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REPRESENTATION OF WEATHER CONDITIONS IN BUILDING PERFORMANCE SIMULATION: A CASE STUDY OF MICROCLIMATIC VARIANCE IN CENTRAL EUROPE

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ABSTRACT

In order to predict the performance of a building regarding energy demand and indoor conditions, reliable input information is needed. Weather data represents an important component of such input information for performance simulation. Currently, standard weather files are typically used for this purpose. These are based on long-term observations (weather records) from weather stations. Frequently, this data is generated from weather stations in the proximity of airports. However, such files do not necessarily represent in a detailed manner the microclimatic conditions around the designated location of a building. In this context, the present paper explores the possibility of generating weather information for urban areas that is more in tune with the conditions around specific building locations. This local adjustment of the weather information and its consideration in weather files could improve the reliability of simulation-based predictions of building performance.

INTRODUCTION

Recently, a number of research efforts have been initiated to better understand the variance in microclimatic conditions due to factors such as urbanization, presence and density of industrial or commercial buildings, green areas, bodies of water, etc. (Grimmond 2007; Alexandri 2007). The geometry, spacing and orientation of buildings and surrounding open areas greatly influence the microclimate in the city (Kleerekoper et al. 2012). Looking on the smaller scale, microclimate can vary significantly across an area consisting of even a few streets. On a greater scale, this deviation is observed in terms of significantly higher urban temperatures than that of the surrounding rural environment. This circumstance (see, for example, Voogt 2002) is referred to as the urban heat island phenomenon (UHI). Furthermore, the UHI effect is directly related to (and worsened by) the climate change. Increase in average temperatures is believed to adversely affect the health of people living in cities (Harlan et al. 2011). Additionally, higher air temperatures have a direct effect on the energy use due to increased deployment of air conditioning (Akbari 2005).

In this context, this paper presents the results of an on-going research project that investigates the urban heat island phenomena in the Central European area (Mahdavi et al. 2013). In addition to the comparison of UHI effects in each of the participating cities, we also address the variation in the microclimatic conditions in different locations in the city of Vienna. Consideration of the micro-climatic variations of the weather information, in terms of temperature and urban heat island intensity, can improve the reliability of simulation-based predictions of building performance. Specifically, the present paper explores the possibility of generating weather information for urban areas that is more in tune with the conditions around specific building locations.

Toward this end, we pursue a three-step approach. First, the data from participating cities are collected and analyzed. Specifically, long-term weather station data from urban and rural weather stations in Stuttgart, Warsaw, Prague, Padua, Modena, Ljubljana and Budapest are collated and included in the analysis. We shall consider the applicability of the results in a broader geographical context involving the Central European region. Second, data from multiple weather stations in the city of Vienna are collected and analyzed. The results show a considerable variance, which, if ignored, would lead to major uncertainties in inferences made based on performance simulation. Subsequently, this variance is studied in view of the physical features of the aforementioned weather station locations. Specifically, we explore the possibility to explain and approximately predict microclimatic variance based on location specifics. Furthermore, as a final step, we'll introduce a systematic framework for the evaluation of UHI's far-reaching implications for microclimate, energy use, and human requirements pertaining to health and comfort. Within our framework, the magnitude of UHI phenomenon is expressed for specific clearly bounded segments of the urban domain that could be defined in terms of an "Urban Units of Observation" or "U2O" (Mahdavi et al. 2013). These well-defined segments may share characteristic features in view of geometry, massing, or other aspects of the physical structure.

URBAN HEAT ISLAND PHONOMENON IN THE CENTRAL EUROPEAN REGION

Given the complexity of the UHI phenomena, it needs to be explored in a broader geographical context. Within the framework of the aforementioned research project, we investigate the urban heat island phenomena in the Central European area. Analysis of the data provided by each participating city reveals the extent of the UHI effect and a considerable variance in its manifestations.

Assessment of UHI intensity

Each participating city provided data (including air temperature, wind speed and precipitation) from two representative weather stations (one urban and one rural). Specifically, data from seven consecutive summer days were analyzed in terms of hourly values of the urban heat island intensity in the course of a reference day. Figure 1 shows the mean hourly UHI intensity values in the participating cities (Urban heat island intensity denotes the difference between urban and rural temperature). Figure 2 shows the cumulative frequency distribution of UHI values for the reference week. Using this figure, one can define the percentage of time, during which the UHI intensity is below (or above) a certain value. Figure 3 shows hourly values of urban temperatures for the reference summer day.

