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The extent and implications of the urban heat island phenomenon in Central European region

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ABSTRACT: Metropolitan areas worldwide display highly diverse microclimatic circumstances that are influenced by a variety of morphologies, structures, materials (particularly urban surface properties), and processes (mobility, industry, etc.). This diversity influences the intensity and extent of the urban heat island effect (UHI) in different cities. UHI may be understood in terms of emerging divergence between micro-climatic conditions in the city proper versus the rural environs. Significantly higher temperatures are observed in the urban area as compared to the surrounding suburban and rural neighborhoods. A further rise in the appearance and intensity of UHI phenomena is to be expected in the coming years due to the on-going population increase in urban areas. Furthermore, the UHI effect is believed to be related to (and worsened by) the climate change. Thereby, the rise of global temperatures is likely to affect not only the health of the urban population (urban heat distress, pedestrian discomfort) but also the energy performance of the built environment (higher outdoor air temperatures lead to a significant increase in buildings' energy use for cooling). In this context, this paper presents the results of an on-going EU-supported research project, which investigates the urban heat island phenomena in a number of urban regions in Central European countries (Stuttgart, Warsaw, Prague, Padua, Ljubljana, Modena, and Budapest). Toward this end, we pursue a two-fold approach. First detailed information regarding urban and rural climate in a 7-day period for each of the participating cities was collected and analysed. The results show a considerable variance, which, if ignored, would lead to major uncertainties in inferences made based on performance simulation. Secondly, long term data on rural and urban climate was obtained for all participating cities and included in the analyses.

1 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). It is usually quantified by the term Urban Heat Island Intensity ($\Delta\theta$), which is the difference between urban and background rural temperatures. Furthermore, the UHI effect is thought as being 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). Within the framework of the aforementioned UHI project, we collected a large set of data concerning the extent of the UHI effect in multiple cities in Central Europe. Analysis of the data reveals the extent of the UHI effect and a considerable variance in its manifestations.

Toward this end, we pursued a two-fold approach. First, detailed information regarding urban and rural climate in a 7-day period for each of the participating cities was collected and analysed. The results show a considerable variance, which, if ignored, would lead, amongst other things, to major uncertainties in inferences made based on thermal performance simulation. Secondly, long term data on rural and urban climate was obtained for all participating cities and included in the analyses.

2 URBAN HEAT ISLAND QUANTIFICATION

Numerous studies have been carried out discussing and quantifying the UHI phenomenon (see, for example, Arnfeld 2003, Blazejczyk 2006). Efforts have been made to describe the characteristics and patterns of UHI (Voogt 2002, Hart and Sailor 2007). Observations have shown that the UHI phenomenon shows different characteristics during different seasons (Gaffin et al. 2008) and that is pronounced differently during the night and the day (Oke 1981). Furthermore, the intensity of urban heat islands is believed to rise proportionally to the size and population of the urban area (Oke 1972). More recently, Gaffin et al. (2008) performed a detailed spatial study of New York city's current UHI and concluded that summer and fall periods were generally the strongest UHI seasons, consistent with seasonal wind speed changes in the area.

The UHI most often refers to the increase of urban air temperature when compared to rural. Generally, heat island intensities are quantified in the range of 1–3 K (Voogt 2002). Furthermore, Voogt also noted that under certain atmospheric and surface conditions, the maximum observed heat island magnitudes can be as high as 12 K.

The UHI phenomenon has also been extensively studied in terms of the effect on the urban microclimate and energy use for heating and cooling of buildings (Stewart and Oke 2012, Kolokotroni et al. 2007). Furthermore, material properties of urban surfaces can result in higher urban temperature compared to that of rural area (Grimmond et al. 1991, Akbari et al. 2001). Taha (1997) examined the impacts of surface albedo, evapotranspiration, and anthropogenic heat emission on the near-surface climate and found out that increases in urban albedo or increase in vegetation in urban areas can reduce air temperature up to 2 K.

3 METHODOLOGY

The definition, description, and quantification of the UHI effect rely on a large body of both short-term and long-term measurement results (Gaffin et al. 2008). In this context, we were particularly interested in quantifying the frequency, magnitude, and time-dependent (diurnal and nocturnal) UHI intensity distribution in a course of a reference week. Long-term development of urban and rural temperatures was another point of interest.

The magnitude of the UHI effect can be expressed, amongst others, in terms of Urban Heat Island intensity ($\Delta\theta$). This term denotes the temperature difference (in K) between simultaneously measured urban and rural temperatures. While there may be more detailed and informative means of expressing the urban heat island effect, for the purposes of presented analysis, we operate with $\Delta\theta$ as a generic indicator.

