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The Urban Climate

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ABSTRACT

Cities represent massive anthropogenic interventions in the planetary environment. They contribute to climate change and are affected by it. The world population increasingly lives in cities, implying the critical need for a better understanding of the complexity of the climatic context of urban agglomerations and their inner microclimatic characteristics. The urban microclimate is not only relevant to people's experience of outdoor thermal conditions in the cities: The temporal and spatial variance of urban microclimate is also causally related to the thermal performance of buildings. These considerations represent the main motivations behind a number of research questions addressed in this paper: To which extent do microclimatic conditions in cities differ from those in the surrounding rural environment? What physical features of the urban environment could explain the variance of urban microclimate? What measures could mitigate adverse developments in microclimatic conditions in the cities? Can computational tools and models contribute to prediction the effects of mitigation measures?

KEYWORDS: Urban climate, Urban Heat Island, Mitigation, Modeling

1 INTRODUCTION

Worldwide research activities concerning urban microclimate have recently gained momentum. There are a number of contributing factors to this development. The climate change discussion has generally raised public and professional awareness with regard to the related critical consequences for cities. Moreover, the world population increasingly lives in cities, implying the critical need for a better understanding of the complexity of the climatic context of urban agglomerations and their inner microclimatic characteristics (Alexandri 2007, Arnfeld 2003, Blazejczyk et al. 2006, Gaffin et al. 2008, Grimmond 2007, Kleerekoper et al. 2012, Oke 1981, Shishegar 2013, Unger 2004, Voogt 2002). The urban microclimate is not only relevant to people's health and their experience of outdoor thermal conditions in the cities (Harlan and Ruddell 2011): The temporal and spatial variance of urban microclimate is also causally related to the thermal performance of buildings (Akbari 2005). These considerations represent the main motivations behind a number of research questions addressed in this paper: To which extent do microclimatic conditions in cities differ from those in the surrounding rural environment? What is the extent of microclimatic variance within cities? What physical features of the urban environment could explain the variance of urban microclimate? What measures are likely to mitigate adverse developments in microclimatic conditions in the cities? What processes and tools can support systematic evaluation of the effectiveness of mitigation measures? Can computational tools and models contribute to predicting the effects of mitigation measures?

2 URBAN VERSUS RURAL CLIMATE: THE CASE OF URBAN HEAT ISLAND

The difference in urban and rural climates has been extensively studied. The concept of Urban Heat Island (UHI) was suggested to express the difference between urban and rural air temperature

(Oke 1972). UHI may be a problematic concept, but is quite pervasive in the literature. The magnitude of the UHI effect can be expressed in terms of Urban Heat Island intensity. This term denotes the temperature difference between simultaneously measured urban and rural temperatures. UHI intensities are generally observed to be in the range of 1 to 3 K, but can be as high as 12 K (Voogt 2002). Urban morphology, physical properties of urban surfaces, presence/absence of vegetated areas and water bodies, as well as anthropogenic heat emissions are believed to influence urban temperatures and spatial and temporal variance (Grimmond et al. 1991, Akbari et al. 2001, Taha 1997).

In a recent research effort supported by the European Union (UHI 2014, Mahdavi et al. 2013), we explored the frequency, magnitude, and time-dependency (diurnal and nocturnal) of UHI intensity as well as the long-term development of urban and rural temperatures in eight Central-European cities, namely Budapest, Ljubljana, Modena, Padua, Prague, Stuttgart, Vienna, and Warsaw. The collected information included hourly data on air temperature, wind speed, and precipitation from two weather stations (one urban and one rural). For these cities, UHI intensity was derived for a reference summer week (with high air temperature and relatively low wind velocity). Figure 1 shows the results in terms of cumulative distribution functions for UHI intensity. To visualize the diurnal pattern of the UHI intensity, Figures 2 includes the respective values for a reference summer day.

These results clearly document the difference in urban and rural temperatures of the Central European cities we studied, especially during the night hours (Figure 2). However, the time-dependent UHI patterns vary considerably across the cities.

We also looked at the long-term development of the urban and rural temperatures. Figures 3 and 4 show the mean annual urban and rural temperatures respectively over a period of 30 years. Figure 5 shows the long-term UHI intensity trend over the same period. The historical temperature records suggest an upward trend concerning both urban and rural temperatures. Consistent with regional and global temperature trends, a steady increase in rural temperatures of up to about 2.5 K can be observed in most cases. In the same 30-years period, the mean annual urban temperature rose somewhere between 1 and 3 K. Note that, while both rural and urban temperatures have been increasing, UHI intensity values have been rather steady (Figure 5).

