SIMULATION-BASED ASSESSMENT OF UHI MITIGATION MEASURES IN CENTRAL EUROPEAN CITIES

Milena Vuckovic, Aida Maleki, Kristina Kiesel, Ardeshir Mahdavi
Vienna University of Technology, Karlsplatz 13, 1040 Vienna, Austria

ABSTRACT

The present paper summarizes the results of a multi-national multi-year effort within the framework of a European project. First, the extent and implications of the UHI phenomena in a number of Central European cities were explored. Subsequently, a number of urban areas were selected for the conception and predictive assessment of urban intervention scenarios (so-called mitigation measures). The selected mitigation measures were then virtually implemented in an advanced urban modelling environment to quantitatively assess their implications for the key indicators of urban climate. The analysis of the simulation results allows for a systematic evaluation and ranking of the aforementioned mitigation measures. Additionally, the paper explores the potential of an empirically-based simulation calibration process. For this purpose, a small control area in the city of Vienna, Austria, was selected. The data obtained from the on-site stationary weather station was used to evaluate the accuracy of the simulation output. The results highlight the potential of the calibration process in improving the quality of simulation-based predictions.

INTRODUCTION

The urban microclimate in general and the Urban Heat Island (UHI) phenomena in particular have recently emerged as major areas of inquiry in environmental analysis and urban modelling (see, for example, Voogt 2002, Arnfield 2003, Mirzaei and Haghighat 2010). Changes in urban climate are believed to have critical ramifications in view of the energy demand of buildings (especially for space cooling), corresponding environmental emissions, and thermal comfort of the city dwellers (Taha 1997, Grimmond 2007, Harlan and Ruddell 2011, Kleerekoper et al. 2012).

In this context, the present contribution focuses on deployment opportunities of numeric simulation applications toward systematic and comprehensive assessment of well-conceived urban intervention scenarios (e.g. mitigation measures pertaining to the Urban Heat Island phenomena). Toward this end, we summarize the results of a multi-national multi-year effort within the framework of a – recently completed – European project (Central Europe Program 2011).

As the first step in the project, the extent and implications of the UHI phenomena in a number of Central European cities were explored (Budapest, Ljubljana, Modena, Padua, Prague, Stuttgart, Vienna, and Warsaw). Subsequently, a number of urban areas were selected that could act as "pilot action" areas for the conception and predictive assessment of urban intervention scenarios (so-called mitigation measures). The candidate mitigation measures include, for example, modification to the built urban surfaces (buildings, pavements, roads), increase in vegetation areas (particularly in open spaces), and deployment of bodies of water. The selected mitigation measures were then virtually implemented in an advanced urban modelling environment to quantitatively assess their implications for the key indicators of urban climate (e.g., ambient temperature, overheating hours).

The analysis of the simulation results allows for a systematic evaluation and ranking of the aforementioned mitigation measures. The results provide thus – together with further consideration pertaining to the economic costs and the political feasibility – a rich information basis to the pertinent stakeholders and decision makers. Needless to say, the value of such results greatly depends on the fidelity and reliability of the simulation tool and its proper use throughout the modelling process. The paper thus concludes with exploring the potential of an empirically-based simulation calibration process. For this purpose, a small control area in the city of Vienna, Austria, was selected. The data obtained from the on-site stationary weather station was used to evaluate the accuracy of the simulation output. The results highlight the considerable potential of the calibration process in improving the quality of simulation-based predictions. Particularly in case of the simulation-based evaluation of large-scale and costly urban interventions, execution of a systematic calibration process is indispensable.

THE URBAN HEAT ISLAND IN CENTRAL EUROPE

To identify and evaluate the extent of the UHI phenomenon in eight Central-European cities (namely, Budapest, Ljubljana, Modena, Padua, Prague, Stuttgart, Vienna, and Warsaw), hourly-based weather dataset pertaining to one-week summer period (with high air temperature and relatively low wind velocity) were obtained from each participating city (Kiesel et al. 2013, Mahdavi et al. 2014a, 2014b). The collected information included hourly data on air temperature, wind speed, and precipitation from two representative weather stations (one urban and one rural). Figure 1 shows the results in terms of the UHI intensity distribution in a course of a reference summer day, derived from the one-week data. Figure 2 shows the cumulative frequency distribution of UHI values for the participating cities for the reference week. The results reveal the existence and significant magnitude of the UHI phenomenon in all participating cities, especially during the night hours. Furthremore, the results point to the distinct variation of UHI intensity amongst the cities, especially in terms of peak values. These findings imply the need for further explorations concerning the UHI in order to explain its distinct dynamics over space (location), time (day, season), and in a broader geographical context.