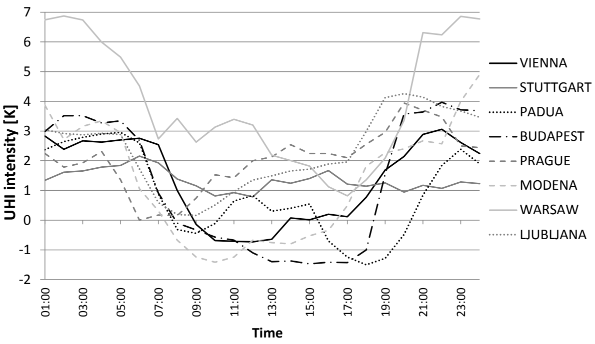

Figure 1 Mean hourly UHI intensity distribution for the reference day

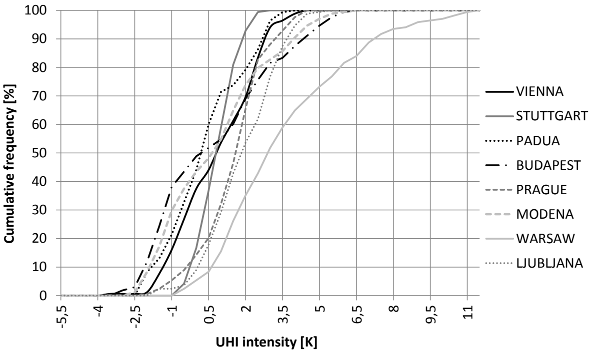

Figure 2 Cumulative frequency distribution of UHI intensity for a one week summer period

These results clearly demonstrate the existence and significant magnitude of the UHI effect in participating cities, especially during the night hours. However, the time-dependent UHI patterns vary considerably across the participating cities. In Warsaw, for example, UHI intensity level ranges from around 2K during daytime to almost 7K during the night, while in Stuttgart levels are rather steady, ranging from 1K to 2K.

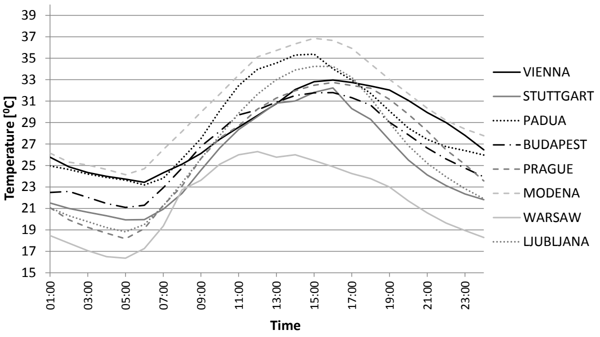

Figure 3 Mean hourly urban air temperature distribution for a day representing the reference week in summer

These variations underline the aforementioned problem of standard weather files used in performance simulation. Simulation-based predictions of individual buildings' thermal performance need to address this problem. Thereby, higher-level (urban, regional) modeling tools could be applied. Such tools, however, would have to be able to account for the impact of cities' main geographical and topographic characteristics. Furthermore, the role of urban layout and morphology, industrial sites, transportation systems and infrastructures, surface properties, green areas, and water bodies on microclimatic conditions need to be understood and modeled. The impact of urban heat island on buildings' energy requirements cannot be ignored. Urban microclimate studies have the potential to provide valuable insights regarding the interaction between buildings' energy balance and their surroundings.

URBAN HEAT ISLAND PHONOMENON IN THE CITY OF VIENNA

Intra-city variations

In order to characterize the spatial and temporal features of the UHI manifestations in the city of Vienna, micro-climatic variations within several city locations were observed and analyzed (Kiesel et al. 2012). The weather data used for this research was collected at several weather stations positioned in different locations throughout Vienna by the responsible organization ZAMG ("Zentralanstalt für Meteorologie und Geodynamik") during 2011. Table 1 provides an overview of these weather stations. For the purposes of the present treatment, we focus on data from summer and winter periods in 2011.