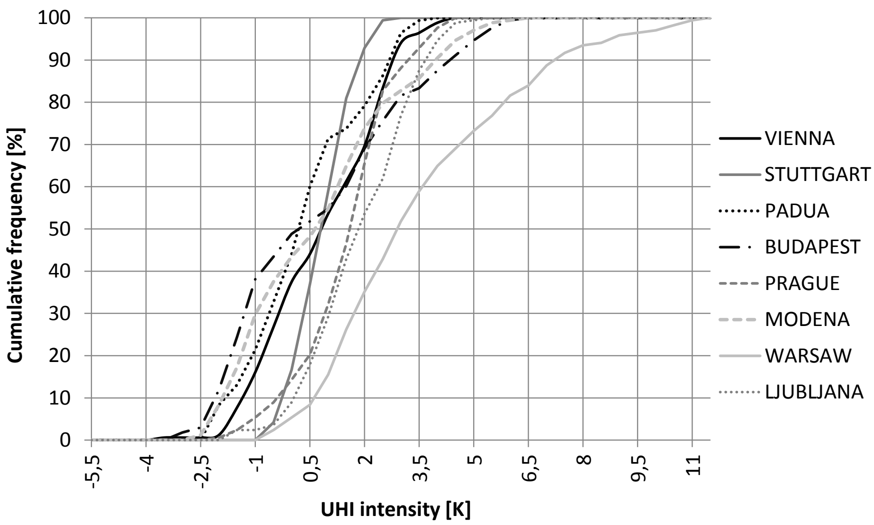

Figure 1: Cumulative distribution function for UHI intensity for a one week summer period in eight European cities

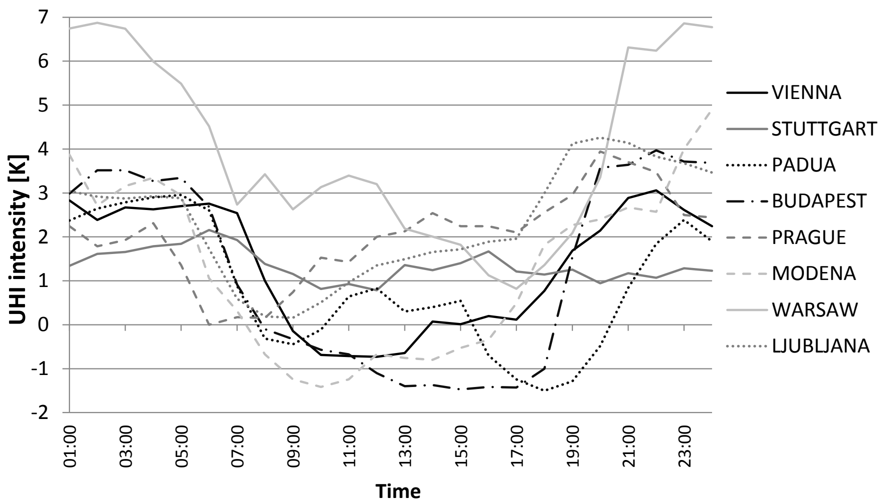

Figure 2: Hourly UHI intensity distribution for a reference summer day in eight European cities

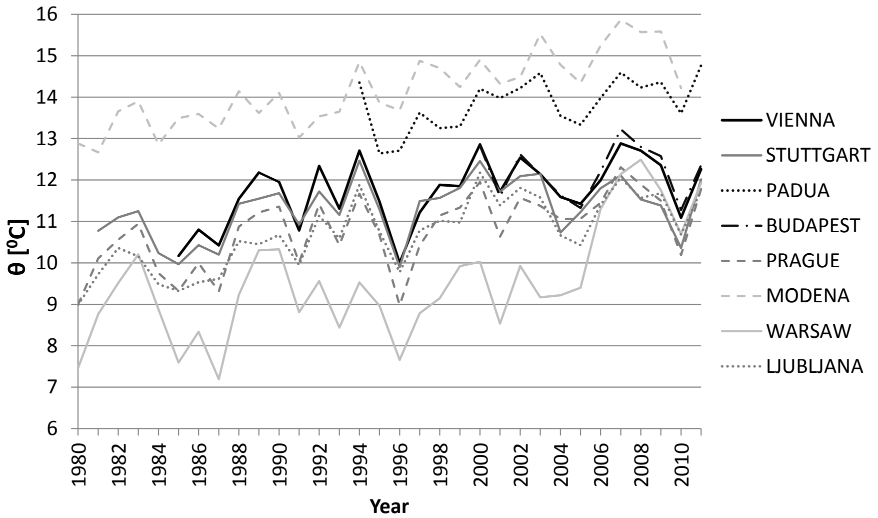

Figure 3: Development of mean annual urban temperatures over a period of 30 years