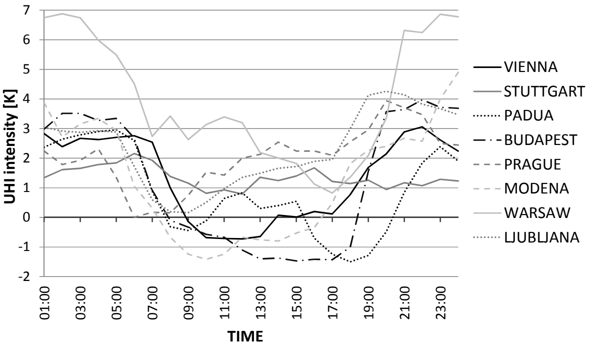

Figure 1 Mean hourly UHI intensity distribution for a reference summer day

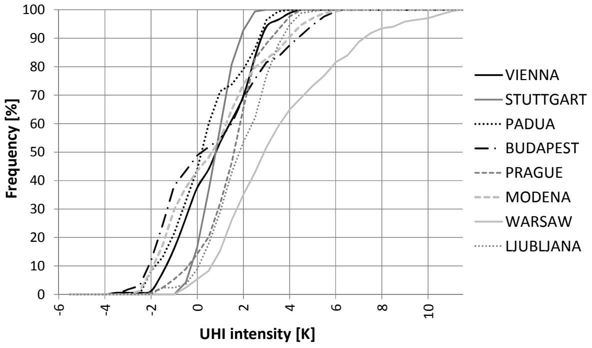

Figure 2 Cumulative frequency distribution of UHI intensity for a one week summer period

MODELLING EFFORTS

Further efforts toward attenuating microclimatic extremes have become imperative. As stated at the outset, the undesired thermal circumstances in the urban environment may have far-reaching implications for energy use, air pollution, and human requirements pertaining to health and comfort. To address these issues, well-conceived urban intervention scenarios (so-called mitigation measures) should be implemented. In this context, scientific experts involved undertook extensive modelling efforts toward comprehensive assessment of the effectiveness of envisioned UHI mitigation measures (Mahdavi et al. 2014b). For this purpose, a specific area within each city was selected ("pilot action" area), that was either targeted for the implementation of mitigation measures or represent likely candidates for such measures. Table 1 provides an overview of the locations of the targeted urban areas.

Table 1
Locations of the pilot action areas

CITY	LATITUDE	LONGITUDE
Budapest	47°30.65' N	19°1.58' E
Ljubljana	46°03.72' N	14°30.84' E
Modena	44°39.05' N	10°53.93' E
Padua	45°22.65' N	11°52.24' E
Prague	50°6.24' N	14°26.42' E
Stuttgart	48°46.54' N	9°9.56' E
Vienna	48°11.88' N	16°22.13' E
Warsaw	52°13.70' N	20°59.58' E

The existing microclimatic circumstances for these areas (base case) were modelled using state of art CFD-based numeric simulation environment ENVI-met (Huttner and Bruse 2009). This tool deals with the complexity of the microclimate system while considering a relatively comprehensive range of factors (building volume, air flow, vegetation, surface properties). Once the base case was modelled and evaluated, the envisioned mitigation measures (M1, M2, M3) were defined for each of these areas (Table 2), and virtually implemented in the simulation environment. Note that, in case of four cities (Vienna, Warsaw, Prague, and Budapest), the initial model results were compared with measurments in order to calibrate the respective models. The details of this calibration process for the Vienna case are provided in the "model calibration" section below.

Table 2
Summary of envisioned mitigation measures

CITY	M1	M2	M3
Budapest	New urban development + Green areas + Water areas	Trees	-
Ljubljana	Green areas	Water areas	-
Modena	Green areas	Cool walls	Green roofs
Padua	Green areas + Trees	Cool pavements	Cool roofs
Prague	New urban development	Green roofs	-
Stuttgart	Green areas	Trees	Water
Vienna	Trees	Green roofs	M1 + M2
Warsaw	Trees + Green roofs	M1 + Pervious pavements	-

To exlore the potential of information that can be aquired from the modelling process, relevant results are provided below for three cities, namely Vienna, Padua, and Warsaw. Figures 3 to 5 show the mean hourly temperature in the course of a reference summer day in Vienna, Padua, and Warsaw, for the base case and respective mitigation scenarios. Figures 6 to 8 show the corresponding temperature differences between the base case and the applicable mitigation scenarios in the course of a reference summer day. Please note that, given the variety of the proposed mitigation measures as well as the diversity of the contextual circumstances, a consistent cross-comparison of post-mitigation implications is not feasible. However, the results do suggest that greening measures in general display a significant potentital toward improving the local microclimatic conditions (see Table 3).