The specific aim of this paper is to identify and evaluate the extent of the UHI effect and its variance in the broader geographical context of the participating cities.

Table 1 includes some general information about our research project's participating cities in terms of area, population, latitude, longitude, and altitude. Additional information concerning cities' location and topology is provided in Table 2.

Table 1. Information about the participating cities.

City	Area [km^2]	Population [millions]	Latitude	Longitude	Altitude range[m]
Budapest	525	1.74	47° 30' N	19° 3' E	90-529
Ljubljana	275	0.28	46° 3' N	14° 30' E	261-794
Modena	183	0.18	44° 39' N	10° 55' E	34
Padua	93	0.21	45° 25' N	11° 52' E	8-21
Prague	496	1.26	50° 5' N	14° 25' E	177-399
Stuttgart	207	0.60	48° 46' N	9° 10' E	207-548
Vienna	415	1.73	48° 12' N	16° 22' E	151-543
Warsaw	517	1.70	52° 13' N	21° 00' E	76-122

Table 2. Information about the urban topology.

City	Topology
Vienna	Vienna is located in north-eastern Austria, at the eastern most extension of the Alps in the Vienna Basin.
Stuttgart	Stuttgart's center lies in a Keuper sink and is surrounded by hills. Stuttgart is spread across several hills, valleys and parks.
Padua	Padua is located at Bacchiglione River, 40 km west of Venice and 29 km southeast of Vicenza. The Brenta River, which once ran through the city, still touches the northern districts. To the city's south west lie the Euganaean Hills.
Budapest	The Danube River divides Budapest into two parts. On the left bank the Buda is located, with over 20 hills within the territory of the capital, and on the right bank the flat area of Pest is located with its massive housing, as well as commercial and industrial areas.
Prague	Prague is situated on the Vltava river in the center of the Bohemian Basin.
Modena	Modena is bounded by the two rivers Secchia and Panaro, both affluents of the Po River. The Apennines ranges begin some 10 km from the city, to the south.
Warsaw	Warsaw is located some 260 km from the Baltic Sea and 300 km from the Carpathian Mountains. Furthermore, Warsaw is located in the heartland of the Masovian Plain.
Ljubljana	Ljubljana is located in the Ljubljana Basin between the Alps and the Karst Plateau.

The assessment of current UHI intensity in observed urban areas has been derived from data sets in a course of a reference week. The reference week was chosen by each participating city independently, in order to provide the most reliable input information. Each participating city provided data (including air temperature, wind speed, and precipitation) from two representative weather stations (one urban and one rural). Data was recorded on hourly basis. These data sets needed to be suitable for the UHI analysis. This presumed that the air temperatures during the whole period should be considerably high, while the wind speed should preferably be below 5 m/s for most of the time.

From the hourly values of UHI intensity the cumulative frequency distribution for the reference week period was calculated. Moreover, the week-long data for each city was processed into mean hourly urban temperature and UHI values of a reference day.

To obtain a long-term impression of the urban and rural temperature development in the participating cities, mean annual (urban and rural) temperatures and UHI values were derived for a period of 30 years. With two exceptions (Modena, Warsaw), the record set was obtained from the same two representative weather stations (urban and rural) used for the short-term analysis.

Table 3 provided an overview of the time periods used for both the short-term and the long-term analyses.

Table 3. Overview for the data sets used for the analysis.

	Reference Week	Long-term Climate Data	
		URBAN STATION	RURAL STATION
Budapest	20-26.8.2011	2000-2011	2000-2011
Ljubljana	20-26.8.2011	1980-2011	1980-2011
Modena	20-26.8.2011	1980-2010	1980-2009
Padua	18-24.8.2011	1994-2011	1994-2011
Prague	8-14.7.2010	1980-2011	1980-2011
Stuttgart	20-26.8.2011	1981-2011	1980-2011
Vienna	20-26.7.2011	1994-2011	1994-2011
Warsaw	9-15.6.2008	1980-2011	1980-2011

4 RESULTS

4.1 *Short-term (reference week) analyses*

Figure 1 shows the cumulative frequency distribution of UHI values for the participating cities for the reference week. Figures 2 and 3 show, for a reference summer day (representing the reference week), the hourly values of urban temperature and the mean hourly UHI values respectively.