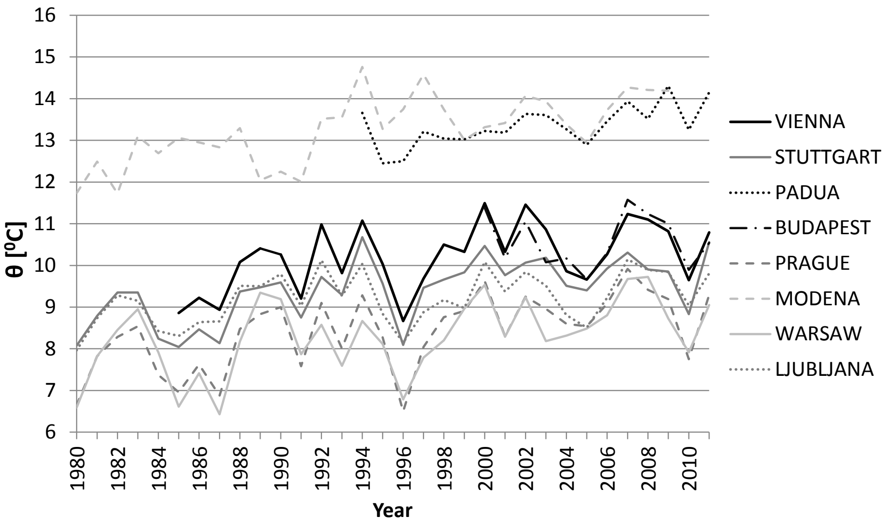

Figure 4: Development of mean annual rural temperatures in eight European cities

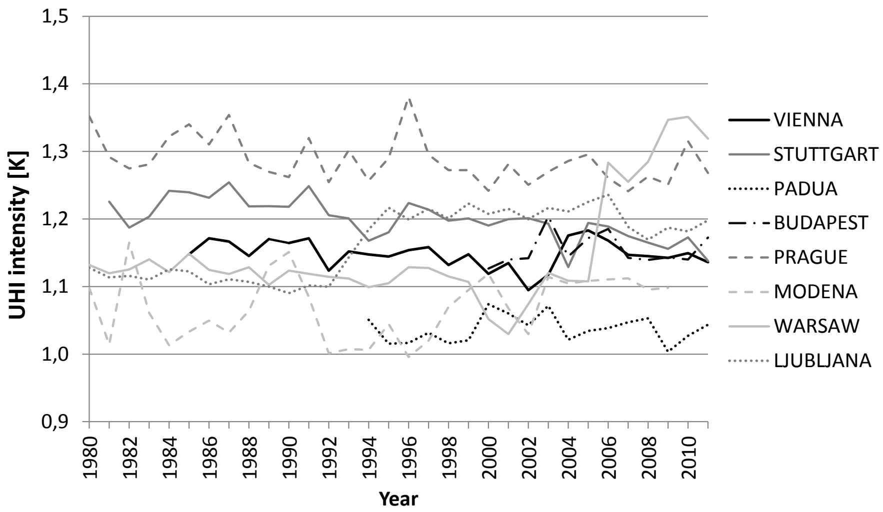

Figure 5: Long-term development of the mean annual UHI intensity in eight European cities

3 URBAN MICROCLIMATE VARIANCE

While it is common to talk about a city's climate, considerable microclimatic variance can exist across a city. An effective way to illustrate such variance is to compare – when possible – weather data reported simultaneously from multiple locations in the city. Such a comparison was performed for the city of Vienna (Kiesel et al. 2012). Thereby, weather data was collected at several weather stations positioned in different locations throughout Vienna. 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. Figures 6 and 7 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. These results suggest that the extent of the temperature differences across a city vary considerably in time (day, season) and space (location). 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 nighttime back radiation, etc.

To further exemplify microclimatic variance on a small urban scale level, consider a case study conducted in a part of one of Vienna's central districts (Kiesel et al. 2013). We deployed mobile weather stations to acquire weather information pertaining to air temperature, humidity, global solar radiation, and wind. Moreover, for each measurement location, sky images were generated using a fish-eye camera (Maleki et al. 2012). 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 1 Description of the weather stations

	WEATHER STATION	**LOCATION TYPE**	**ELEVATION** [meters above sea level]
A	Innere Stadt	Urban (central)	171
B	Hohe Warte	Urban (peripheral)	198
C	Donaufeld	Urban (peripheral)	161
D	Groß-Enzersdorf	Urban (peripheral)	157
R	Seibersdorf	Rural	73

