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Biometeorological Conditions During Hot Summer Days in Diverse Urban Environments of Banja Luka (Bosnia and Herzegovina)

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Abstract

Intensive urbanization and global warming are impacting the health and well-being of urban population. Nevertheless, urban environments with different designs will have different micro and local climate conditions. This study used data from micrometeorological measurements performed in different urban spaces (downtown, urban park, riverside) in Banja Luka, Bosnia and Herzegovina, on hot summer days in June 2021. Air temperature, relative humidity, wind speed, and globe temperature were measured and Mean Radiant Temperature (Tmrt), Psychologically Equivalent Temperature (PET), and modified Psychologically Equivalent Temperature (mPET) were calculated for each location. Results show that the downtown is the most uncomfortable area in terms of the highest Ta, Tg, Tmrt, PET, and mPET values registered at this location. The urban park is the most comfortable area with the lowest values of Tg, Tmrt, PET, and mPET. Relative humidity is the highest at the riverside and the lowest in downtown. Furthermore, riverside had lower average Ta during summer daytime compared to urban park and downtown likely due to the synergy between river cooling effect (evaporation and sensible heat transfer) and tree shade.

Keywords: Urban climate; outdoor thermal comfort; heat stress; urban park; riverside; downtown

Introduction

Urban population is under substantial thermal stress during the extreme temperature events such as heat wave (HW) (Milošević et al., 2016). Nevertheless, their outdoor thermal comfort varies depending on the urban location and its design. Measurement of meteorological parameters of humans provides necessary data to understand the interactions between atmospheric processes and human health (Anderson et al., 2020). In situ and mobile measurements of climate elements are popular approaches to assess the local and microclimate conditions in diverse urban or natural areas (Konstantinov et al., 2018; Dian et al., 2019; Paramita and Matzarakis, 2019; Milošević et al., 2020; Syafii, 2021; Žiberna et al., 2021; Lehnert et al., 2021a; Skarbit et al., 2017; Alonso and Renard, 2020a). In addition to short-term measurements, long-term climate data is

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a valuable resource for obtaining trends and changes in climate and bioclimate parameters (Trbić et al., 2017; Popov et al., 2019; Popov et al., 2018; Konstantinov et al., 2020; Varentsov et el., 2020; Konstantinov et al., 2021; Lukić et al., 2021; Nimac et al., 2021; Allen and Sheridan, 2018). Another approach is to apply urban climate modeling for assessing urban climate characteristics and providing input for the creation of sustainable and climate-sensitive cities under current and future climate change (Bokwa et al., 2019; Castillo et al., 2021; Liu et al., 2019; Cugnon et al., 2019; Wang et al., 2019; Ramadhan et al., 2021; Gál et al., 2021; Bajšanski et al., 2015).

With global changes in climate, making cities climate-proof is becoming increasingly critical (Jänicke et al., 2021). Urban form and design affect the outdoor thermal comfort (OTC), by influencing air temperature, humidity, solar radiation, and wind speed and direction (Webb, 2016). Factors as vegetation and water bodies (Lai et al., 2019; Milošević et al., 2017), urban morphology (Bajšanski et al., 2015; Jamie et al., 2019), ventilation (Tablada et al., 2009), and surface materials (Santamouris et al., 2011; Manavvi and Rajasekar, 2021), are important in determining OTC. Accordingly, the understanding of urban microclimate is imperative to facilitate climate-sensitive city planning and design (Jänicke et al., 2021). In pursuit of urban sustainability, livability and circularity, cities are increasingly using nature-based solutions (NBS), such as urban parks, due to their enormous potential in addressing climate adaptation and mitigation in cities (Langergraber et al., 2021; Pearlmutter et al., 2021; Atanasova et al., 2021; Castellar et al., 2021).