Table 1
Description of the weather stations

	STATIONS	TYPE	ALTITUDE
A	Innere Stadt	Urban (central)	171m
B	Hohe Warte	Urban (peripheral)	198m
C	Donaufeld	Urban (peripheral)	161m
D	Groß-Enzersdorf	Urban (peripheral)	157m
R	Seibersdorf	Rural	73m

Figures 4 and 5 show the mean hourly UHI intensity (in the course of a reference day) for central (A) and peripheral urban locations (B, C, D) for summer and winter respectively. Note that urban heat island intensity is defined here in terms of air temperature difference between measurements made in urban and rural location (R, i.e. Seibersdorf). The results suggest that the extent of the temperature differences across the city vary considerably in time (day, season) and space (location).

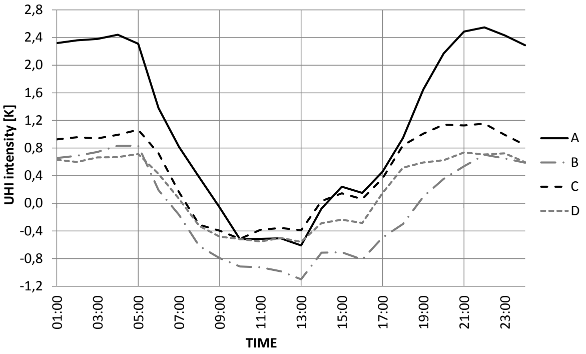

Figure 4 Mean hourly UHI-intensity for central (A) and peripheral urban locations (B, C, D) for summer period

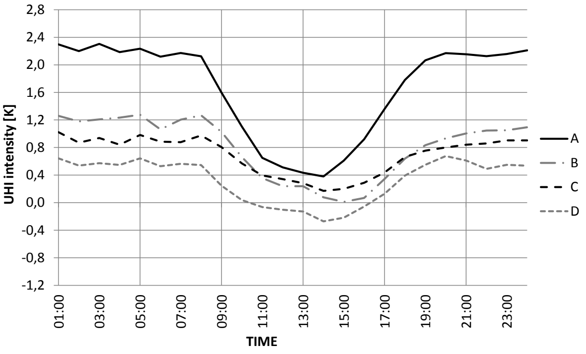

Figure 5 Mean hourly UHI-intensity for central (A) and peripheral urban locations (B, C, D) for winter period

The central urban location clearly displays the highest UHI level, particularly during the night hours. This may be explained via factors related to density, abundance of impervious surfaces, reduction of night-time back radiation, etc.

Temperature differences in urban environment

To further explore microclimatic variance on a small urban scale level, we deployed mobile weather stations to acquire weather information pertaining to air temperature, humidity, global solar radiation, and wind in a part of one of Vienna's central districts. Moreover, for each measurement location, sky images were generated using a fish-eye camera (Maleki et al. 2012).

Data sources and methodology

Data were collected at 13 morphologically differentiated locations (see Table 2). Specifically, collected data were compared with the simultaneously monitored weather conditions as monitored via a stationary weather station. Locations varied in terms of typological category (street, plaza, park, courtyards) as well as sky view factors, presence of vegetation, albedo and thermal properties of surrounding surfaces, and presence or absence of water bodies. Data was collected June to September in 2010 and 2011 on hot and sunny days.

Table 2
Selected measurement locations (SVF: Sky View Factor; H/W height to width ratio)

NO	TYPE	SVF [%]	STREET H/W	VEGETATION
S1	street	30	1.3	no
S2	street	29	1.3	no
S3	street	59	0.5	heavy
S4	street	16	0.5	heavy
S5	street	67	0.4	no
S6	street	47	0.8	no
P1	plaza	16	n/a	heavy
P2	plaza	88	n/a	no
P3	plaza	82	n/a	no
C1	courtyard	20	n/a	no
C2	courtyard	18	n/a	medium
G1	park	90	n/a	medium
G2	park	68	n/a	heavy

Figure 6 summarized the results of these measurements (for a representative summer day) in terms of the temperature difference between temperatures measured at various location and those measured simultaneously at the stationary weather station. The results illustrate the considerable variance in thermal conditions existing even within a relatively small area within the city. The variations appear to be related to certain characteristic features of the locations (e.g., sky view factor, vegetation, etc.). Highest temperatures were monitored at large open plazas with impervious surfaces and little shading. Shaded courtyards and streets displayed the lowest temperatures during the day. The results also point to a relationship (Maleki et al. 2012) between both solar irradiance and air temperature at the measurement locations and the respective sky view factors (SVF) of these locations (Figures 7 and 8).