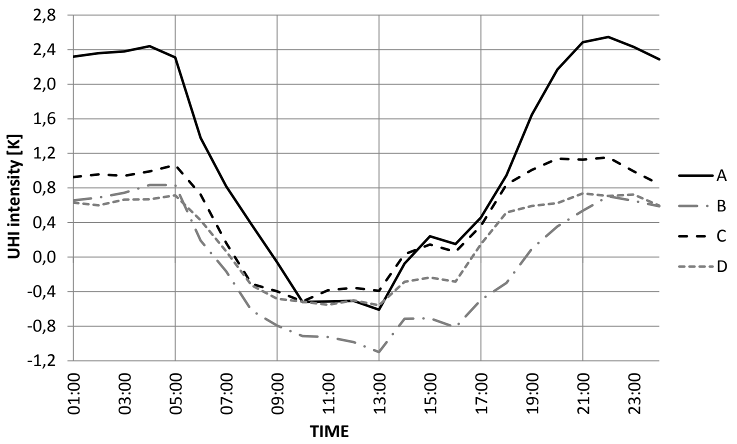

Figure 6: Mean hourly UHI intensity for central (A) and peripheral urban locations (B, C, D) in Vienna, Austria (summer period, 2011)

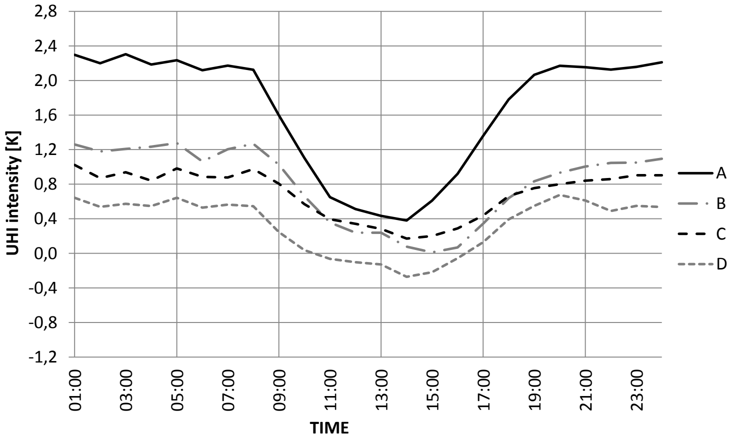

Figure 7: Mean hourly UHI intensity for central (A) and peripheral urban locations (B, C, D) in Vienna, Austria (winter period, 2011)

Figure 8 shows the results of these measurements (for a representative summer day) in terms of the difference between temperatures measured at various locations 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 of 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.

A further case study conducted in city of Vienna highlights significant microclimatic differences between weather data monitored via close-by weather stations (Lim et al. 2014). This study specifically pursued the following question: Is data obtained from standard (stationary) weather stations truly representative of close-by locations within the urban canyon (e.g., at the very location of planned interventions such as building construction)? To answer this question, we compared temperature data from mobile monitoring stations located in urban canyons with simultaneously monitored data from nearby standard (stationary) weather stations across Vienna. Differences, when existing, would suggest that stationary weather station data could not be used without the consideration of specific urban conditions at the selected site for intervention, such as a building construction project.

Table 2 Measurement locations

Location code	Location category	Sky View Factor SVF (%)	Street H/W (height to width ration)	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

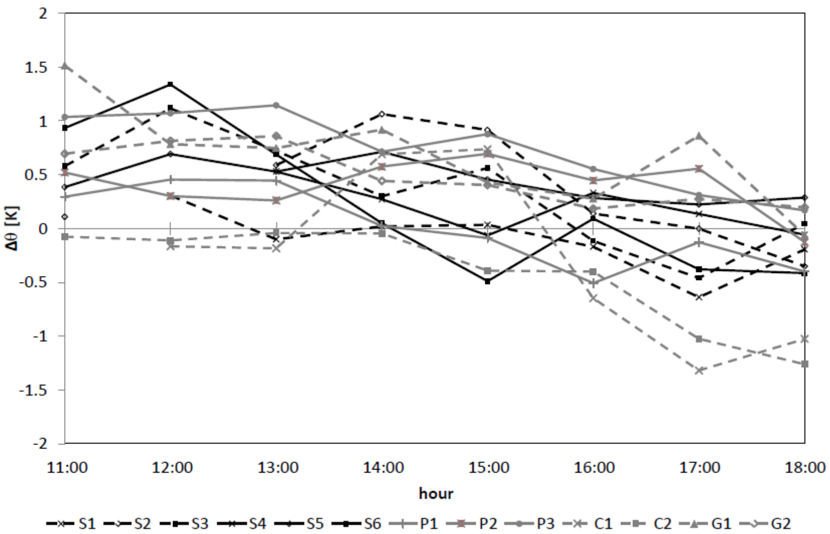

Figure 8: Deviation of measured air temperatures at 13 locations in a central district of Vienna over the course of a typical summer day from reference data of a nearby weather station