Urban areas are complex and the heat wave risk on the population is not uniform (Savić et al., 2018). For example, previous research has shown higher mortality during heat waves compared to other days (Arsenović et al., 2019a; Arsenović et al., 2019b). Projections have also shown that Earth's climate will warm together with increases in the percentage of the world's elderly population (Vecellio et al., 2021) which requires special attention in developing climate comfortable urban neighborhoods. In this perspective, among the most serious impacts of climate change in Central Europe are recognized more frequent and severe heat waves (Geletič et al., 2020). Climate projections are demonstrating that heat waves will occur more frequently and will become more severe in Europe (Fischer and Schär, 2010; Jacob et al., 2018) and are likely to increase during the twenty first century (Leconte et al., 2020). The increase in temperatures and intensity of heat waves has already been recognized in Bosnia and Herzegovina. For example, the highest annual temperature increase occurred in Banja Luka (0.5 °C per decade) probably due to influence of the urban heat island (Trbić et al., 2017). Nevertheless, there is a lack of local and microclimate measurements in the cities of Bosnia and Herzegovina, making them unprepared for the current and projected increases in air temperatures and heat stress.

The present study fills this research gap by providing micrometeorological measurements during hot summer days in diverse urban environments of the city of Banja Luka, Bosnia and Herzegovina. Obtained data on the micrometeorological conditions and OTC of urban dwellers in Banja Luka can be valuable for the urban design and planning. To the best of authors knowledge, this is the first micrometeorological measurement campaign and study performed in the cities of Bosnia and Herzegovina. The following tasks were performed:

- Measurement of micrometeorological conditions in diverse urban environments (downtown, urban park, riverside) in Banja Luka during hot summer days in 2021;
- Spatial and temporal analysis of micrometeorological and OTC data obtained during the field measurements in Banja Luka; and
- Discussion of obtained results and provision of urban climate information for the city of Banja Luka in order to track the heat and develop appropriate mitigation guidelines.

Study area, data and methods

Study area

City of Banja Luka is located in Southeast Europe, in the northern part of Bosnia and Herzegovina (B&H) (Figure 1). City coordinates are 44°46`N and 17°11`E with absolute elevation of 163 m. Banja Luka is the capital of Republic of Srpska (one of two entities in B&H) and the second largest city in the country with population of about 200,000 people (based on census from 2013) and built-up area of about 56 km². In the last 25 years, the city developed quickly, which means that some districts with low buildings have been transformed to multi-story buildings. With rapid urbanization more and more urban areas are being characterized as densely built-up zones with residential mid-rise (four-to-eight stories) buildings or administrative/commercial high-rise (more than eight stories) buildings. Based on this, a substantial modification of climatic characteristics in the city can be expected, due to a combination of intensive urbanization and current climate changes, and this is man-

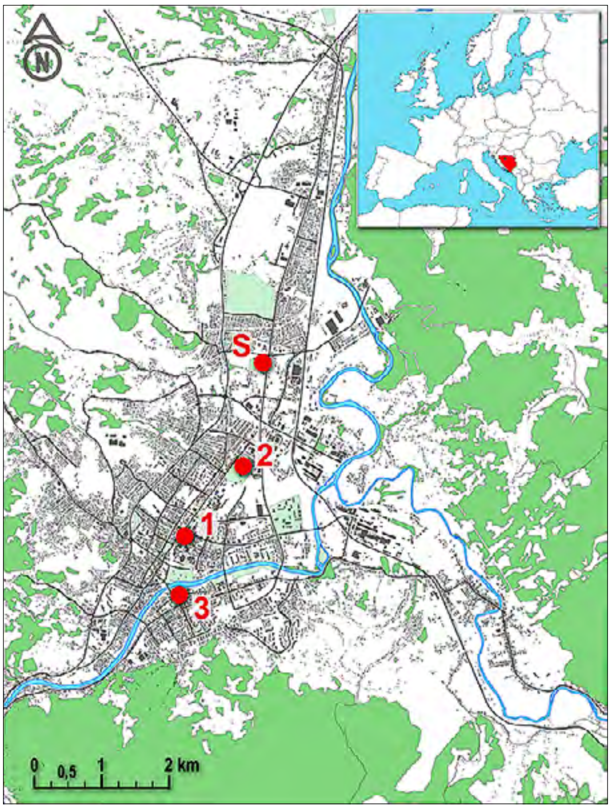

Figure 1. Location of Banja Luka in B&H (black dot) and measurement locations: 1) Downtown; 2) Urban park; 3) Riverside; and S) Official weather station

ifested through longer and more intense heat waves with extreme temperatures, more intense droughts, pluvial floods, more frequent thermal discomfort, etc.