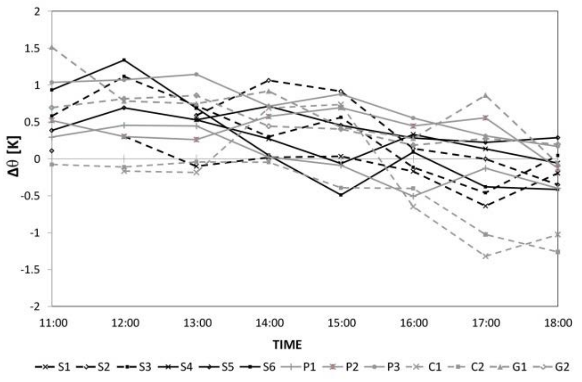

Figure 6 Deviation of measured air temperatures at 13 locations in a central district of Vienna over the course of a typical summer day from reference data of a nearby weather station

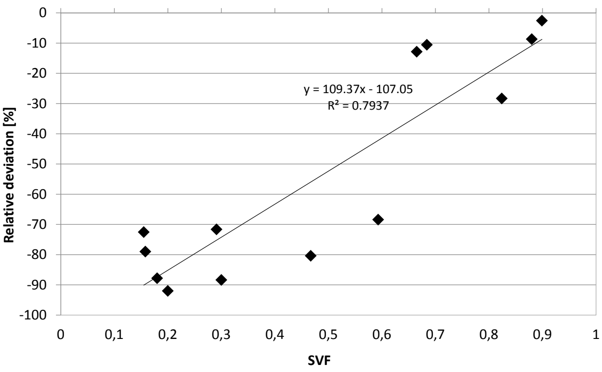

Figure 7 Relationship between SVF and the relative deviation (in percentage) of the location irradiance from the simultaneously measured irradiance at the reference weather station

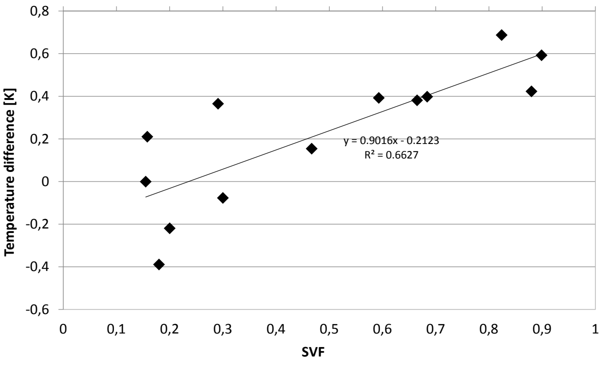

Figure 8 Relationship between SVF and temperature difference (location temperature and the simultaneously measured temperature at the reference weather station)

A FRAMEWORK FOR THE EVALUATION OF UHI

Within the aforementioned European project, further efforts are being made to formulate a systematic approach to the detection, description, and mitigation of UHI phenomena. These efforts are driven by the insight that the urban microclimate is influenced by factors such as different morphologies, building structures, and surface materials (Grimmond and Oke 1999, Stewart and Oke 2012) that can be influenced via proper design and retrofit strategies. In this context, we describe a systematic framework for the evaluation of UHI's far-reaching implications for microclimate, energy use, and human requirements pertaining to health and comfort (Mahdavi et al. 2013). The framework is intended to incorporate both detailed numeric simulation methods and empirically driven statistically-based calculation tools.

Framework introduction

The definition, description, and quantification of the urban heat island effect rely on a large body of both short-term and long-term measurement results. Within the proposed framework, the magnitude of UHI phenomenon is expressed for specific clearly bounded segments of the urban domain that could be defined in terms of an "Urban Unit of Observation" (U2O). A spatial dimension (diameter) of approximately 400 to 1000 m has been targeted. These well-defined segments may share characteristic features in view of geometry, massing, or other aspects of the physical structure.