To provide an impression of the results of this study, Figure 9 compares the mobile weather station temperature data (θ_M) with the simultaneously monitored data from nearby stationary weather stations (θ_S) for two urban and two suburban locations in Vienna. The results suggest that temperature data from mobile monitoring stations located in the urban canyon were generally higher than the simultaneously measured weather station data. Specifically, the mean deviation of the mobile monitoring results from the stationary weather station data (Figure 9) was 5.9 ± 7.5%. This difference is arguably due to the specific urban conditions (morphology, property of the surfaces in the surroundings, fraction of visible sky, etc.). When microclimatic data from stationary weather stations are used for decision making processes (e.g., building design and retrofit applications), potential differences between such data and actual conditions within the urban fabric (e.g., at the specific location of planned interventions) must be taken into consideration.

As mentioned earlier, multiple morphological and physical properties may be responsible for the existence and magnitude of the observable microclimatic variance across an urban region. To illustrate this point, consider again the results shown in Figure 8, which display the 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. We explored these results in view of possible relationships between the observed temperature and solar irradiance differences between the locations and candidate morphological and physical location variables (Maleki et al. 2012). Thereby, the location variable “sky view factors” (SVF) displayed a noteworthy correlation with both temperature and irradiance differences (see Figures 10 and 11).

In certain cases, the microclimatic effects of the physical urban features can be directly observed. To illustrate this, consider the following case study regarding trees in the urban canyon (Blagovesta et al. 2014). Thereby, we explored the diversity of microclimatic conditions in two parallel streets (in Vienna, Austria), one with trees, and the other without. These streets are otherwise very similar in view of other parameters (e.g., orientation, width, and surrounding building properties). Simultaneously monitored data from two mobile weather stations was obtained for the selected study areas during hot and sunny days in August 2012. Using the collected data, the temporal cooling effects of vegetated areas was systematically studied. Figures 12 and 13 show the monitored difference between non-vegetated and vegetated canyons with regard to temperature, global solar radiation, absolute humidity, wind speed, and CO_2 concentration.

The results clearly demonstrate the significant difference between the vegetated and non-vegetated urban canyons. The measured temperature difference varies from 0.1 to 0.7 K, depending on the time of the day. In the afternoon, the air temperature was consistently higher in the non-vegetated canyon. The data further reveals that as the amount of incoming solar radiation increased substantially in the afternoon, the vegetated canyon stayed cooler. This further stresses the important role of tree shading and evapotranspiration, especially during summer months.

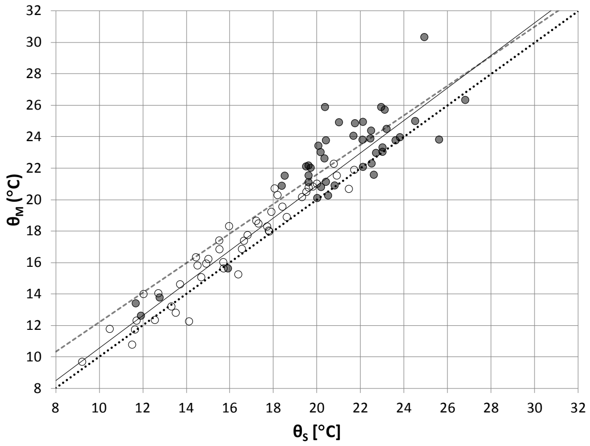

Figure 9: Mobile (θ_M) versus stationary (θ_S) temperature measurements in four distinct locations in Vienna, Austria (white dots + solid regression line: morning measurements, dark dots + dashed regression line: afternoon measurements)

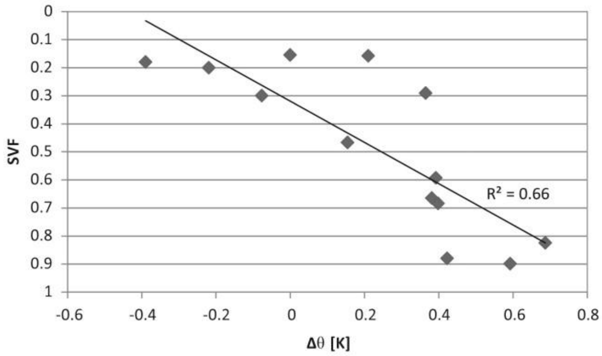

Figure 10: Relationship between SVF and temperature difference between temperatures measured at various locations (see Table 2) and those measured simultaneously at the stationary reference weather station

