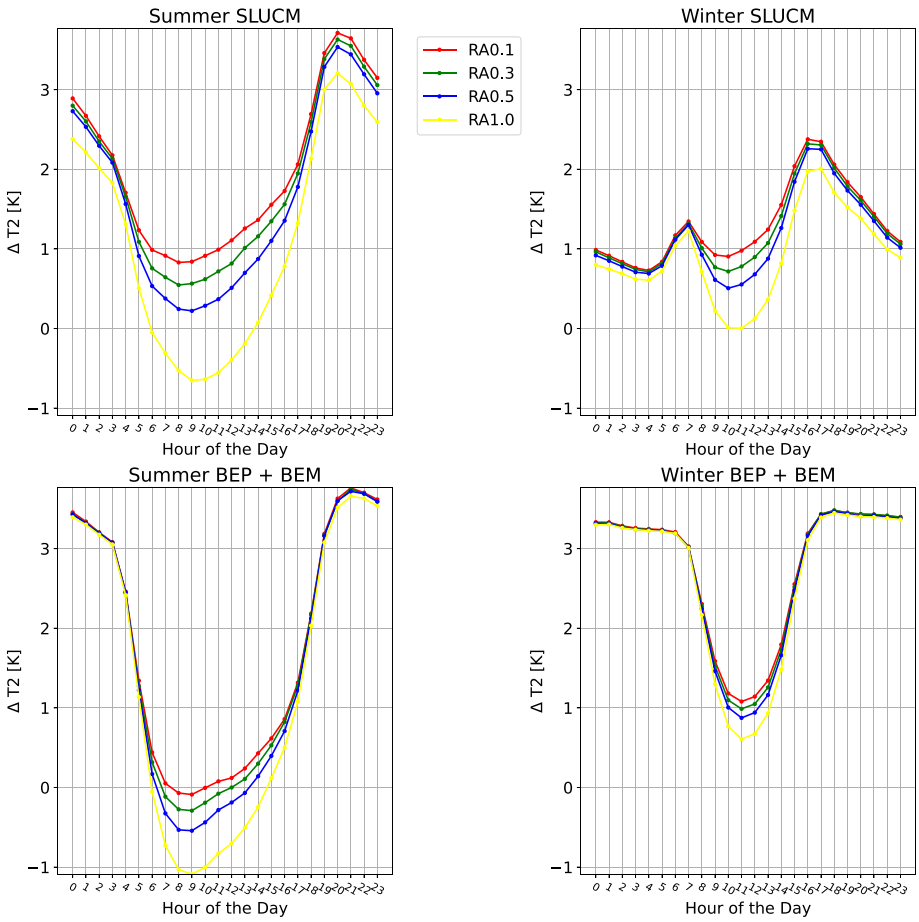

Figure 10. Dependence of the diurnal cycle of modeled UHI intensity on roof albedo. Displayed values represent averages within all selected European cities; the time axis is in UTC.

model UHI biases in the Prague urban area, a better capture of UHI intensity by SLUCM than the BEP+BEM urban model (namely in winter) was previously revealed for three central European cities by Karlický *et al* (2018). 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 AH calculations) and was also noticed in previous studies (Liao *et al* 2014, Karlický *et al* 2018), with a similar magnitude.

When we focus on urban-induced effects, we can conclude that, similar to air temperature, both models also indicate a high difference in the urban-induced effect on surface temperature (figure 3).