Methods

Micrometeorological measurements

Micrometeorological measurements have been performed at three locations in Banja Luka on three hot summer days (from 22nd to 24th June 2021). Field work conditions were hot with maximum daily T_a of about 39 °C, no precipitation, low cloud cover, low wind speed, and intense solar radiation (Republic Hydrometeorological Service of Republic of Srpska, Bosnia and Herzegovina, 2021). Measurements were conducted at three urban sites with different design: a) downtown (densely urbanized “grey” area), b) urban park (natural “green” area), and c) riverside (natural “blue-green” area near the Vrbas River) (Figures 1 and 2). The three locations are popular pedestrian and/or relaxation areas in the city.

Three Kestrel 5400 Heat Stress trackers (Figure 2, right) were used to obtain one-minute measurements of air temperature (T_a, in °C), relative humidity (*RH*, in %), wind speed (v, in m s^{-1}), and globe temperature (T_g, in °C) during each day in the period 9-18 h (Central European Summer Time - CEST). Measured values were averaged into 10-minute means for the statistical analysis. The Kestrel Heat Stress Trackers were deployed at least 15 minutes before the start of the measurement in order to allow the sensors to equilibrate to the atmospheric conditions. The equipment is calibrated in accordance with the manufacturer’s specifications. Sensors’ accuracy and range are given in Table 1.

Table 1. Accuracy, resolution and range of Kestrel 5400 Heat Stress Tracker sensors used for human-biometeorological measurements in Banja Luka (Bosnia and Herzegovina)

Sensor	Accuracy (+/-)	Resolution	Range
Air temperature	0.5 °C	0.1 °C	-29.0 to 70.0 °C
Relative humidity	±2%RH	0.1 %RH	10 to 90% 25°C non-condensing
Wind speed	Larger of 3% of reading, least significant digit or 20 ft/min	0.1 m/s	0.6 to 40.0 m/s
Globe temperature	1.4 °C	0.1 °C	-29.0 to 60.0 °C

Banja Luka has a *Cfb* climate (temperate climate, fully humid, warm summers, with at least four months of average air temperature above 10 °C) based on the Köppen-Geiger climate classification system (Kottek et al., 2006; Trbić 2011). The mean annual air temperature is 11.3 °C and the mean annual precipitation is 1.036 mm (1961-2020 period). Since 2003, heat waves have occurred more frequently in B&H, mostly during the summer. Multiple intensive heat waves have occurred in Banja Luka in 2007, 2012, 2015, 2017, 2019, and 2021.

Calculation of biometeorological indices

For the estimation of OTC, Mean Radiant Temperature (T_{mrt}), Physiologically Equivalent Temperature (PET) and modified Physiologically Equivalent Temperature (mPET) were selected. T_{mrt} can be calculated from the measured values of T_g, T_a and v as follows (Thorsson et al., 2007):

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1 \cdot 10^8 \cdot v^{0.6}}{\varepsilon \cdot D^{0.4}} \cdot \left(T_g - T_a\right) \right]^{1/4} - 273.15$$

(1)

Figure 2. Locations of micrometeorological measurements in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021: 1) Downtown; 2) Urban park; and 3) Riverside

where, *D* is globe diameter (mm) and *ε* is globe emissivity.

Based on the calculated values of T_{mrt}, measured T_a, *RH, v*, and default values for personal characteristics, we calculated 10-minute average PET and mPET values for all sites. A new thermal index, named modified Physiologically Equivalent Temperature (mPET) has been developed by Chen and Matzarakis (2018) for the application in different climates. The mPET enhanced the evaluation of humidity and clothing variability and has been improved against the weaknesses of the original PET. The calculations were performed using the RayMan microclimate model (Matzarakis et al. 2007; Matzarakis et al. 2010). PET and mPET estimates were used to assess OTC in Banja Luka based on the physiological stress classes for humans specifically developed for Europe (Matzarakis and Mayer, 1996) (Table 2).