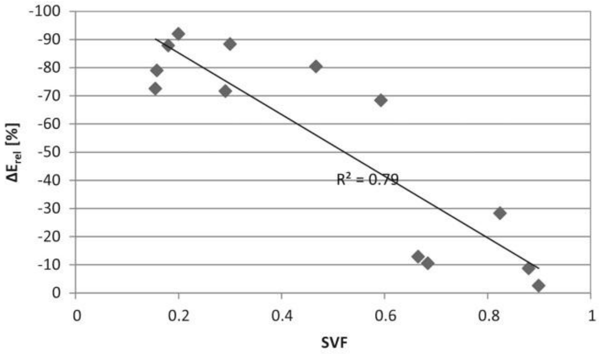

Figure 11: Relationship between SVF and the relative deviation (in percentage) of solar irradiance measured at various locations (see Table 2) and those measured simultaneously at the stationary reference weather station

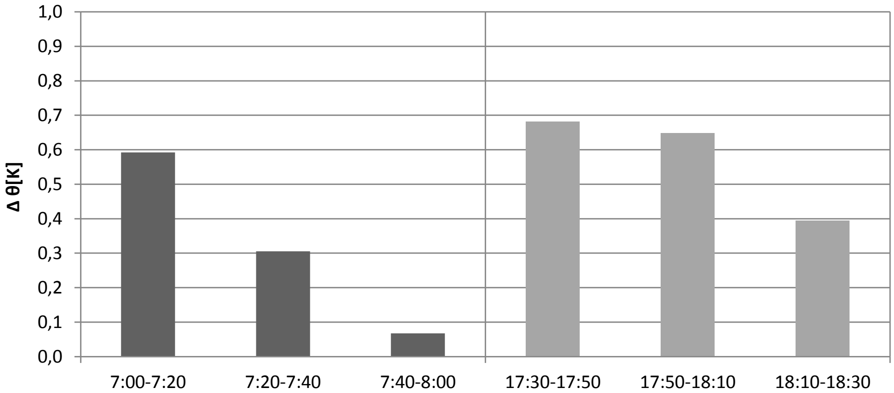

Figure 12: Mean air temperature differences between non-vegetated and vegetated canyon for 20 minute time intervals in the morning (left) and in the late afternoon (right)

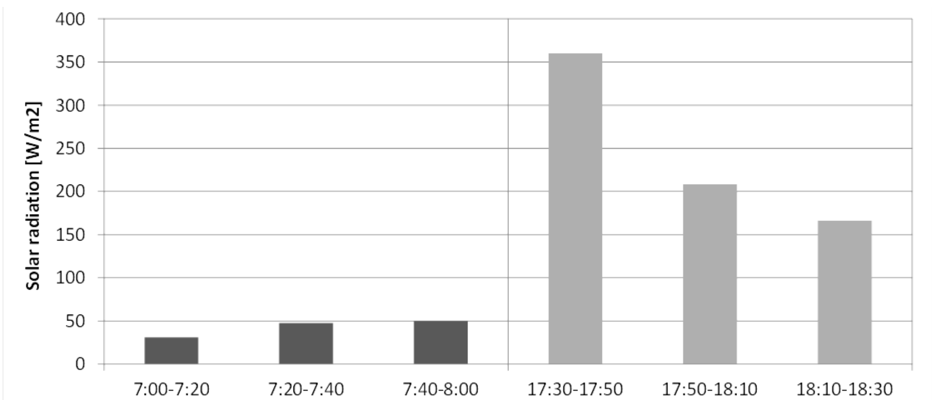

Figure 13: Mean global solar radiation differences between non-vegetated and vegetated canyon for 20 minute time intervals in the morning (left) and in the late afternoon (right)

4 A FRAMEWORK FOR DEFINITION AND EVALUATION OF URBAN CLIMATE MITIGATION MEASURES

A recurrent challenge with regard to the UHI phenomenon concerns the identification and evaluation of potential mitigation measures. As discussed before, certain interventions in the urban context (increase in vegetation, modification of urban surface properties, and reduction of emissions due to buildings, transportation, and industry) are believed to influence the urban microclimate and ameliorate the UHI ramifications. As these kinds of mitigation measures require substantial resources and cause major expenses, they must be carefully assessed and evaluated before they are implemented. Toward this end, effective procedures, methods, and tools are needed. In the course of the previously mentioned project (UHI 2014), we developed a systematic framework (Mahdavi et al. 2013) to assess – for a specific urban location – the urban heat island phenomenon, to specify potential mitigation and adaptation measures, and to evaluate such measures via adequate modeling approaches. The framework involves the following steps:

i) Definition of "Urban Units of Observation" (U2O): These are properly bounded areas within an urban setting selected as the target and beneficiary of candidate UHI mitigation measures.
ii) Description of the status quo of U2O in terms of a structured set of geometric and physical properties.
iii) Specification of the existing UHI intensity.
iv) Specification of the candidate mitigation measures in terms of projected changes to the geometric and/or physical properties defined in step ii above.
v) Prediction of the effect of mitigation measures using empirically based and/or numeric models.
vi) Expression of the mitigation measures' impact in term of predicted changes in UHI intensity.
vii) Overall evaluation of the mitigation measures' effectiveness based on modeling results together with their estimated financial and logistic ramifications.