The winter difference has the same reason as in the case of air temperature (noted in the previous paragraph), and partly also the summer one, because SLUCM assumes constant AH independent of 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 in PBLH increase in urban areas between the SLUCM and BEP+BEM simulations in winter (figure 3) is caused by the direct interaction of the BEP+BEM urban scheme with model layers, which is not the case for SLUCM. Similar overestimation of BEP+BEM was also found in previous studies (Karlický *et al* 2018, Ribeiro *et al* 2021). The decrease of specific humidity in cities in summer can be explained well by impervious materials and rainwater drainage in cities; the same feature was found by Langendijk *et al* (2019), and Karlický *et al* (2020) state the annual mean urban–rural difference as 0.5 g kg^{-1}, which corresponds 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 the more oceanic climate of Prague than the average of the selected cities. A partly similar feature can be seen in the case of the urban-induced effect on daily precipitation. The value of the increase in daily precipitation in summer in urban areas (0.5 mm d^{-1}) is well in line with the observation study of Manola *et al* (2020), who indicated a summer precipitation increase in Amsterdam of about 40 mm. The same study showed a winter precipitation increase of 20 mm, which is less than that indicated by the BEP+BEM simulation for all European cities, but more than that indicated by the SLUCM simulation and BEP+BEM for Prague. The reduction of wind speed in city areas given by the BEP+BEM simulation corresponds to Karlický *et al* (2018), who described wind speed reduction in a vertical profile including the first model layer. The high difference between the SLUCM and BEP+BEM urban wind speeds (about 1 m s^{-1} in summer), caused by the 3D concept in BEP+BEM, is also documented by Huang *et al* (2019) in their short-term WRF model tests. In the case of the SLUCM simulation, the almost zero effect contrasts with the results of other studies (e.g. Droste *et al* 2018); however, Karlický *et al* (2020) indicated a very high sensitivity of the urban wind speed reduction to the boundary-layer scheme; the one used in our study performed the decrease in 10 m at only about 0.3 m s^{-1}, which is not 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.

After commenting on the UMI behavior in both base simulations, we now discuss the dependence of urban-induced effects on UCPs, beginning with temperature and its sensitivity to UCP alterations (figure 4). The high sensitivity of an increase in urban temperature to AH was confirmed by Qian *et al* (2023), who estimated AH in Chinese cities and found a positive relationship with the intensity of UHIs. The impact of UF was previously estimated experimentally by Bassett *et al* (2020), following their conclusions that the difference between extreme values of UF would be 0.3 °C, which is close to the results of the BEP+BEM simulations (0.4 °C) but not to the SLUCM simulations (0.8 °C). Our findings are also similar to those revealed by Steeneveld *et al* (2018), who tested the dependence of urban temperatures during summer days on AH, RA, and vegetation fraction. They found a similar sensitivity of urban temperature to AH and RA, but a higher temperature increase within the vegetation fraction decrease, as far as identified with the increase in UF considered in our study. The influence of RA was previously investigated as part of potential mitigation strategies; Oleson *et al* (2010) modeled the impact of RA increase from 0.32 to 0.9 globally with a UHI intensity reduction of 0.5 °C in summer, comparable with our findings (figure 4). Wang *et al* (2022) studied the effects of RA with the SLUCM model for Berlin, increasing the RA from 0.163 to 0.850 with the temperature decreasing almost 1 °C during the daytime and 0.5 °C at night, which is close to our results (figure 10). Similarly, the effect of GR was evaluated for mitigation purposes, but a noticeable effect in the summer is achieved only if green roofs are also irrigated. Green roofs alone cause a UHI intensity reduction of only 0.2 °C, which is less than that indicated by Wang *et al* (2022), but this study also reveals the importance of irrigation for additional reduction of urban temperature. Although the impact of BH is not very significant in comparison to other UCPs mentioned previously, the trend showing that higher buildings mean a more intensive UHI is the same as described by Xi *et al* (2021).

Moving to the dependence of variations of other UMI components on UCP values, we can conclude that the sensitivity of urban PBLH (figure 5) and daily precipitation in summer (figure 6) to the same UCPs as in the case of UHI intensity is possibly explained by enhanced convection above urban areas, caused by higher surface and air temperatures. Enhanced convection leads to greater mixing, higher PBLH, and the more frequent presence of convective precipitation (Theeuwes *et al* 2019). On the other hand, the impact of UCP alteration on the urban wind speed (figure 7) has a very distinct pattern: parameters describing the urban morphology (BH, BW, and SW) play a major role; UCPs influencing convection (AH, UF, and RA) have only a minor effect in summer.