Table 2. PET index threshold values for thermal sensation and the physiological stress level of humans (after Matzarakis and Mayer, 1996).

PET (°C)	Thermal sensation	Physiological stress level
<4.1	Very cold	Extreme cold stress
4.1 – 8.0	Cold	Strong cold stress
8.1 – 13.0	Cool	Moderate cold stress
13.1 – 18.0	Slightly cool	Slight cold stress
18.1 – 23.0	Comfortable	No thermal stress
23.1 – 29.0	Slightly warm	Slight heat stress
29.1 – 35.0	Warm	Moderate heat stress
35.1 – 41.0	Hot	Strong heat stress
>41.0	Very hot	Extreme heat stress

Results and Discussion

Background weather

The background weather conditions during the micrometeorological measurements were acquired from the official weather station in Banja Luka. It can be noticed (Figure 3, Table 3) that the weather was hot with maximum T_a of about 39 °C and minimum of about 18 °C. Relative humidity was low during daytime (30-40%), while it increased substantially during nighttime. The weather was calm with low wind speeds (0.9 m s^{-1} on average) and low cloud cover (1.4 on average). This weather was ideal for the development of micrometeorological differences inside the city.

Table 3. Statistics on the weather conditions in Banja Luka (Bosnia and Herzegovina) during the measurement period (22-24 June 2021)

Statistics	Ta	RH	v	N
average	28.5	62.8	0.9	1.4
max	38.7	97.5	2.6	8
min	17.7	34.4	0	0
range	21.0	63.1	2.6	8