In this framework, the notion of U2O is applied to systematically address the local variation of the urban climate throughout a city. A fixed spatial dimension for U2O cannot be set *a priori*, but a diameter of approximately half to one kilometer has been found to work well. As the urban microclimate is believed to be influenced by different urban morphologies, physical surface properties, vegetation, water, and emissions, we identified a set of related variables for the inclusion in the framework. The idea is to express potential UHI mitigation measures in terms of changes to the values of the U2O variables. Toward this end, we used both existing schemes and our own reasoning (Mahdavi et al. 2013, Kiesel et al. 2013) to define such a set of variables (see Tables 3 and 4).

Once U2Os and their respective variables are defined, potential mitigation measures may be expressed in terms of respective changes to the variable attributes. For example, introduction of green roofs or green facades in an U2O would modify the variables pertaining to surface albedo, emissivity, thermal conductivity, specific heat capacity, and density. Table 5 provides a concise summary of the most common mitigation measures. These measures can be divided into three main realms of interventions: buildings, pavements, and vegetation. Table 5 also includes a brief description of expected benefits of such measures.

Finally, the impact of those mitigation measures can be estimated based on appropriate calculation tools and modeling methods. For this purpose, we considered two principal approaches: statistical analysis of empirical data, and numeric (typically CFD-based) computational models. Correlations between measured urban heat island intensity in different locations within an urban environment and the physical features of these locations can be exploited to derive empirically based estimation methods. For numeric computation, different simulation tools can be applied, ranging from regional climate models to single-building models (Mirzaei and Haghighat 2010). To illustrate the application of the framework, consider a case study regarding a U2O in the center of Vienna, Austria. Figure 14 shows the existing attributes of the variables for this U2O together with the changes in these variables as a consequence of three envisioned mitigation measures: *i)* Planting trees within the urban canyon; *ii)* Green roofs; *iii)* A combination of measures 1 and 2. In this case, the estimation of the implications of the mitigation measures was conducted using a numeric simulation application (ENVI-met 2014). Figure 15 shows the modeling results in terms of predicted reduction of UHI index in the course of a reference summer day.

Table 3 Variables to capture the geometric properties of a U2O

GEOMETRIC PROPERTIES	DEFINITION
Sky View Factor	Fraction of sky hemisphere visible from ground level
Aspect ratio	Mean height-to-width ratio of street canyons
Built area fraction	The ratio of building plan area to total ground area
Unbuilt area fraction	The ratio of unbuilt plan area to total ground area
Impervious surface fraction	The ratio of unbuilt impervious surface area to total ground area
Pervious surface fraction	The ratio of unbuilt pervious surface area to total ground area
Mean building compactness	The ratio of built volume (above terrain) to total building plan area
Built surface fraction	The ratio of total built surface area to total built area
Wall surface fraction	The total area of vertical surfaces (walls)
Roof surface fraction	The total area of horizontal surfaces (roofs)
Mean sea level	Average height above sea level

Table 4 Variables to capture the surface and material properties of a U2O

PHYSICAL PROPERTIES	DEFINITION
Reflectance/albedo	Fraction of reflected shortwave radiation
Emissivity	Surface property regarding (long wave) radiation
Thermal conductivity	A material's heat conduction property
Specific heat capacity	A material’s capacity to store heat
Density	Material mass contained per unit volume
Anthropogenic heat output	Heat flux due to human activity (traffic, industry, buildings, etc.)

Table 5 A summary of principal mitigation measures

CATEGORY	MEASURE	EXPECTED BENEFIT
Buildings	Cool roofs	High solar reflectance and thermal emissivity
	Green roofs	Shading and evapotranspiration
	Green facades	Reducing ambient air temperature, shading properties, natural cooling, control airborne pollutants, energy efficiency
	Façade construction and retrofit	Reducing cooling/heating load, reducing ambient air temperature, improving building envelope quality
	Geometry of urban canyon (new projects)	Fresh air advection, cool air transport into the city
Pavements	Cool pavements	Decreasing ambient air temperature
	Pervious pavements	Storm water management
Green areas	Planting trees within the urban canyon	shading (in case of trees) and evapotranspiration, lower peak summer air temperatures, reducing air pollution
	Parks, green areas	