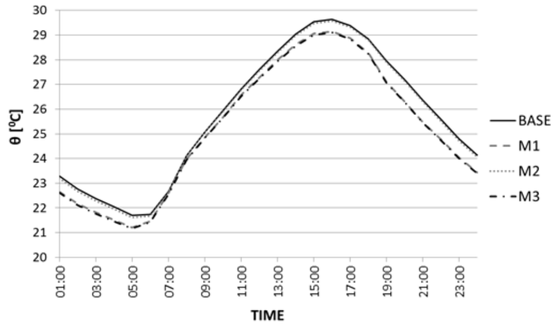

Figure 3 Mean hourly temperature in the course of a reference summer day in Vienna for the base case and three mitigation scenarios

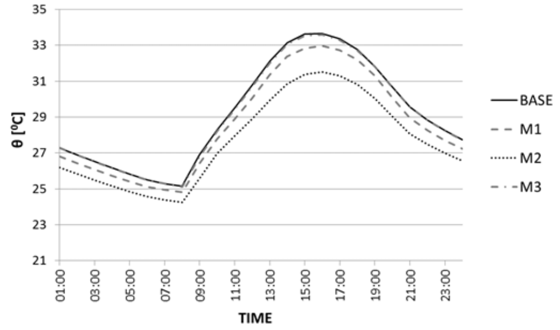

Figure 4 Mean hourly temperature in the course of a reference summer day in Padua for the base case and three mitigation scenarios

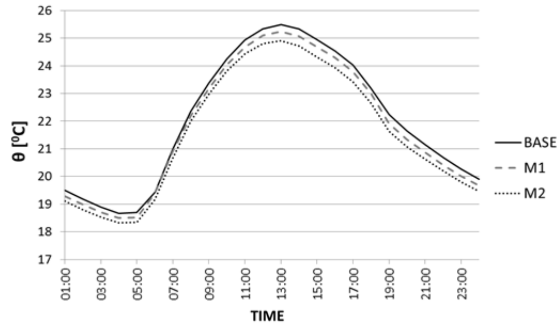

Figure 5 Mean hourly temperature in the course of a reference summer day in Warsaw for the base case and two mitigation scenarios

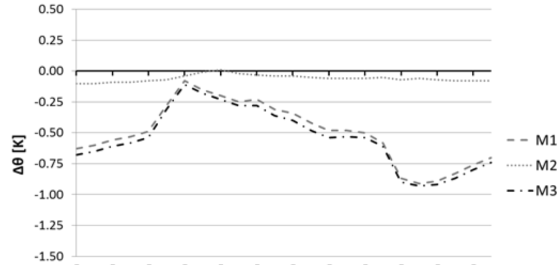

Figure 6 Temperature difference between the base case and three mitigation scenarios in the course of a reference summer day in Vienna

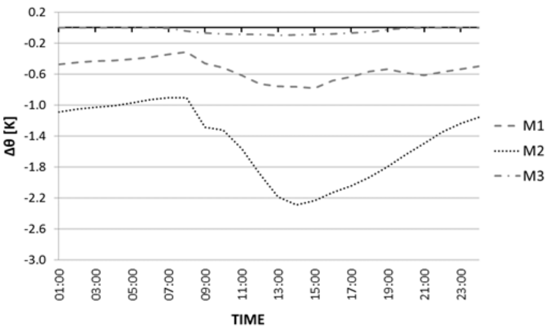

Figure 7 Temperature difference between the base case and three mitigation scenarios in the course of a reference summer day in Padua

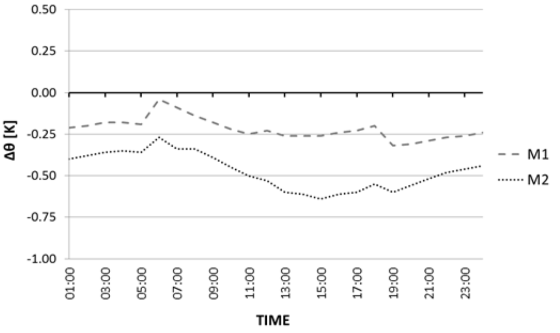

Figure 8 Temperature difference between the base case and two mitigation scenarios in the course of a reference summer day in Warsaw

These results illustrate the varying impacts of different mitigation measures. In case of the targeted area in Vienna, for example, the implementation of green roofs do not appear to noticeably influence the air temperature in the urban canyon. The implementation of trees, on the other hand, appeared to be more benefitial, while the combination of these two measures proved to be most effective.