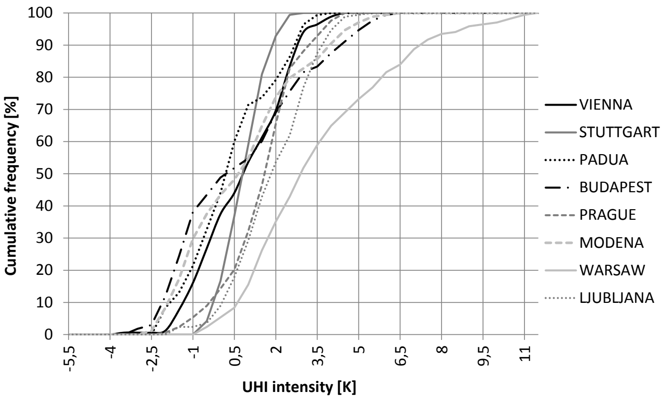

Figure 1. Cumulative frequency distribution of UHI intensity for a one week summer period.

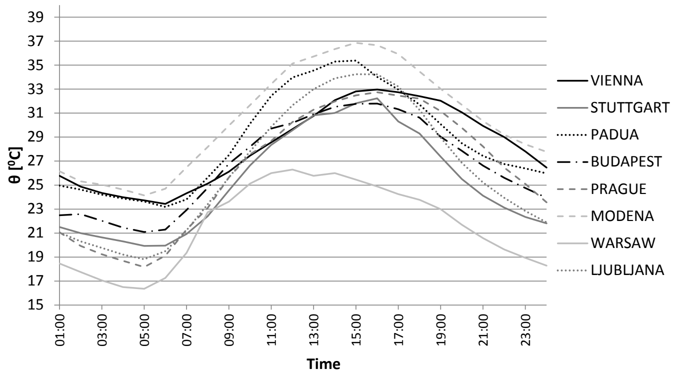

Figure 2. Mean hourly urban temperature for a reference summer day.

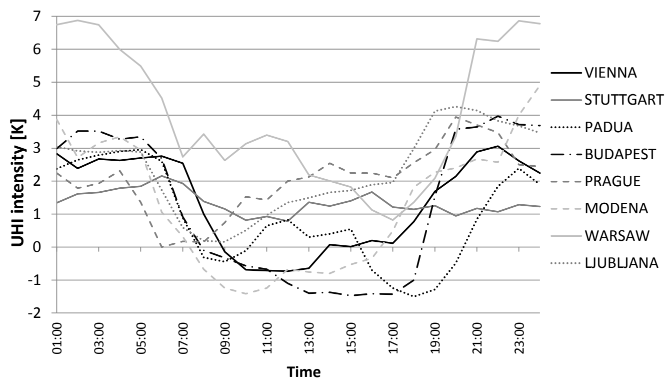

Figure 3. Mean hourly UHI intensity distribution for a reference summer day.

4.2 *Long-term analyses*

Figures 4 and 5 show for the participating cities the (mean annual) urban and rural temperatures respectively over a period of 30 years. Figure 6 shows the long-term UHI intensity trend over the same period.

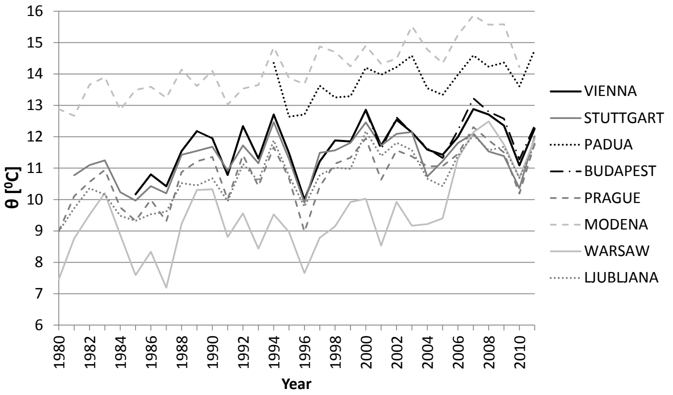

Figure 4. Development of (mean annual) urban temperatures over a period of 30 years.

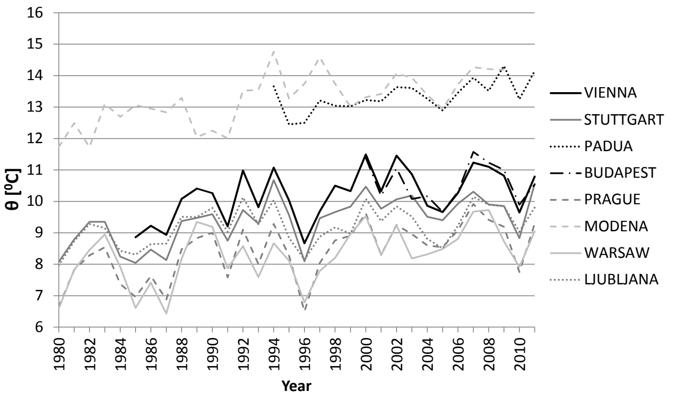

Figure 5. Development of (mean annual) rural temperatures over a period of 30 years.