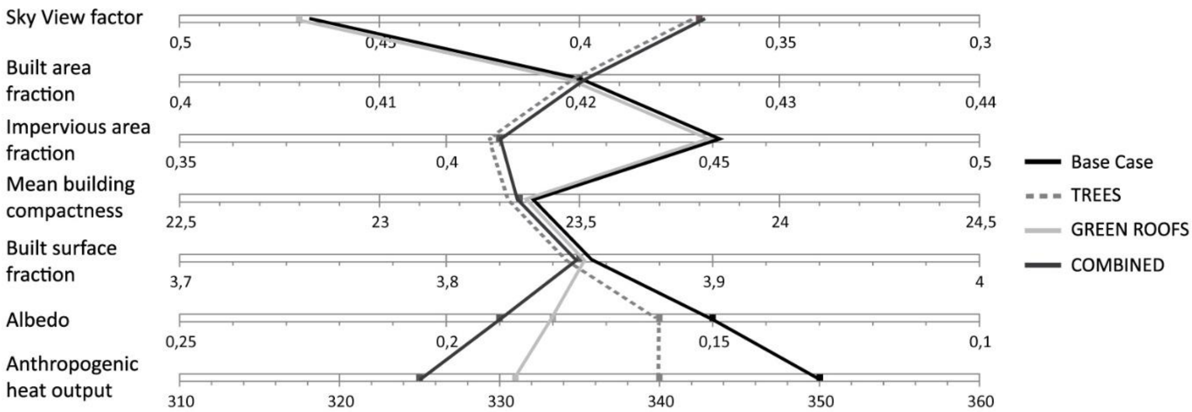

Figure 14 The existing values of the U2O variables for the Vienna case study together with modified values associated with proposed mitigation measures

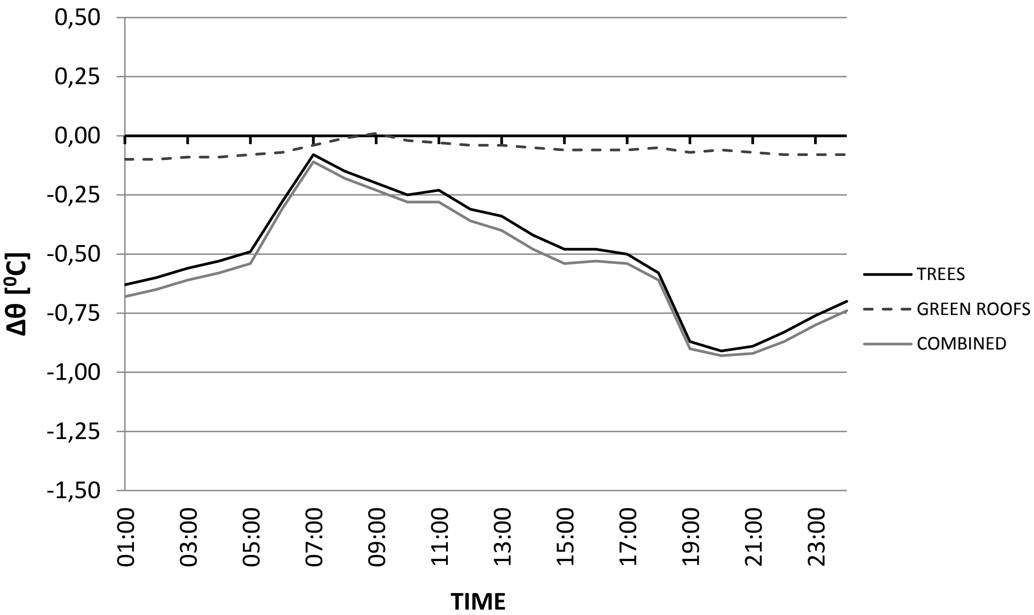

FIG 15: The modeled mean hourly temperature difference ("Innere Stadt", Vienna)

5 CONCLUSION

The climate change and the urban heat island discussions have drawn public attention to microclimatic conditions in the cities. As noted at the outset of the present contribution, the world population increasingly lives in cities, implying the critical need for the understanding of the complexity of the climatic context of urban agglomerations and their inner microclimatic characteristics. A recent study of Central European cities does indicate significant temperature differences between urban agglomerations and their rural surroundings. Moreover, convincing evidence suggests that cities cannot be viewed as climatically homogenous entities. Case studies pertaining to the city of Vienna as well other studies worldwide point to substantial microclimatic variance within cities. Observations to date point to possible influences of the morphological and physical features of specific urban areas on the respective microclimatic circumstances. The understanding of such influences is of utmost importance for the appropriate conception and efficient realization of urban intervention (design, mitigation) measures. Toward this end, both empirically based and computation methods and tools can be gainfully deployed. [It might be useful to refer here to the recent work of Stewart and Oke on defining Local Climate Zones within cities]

6 ACKNOWLEDGEMENTS

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