With regard to the temporal pattern of the effects in the Vienna case, it can be noted that the difference in air temperature is more pronounced during evening and night hours. In case of Padua and Warsaw, however, the envisioned mitigation measures appear to be more effective during the day. This further stresses the overall complexity of microclimate responses to specific mitigation practices.

To further investigate the temporal nature of UHI intensity values ($\Delta\theta$) and their sensitivity to various mitigation measures, we introduced the concepts of Cumulative Temperature Increase (CTI) and Cumulative Temperature Decrease (CTD) (Mahdavi et al. 2015). CTI and CTD are computed as the cumulative sum of all positive and negative $\Delta\theta$ values in the course of a reference day, expressed in Kh:

$$CTI = \sum_{i=1}^{24}(\theta_{B,i} - \theta_{M,i}), \text{ subject to: } \theta_{B,i} < \theta_{M,i} \quad (1)$$

$$CTD = \sum_{i=1}^{24}(\theta_{B,i} - \theta_{M,i}), \text{ subject to: } \theta_{B,i} > \theta_{M,i} \quad (2)$$

Here, $\theta_{B,i}$ is the modelled air temperature at interval *i* and $\theta_{M,i}$ is the corresponding modelled post-mitigation air temperature. A summary of the results (predicted CTD and CTI values for summer and winter seasons for all mitigation measures in each participating city) is provided in Table 3. Note that in case of Prague the pilot area concerned was targeted for brownfield rehabilitation, and the CTD/CTI values were computed from the base case (brownfield).

Table 3
Summary of predicted CTD and CTI values

CITY		SUMMER		WINTER	
		CTD	**CTI**	**CTD**	**CTI**
Budapest	M1	16	7	18	0
	M2	2	0	1	0
Ljubljana	M1	1	0	2	0
	M2	1	0	0	0
Modena	M1	21	0	N/A	N/A
	M2	0	4	0	1
	M3	6	0	1	0
Padua	M1	13	0	1	0
	M2	35	0	6	0
	M3	1	0	0	2
Prague	M1	0	21	0	31
	M2	0	26	0	30
Stuttgart	M1	7	0	99	0
	M2	7	1	0	6
	M3	0	0	11	0
Vienna	M1	12	0	1	0
	M2	1	0	0	0
	M3	13	0	1	0
Warsaw	M1	5	0	0	0
	M2	11	0	1	0

The above summary provides a useful basis to urban planners, architects, and decision makers toward evaluation and realization of effective urban intervention scenarios.

MODEL CALIBRATION

Numerical modelling is being increasingly deployed in the realm of urban climate studies. However, the value of model output depends in part on the accuracy and quality of input data (Avila and Pitt 2008, Hajdukiewicz et al. 2011, Mahdavi and Tahmasebi 2012). To further address these issues, we explored the potential of an empirically-based simulation calibration process. For this purpose, a specific location in the city of Vienna was selected (Figure 9). Specifically, the actual air temperature measurements at this location were compared with simulated results, whereby multiple versions of the simulation application (more precisely, ENVI-met

3.1 and ENVI-met 4.0), different settings, as well as different forcing parameters were considered (Maleki et al. 2014). An overview of the input parameters for all simulation options considered is provided in Table 4. The weather data was collected from two stationary weather stations: one located at the highest point of the Vienna University of Technology, above the urban canopy (hereafter referred to as the BPI), and the second located inside the urban canopy (hereafter referred to as the C*). As the representation of the domain's geometry itself was not subjected to calibration, a moderately simple representation was adapted for the entire set of the parametric studies (Figure 10).