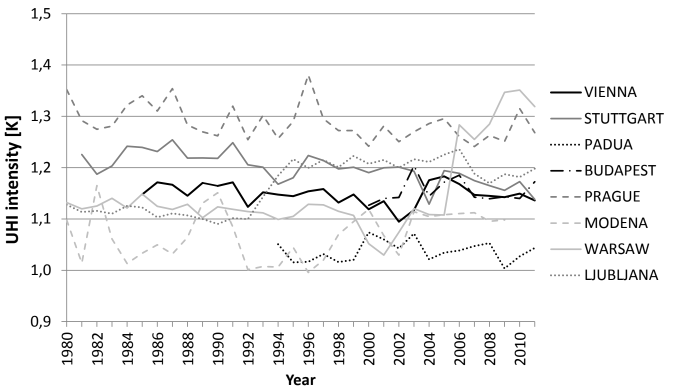

Figure 6. Long-term development of the UHI intensity over a period of 30 years.

5 DISCUSSION

The reference week data clearly demonstrate the existence and significant magnitude of the UHI effect in participating cities, especially during the night hours (Figures 1 and 3). However, the time-dependent UHI patterns vary considerably across the participating cities. In Warsaw, for example, UHI intensity level ranges from around 2 K during daytime to almost 7 K during the night, while in Stuttgart levels are rather steady, ranging from 1 K to 2 K. The UHI pattern differences are also visible in the cumulative frequency distribution curves of Figure 1. In this Figure, a shift to the right denotes a larger UHI magnitude.

The historical temperature records suggest an upward trend concerning both urban and rural temperatures (see Figures 4 and 5). Consistent with regional and global temperature trends, a steady increase in rural temperatures of up to about 2.5 K can be observed in all selected cities (with the exception of Budapest, for which data was available only for a rather short period).

In the same 30-years period, the mean annual urban temperature rose somewhere between 1 K (Stuttgart) and 3 K (Warsaw). A number of factors may have contributed to this trend, namely increase in population, energy use, anthropogenic heat production, and physical changes in the urban environment (e.g., more high-rise buildings, increase in impervious surfaces).

Note that, while both rural and urban temperatures have been increasing, the value of the UHI intensity has been rather steady. Our data suggest increasing UHI intensity trends in Warsaw and Ljubljana, whereas a slight decrease can be discerned from Stuttgart and Prague data (see Figure 7).

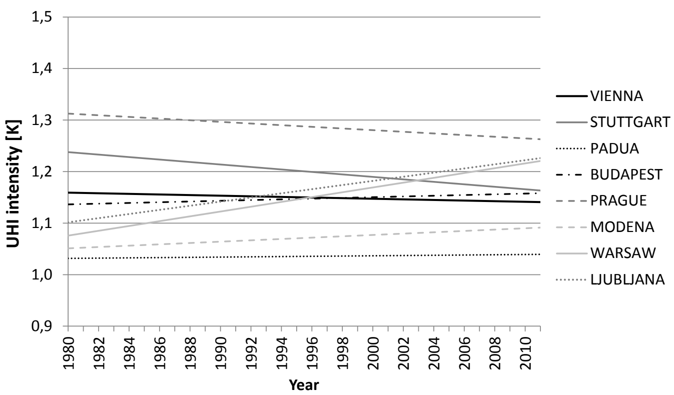

Figure 7. Long-term UHI intensity trend over a period of 30 years.

6 CONCLUSION

We presented the initial results of an EU-supported project concerned with the extent of the UHI phenomena in a number of Central European cities. The objectives of this project are to provide a common understanding of the UHI effects and to conceive and evaluate appropriate mitigation and adaptation measures.

We presented both short-term and long-term data with regard to urban and rural temperatures in the participating cities (Stuttgart, Warsaw, Prague, Padua, Ljubljana, Modena, Vienna, and Budapest). The analysis results demonstrate the existence and significant magnitude of the UHI effect in all participating cities. A time-dependent (diurnal and nocturnal) pattern could be observed implying larger UHI intensities during the night hours. However, the hourly based observations show a significant variation in UHI intensity in different cities, especially in terms of peak values. These results imply the need for further studies concerning UHI as a variable phenomenon over space and time and especially in a broader geographical context.

Finally, the findings stress the importance of assessment and modeling approaches that would establish a link between UHI intensity and salient urban variables such as urban density and morphology, block layout, canyon geometry, surface properties, vegetation, bodies of water industrial sites, transportation systems and infrastructures. The development of a systematic UHI assessment and modeling framework (Mahdavi et al. 2013) represents a critical component of our ongoing project.

7 ACKNOWLEDGEMENTS

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