If we now focus on the dependence of diurnal profiles of UHI intensity on UF, GR, and RA alterations, it is clearly visible that UF significantly influences nighttime urban temperatures (summer urban

temperature decreases up to 1.5 °C; figure 8), whereas RA influences daytime temperatures (with a similar magnitude around noon; figure 10), and the same is correct for the impact of fully covered and irrigated green roofs (with a magnitude of about 0.5 °C; figure 9). This feature is physically determined by a smaller amount of heat stored in the ground and released during the night in the case of decreased UF (artificial surfaces have high conductivity and heat capacity and thus store the heat well) and a reduction of absorbed solar radiation during the daytime in the case of high RA and a reduction of sensible heat release during daytime due to an increase in latent heat consumption in the 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).

To summarize, we can conclude that specific values of UCPs influence urban modification of all considered variables or all UMI components; models are significantly sensitive to their alterations, but with different magnitudes depending also on the model and season. The most discussed UMI component, the UHI intensity, is the most sensitive to UF, RA, green roofs with irrigation, and AH, while urban wind speed is affected by parameters describing urban canyon geometry (BH, BW, and SW). The revealed high sensitivity of UMIs to UCPs also 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 for different urban areas in regional climate models to avoid model biases.

We can also use previously discussed results in order to reveal suitable mitigation strategies for the reduction of negative aspects of urban-induced changes in meteorological variables or UMIs. As the most negative component of UMIs in view of human living conditions is the summer UHI, we have to track the dependence of its intensity on the alteration of UCP values. In this sense, the decrease of UF (adding of green areas or parks into cities in practice) and RA increase (use of high-reflective or cool roofs) have the highest impact. The corresponding potential UHI intensity decrease would be 0.5 °C under a UF change from 0.8 °C to 0.6 °C, and 0.7 °C under an RA increase from 0.3 to 1.0 following SLUCM simulations. The combination of these two strategies would benefit in a whole-day decrease in temperature because they are realized in different parts of the day (figures 8 and 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 in AH release influences the intensity of UHIs in the winter season, and changes in urban morphology parameters do not influence urban temperature at a considerable rate. This statement is in line with the study by Shen *et al* (2019), who concluded that the UF affects the temperature in urban areas more than the urban morphology, which instead impacts urban wind speed.

5. Conclusion

We present the results of a series of simulations with the WRF model, focusing on the sensitivity of the model results to the values of UCPs used in two urban models (SLUCM and BEP-BEM). The simulations were performed in the European domain with a horizontal resolution of 9 km for the 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. Validation of the model temperatures was performed using E-OBS and station data from CHMI.

Validation and comparison between simulations with the SLUCM and BEP+BEM urban models showed significant differences in some aspects of the results, based on the distinct structure of both urban models. In particular, BEP+BEM tends to largely overestimate the winter urban air temperature, above 1.5 °C. 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 to changes in values of UCPs. The intensity of UHIs is mainly influenced by changes in UF, roof albedo, green roofs with irrigation, and also by AH in winter, with a magnitude of around 0.5 °C from the base setup in all cases. The 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 to the same UCPs, but urban wind speed is influenced by parameters describing the urban morphology, about 0.1 m s^{-1}. The presented high sensitivity of the results to UCPs confirms previous studies that conclude the need for a correct setting of UCPs in regional climate simulations.

In view of potential mitigation strategies, our results show that decreasing UF and increasing roof albedo appear to be the most efficient strategies to reduce the intensity of UHIs 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 UF can reduce nighttime temperatures by 1 °C, an increase in roof albedo can reduce daytime temperatures by the same value.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.48700/datst.nwh2j-tbh43. The source code of the WRF model is publicly available.

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Conflict of interest

The authors declare that they have no conflict of interest.

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