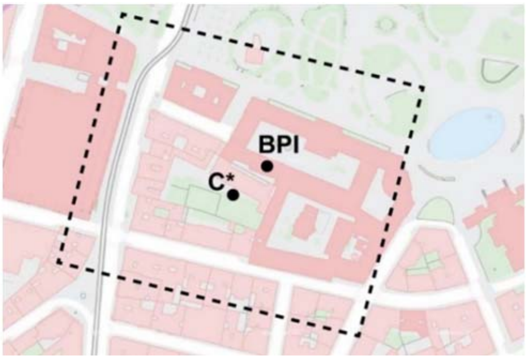

Figure 9 The plan of the area selected for model calibration process with the positions of the two stationary weather stations

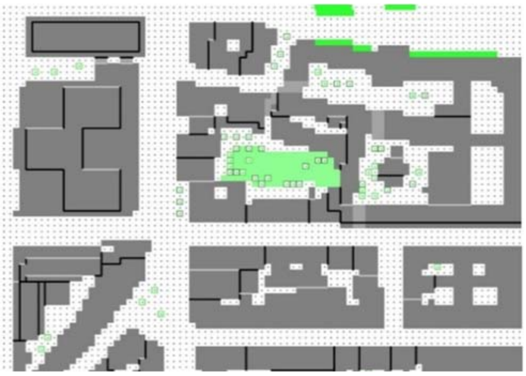

Figure 10 The modelled urban domain in the urban microclimate simulation application

In the present case, calibration relied on a heuristically guided trial and error process. A number of scenarios involving various input information were explored until an acceptable convergence of the simulated and measured results was achieved. The calibration process proceeded as follows: Modifications to the default system settings (following the developer's recommendations) for trial run (Scenario 0 in Table 4) using ENVI-met 3.1 ("none-forcing" mode) resulted in the input data set of Scenario Ia and a better predictive performance. Subsequently, the use of the same input information (Scenario Ib) with the updated ENVI-met 4.0 further improved the results, albeit slightly. Scenario II tested the recently introduced possibility of user defined diurnal variations of atmospheric boundary conditions (forcing) in ENVI-met 4.0, with hourly forcing mode. Again, an improvement was achieved. However, the forcing option with predefined minimum and maximum air temperature values (Scenario III) did not result in improvements.

Table 4
Simulation input data for various model calibration stages (22nd of July 2010)

SCENARIOS		0	Ia	Ib	II	III
Basic Input data	ENVI-met	3.1	3.1	4.0	4.0	4.0
	Wind Speed [m.s^{-1}]	0.2	2	2	2	2
	Initial Temp. [K]	301	303	303	303	303
	Solar Adjustment	1	0.82	0.82	0.82	0.82
	Specific Humidity [g/kg air^{-1}]	7	8	8	8	8
Buildings	Albedo walls	0.2	0.4	0.4	0.4	0.4
	Albedo roofs	0.2	0.4	0.4	0.4	0.4
Forcing	Max temp.[K]	-	-	-	306.85	306.85
	Time of Max temperature	-	-	-	16:00	16:00
	Min temp. [K]	-	-	-	295.15	295.15
	Time of Min temperature	-	-	-	04:00	04:00
	Max relative humidity [%]	-	-	-	76	76
	Time of Max relative humidity	-	-	-	04:00	04:00
	Min relative humidity [%]	-	-	-	39	39
	Time of Min relative humidity	-	-	-	17:00	17:00
	Forcing	-	-	-	hourly	min / max

To evaluate the deviation between the modelling output and actual measured data, three different indicators were defined. First indicator was the index of agreement (d) suggested by (Willmott 1982):

$$d = 1 - \frac{\sum_{i}^{n}(s_i - m_i)^2}{\sum_{i}^{n}(|s_i'| - |m_i'|)^2} \qquad 0 \le d \le 1 \tag{3}$$

Here $s_i' = s_i - \bar{m}$ and $m_i' = m_i - \bar{m}$. $\bar{m}$ is the mean value of measured variables, m_i is the measured variable, and s_i the simulated one.

The second indicator was the *Root-Mean Square Error* (RMSE), a measure of the differences between model outcome and the associated observed values:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \quad (4)$$

The third indicator was the *Coefficient of Variation of the Root Mean Square Deviation* CV (RMSE):

$$CV(RMSE) = \left(\frac{RMSE}{\bar{m}}\right) \times 100 \quad (5)$$

The obtained results (see Figures 11, 12 and 13) suggest that predictions based on computation may significantly deviate from actual measurements, thus undermining the model application utility. It can be observed that none of the model instances yield perfect reproductions of the measurements, but some model scenarios (in this case, scenario II) perform appreciably better than the others. The respective statistics pertaining to the comparison of modelled and measured results are given in tables 5 to 7.