In order to predict, estimate, and verify the effect of UHI on buildings energy requirements, we need to express this phenomenon in terms of changes it introduces in an U2O. We thus need a structured approach to systematically capture the essential geometric and physical features of an U2O. These variables, which constitute model input information both for simulation applications and simplified calculations, are presented in Tables 3 and 4.

The geometric properties are applied for identification of the urban morphology in an U2O. The Sky view factor (SVF) depicts the fraction of the sky hemisphere visible from ground level. The aspect ratio gives information on the height-to-width ratio of street canyons. Built area fraction, unbuilt area fraction, impervious surface fraction, and pervious surface fraction (green, earth, water) give information on the configutation of the ground area. The mean building compactness denotes the ratio of built volume above terrain to total building plan area. The built surface fraction denotes the ratio of total built surface area (above terrain) of buildings including wall area and the total roof area (impervious and pervious) to total built area.

The physical properties describe the thermal characteristics of urban surfaces. These include the albedo, emissivity, thermal conductivity, specific heat capacity, and density. Additionally the anthropogenic heat output is considered.

Table 3
Geometric properties of an U2O

PROPERTIES	**SYMBOL**	**RANGE**
Aspect ratio	H/W	0-3+
Built area fraction	A_b/A_{tot} A_b : building plan area A_{tot} : total ground area	0-1
Unbuilt area fraction	$1- A_b/A_{tot}$	0-1
Impervious surface fraction	A_i	0-1
Pervious surface fraction	$A_p = (A_e+ A_g+ A_{H2O})$ A_e : earth A_g : green A_{H2O} : water	0-1
Mean building compactness	$l_c = V_b/A_b$ V_b : built volume	-
Built surface fraction	A_s/A_b A_s : total built surface area	-
Walls	A_W/A_b A_W : total wall area	-
Roofs	A_R/A_b $A_R = (A_R,i + A_R,p)$ A_R : total roof area	-
Impervious roofs	$A_R,i /A_b$ A_R,i : total impervious roof area	-
Pervious roofs	$A_{R,p} /A_b$ $A_{R,p}$: total pervious roof area	-
Mean sea level	h_{sl}	-

Table 4
Surface/material properties of an U2O

PROPERTIES	**SYMBOL**	**RANGE**
Reflectance/albedo	ρ_{sw}	0-1
Emissivity	ε_{lw}	0-1
Thermal conductivity	$\lambda = (\lambda_i + \lambda_p)$ λ_i : impervious surface λ_p : pervious surface	-
Specific heat capacity	$c = (c_i + c_p)$ c_i : impervious surface c_p : pervious surface	-
Density	$\rho = (\rho_i + \rho_p)$ ρ_i : impervious surface ρ_p : pervious surface	-
Anthropogenic heat output	Q_F	-

Once U2Os and their respective variables are defined, potential mitigation measures may be expressed in terms of respective changes to the variable attributes. Once the specifics of envisioned mitigation measures are determined, their impact can be estimated: Toward this end, we have been considering two principal approaches. One approach relies on the statistical analyses of empirical data. Thereby, correlations between measured urban heat island intensity at different locations in a city and the physical features of these locations are exploited to derive empirically based formulas. The other approach explores the potential of numeric (typically CFD-based) computational models for performing predictions. A combination of both of the above-mentioned approaches will help us explain UHI variability over space and time. Thereby, the numeric simulation tools can be calibrated based on available empirical data. Additionally, the framework can facilitate the exploration of the UHI implications for the thermal performance of individual buildings.

CONCLUSION

The Urban heat island could be documented for multiple cities in central Europe. Furthermore a more detailed look at the city of Vienna revealed significant differences in the microclimate across multiple districts. This stresses the importance of studying microclimatic variance. The analysis of local microclimatic conditions shows that they can vary considerably depending on the site features such as urban geometry, surface properties, prevailing wind situation, extent of vegetation, and sources of anthropogenic heat emissions. Additionally a systematic framework for the evaluation of UHI mitigation measures was introduced. This framework facilitates the simulation based assessment of the impact of mitigation measures on local microclimatic conditions in cities.

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