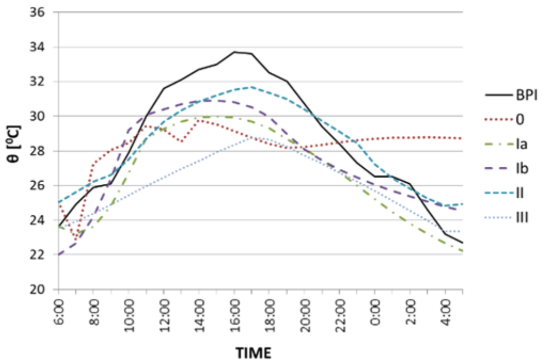

Figure 11 Comparison of measured urban temperatures at weather station BPI with the results of simulation under different settings and input assumptions (22nd July 2010)

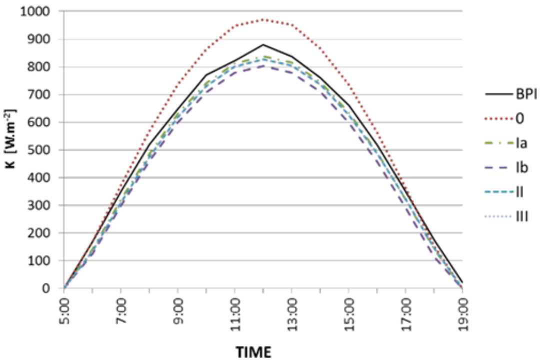

Figure 12 Comparison of measured global solar radiation at weather station BPI the results of simulation under different settings and input assumptions (22nd July 2010)

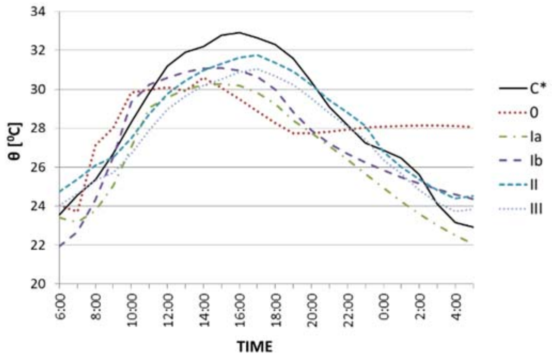

Figure 13 Comparison of measured urban temperatures at weather station C with the results of simulation under different settings and input assumptions (22nd July 2010)*

Table 5

d, RMSE, and CV (RMSE) for comparison of simulated temperatures with weather station measurements (BPI)

SCENARIOS	0	Ia	Ib	II	III
d	0.50	0.88	0.92	0.95	0.92
CV(RMSE) [%]	11.04	7.84	6.32	4.51	11.04
RMSE [K]	3.15	2.24	1.80	1.29	3.15

Table 6

d, RMSE, and CV (RMSE) for comparison of simulated global solar irradiance values with weather station measurements (BPI)

SCENARIOS	0	Ia	Ib	II	III
d	0.98	1.00	0.99	1.00	1.00
CV(RMSE) [%]	13.82	5.05	10.44	6.45	6.45
RMSE [W.m^{-2}]	73.81	27.00	55.79	34.45	34.45

Table 7

d, RMSE, and CV (RMSE) for comparison of simulated temperature with weather station measurements (C)*

SCENARIOS	0	Ia	Ib	II	III
d	0.67	0.91	0.94	0.97	0.95
CV(RMSE) [%]	9.25	6.89	5.30	3.36	10.04
RMSE [K]	2.64	1.97	1.51	0.96	2.87

These results suggest that the input value set of scenario II yields the closest approximation of the measured values. Thus, despite the residual difference to measurments, it was selected for the assessment of the effectiveness of environmental mitigation strategies.

CONCLUSION

We presented the results of EU-supported project concerned with the extent of the UHI phenomena in a number of Central European cities. The main goal was to provide a common understanding of the UHI effects which will facilitate the implementation of concrete UHI mitigation measures within specific and clearly defined urban segments. The analysis of current weather conditions demonstrated the existence and significant magnitude of the UHI effect in all participating cities, implying more intense UHIs during the night hours.

To address the need for effective means of evaluating and mitigating UHI effects, a comprehensive modelling effort was undertaken. Thereby, using advance numeric modelling tools and techniques, selected mitigation measures were evaluated. The results highlight differences in impact levels, both in space (when applied to different locations), and in time (with regard to temporal patterns). We thus conclude that the effectiveness of different mitigation options must be always evaluated in the specific spatio-temporal context they are intended for.

To address questions concerning the reliability and quality of the modelling output, we further explored the potential of an empirically-based simulation calibration process. Generally speaking, a properly calibrated tool is likely to yield a better predictive performance and thus can be used to evaluate the effects of different urban intervention scenarios and support climate-aware urban design practices.

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