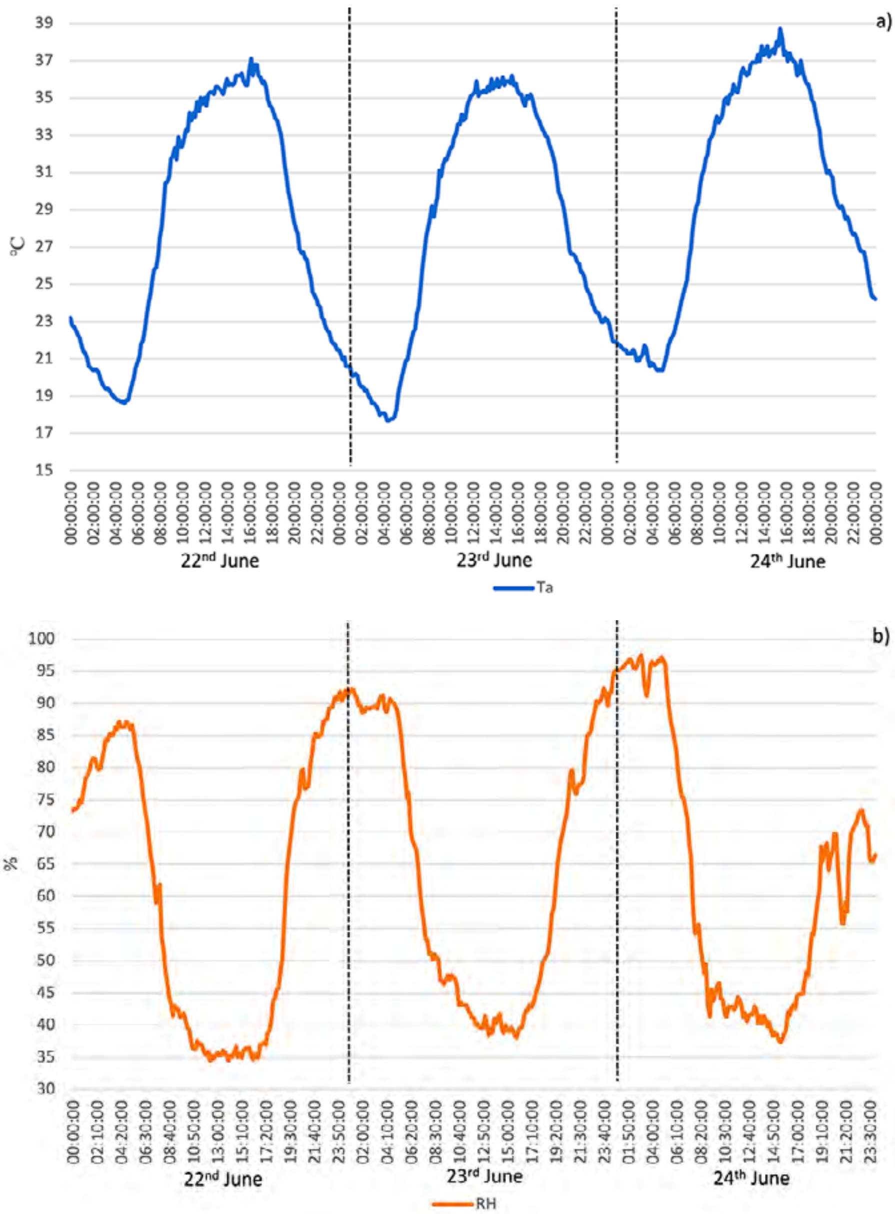

Figure 3. Weather conditions in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021: a) T_a and b) *RH*

Micrometeorological measurements

Air temperature

The highest average T_a (35.5 °C) was recorded in downtown, while similar values of about 33-34 °C were recorded in urban park and at the riverside (Table 4). Extreme temperatures (T_{max} and T_{min}) were also highest in the most urbanized location (downtown), while urban park had lower T_{max} and higher T_{min} values compared to the riverside. The river location had the largest temperature range (12.9 °C) and highest standard deviation (3.2 °C) compared to other locations (Table 4).

10-minute T_a differences between locations provide detailed insights into the temporal variability of air temperature in Banja Luka (Figure 4). The most intensive intra-urban T_a differences of about 5-6 °C occur between hot downtown and cooler urban park and riverside in the morning hours, especially between 9 AM and noon. In the afternoon, T_a differences between downtown and other locations swiftly decrease to about 1-2 °C and sometimes can go to below 0 °C (around 5-6 PM), indicating the occurrence of a slight urban cool island in the downtown. This could be the consequence of the shadowing effect from buildings surrounding the measurement location in the downtown (see Figure 2). Urban park had about 1 °C higher T_a compared to the riverside throughout the day, except for a few hours in the afternoon (Figure 4). The measurement locations at the riverside and in the urban park were under a tree; however, the proximity of the river could additionally lower T_a at the riverside compared to the urban park location. In general, differences in air temperature decreased in the afternoon between the locations and this could be due to the shading effect and less intensive heating in the afternoon hours (Milošević et al., 2021).

Similar to this study, previous studies have shown that the highest temperatures are usually found in more urbanized areas of the city. For example, Oliveira et al. (2021a) showed that more compact areas of Lisboa, Portugal, had the highest temperatures and these temperatures were proportional to the background air temperature change. The heat wave periods with hot weather are especially characterized with strong nocturnal urban heat island (UHI) as shown in Szeged, Hungary (Unger et al., 2020). During daytime, temperature differences in urban areas are mainly linked to shading. For example, Top et al. (2020) showed that urban park in Ghent (Belgium) is overall characterized by lower temperatures with up to 1.0 °C lower mean T_a during summer daytime when compared to the downtown located 2 km away. Gál et al. (2021) pointed out that urban green spaces generally cool the environment, although their cooling potential differs depend-

Table 4. Main statistical characteristics of air temperature (T_a), globe temperature (T_g), relative humidity (*RH*), wind speed (*v*), Mean Radiant Temperature (T_{mrt}), Physiologically Equivalent Temperature (PET) and modified Physiologically Equivalent Temperature (mPET) in diverse urban environments of Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST).

Element	T_a			T_g			*RH*			*v*			T_{mrt}			PET			mPET		
Location	D	P	R	D	P	R	D	P	R	D	P	R	D	P	R	D	P	R	D	P	R
Average	35.5	33.9	33.6	43.9	36.2	39.9	35.7	39.0	41.4	0.7	0.6	0.7	55.6	39.7	50.2	45.6	36.7	41.5	41.4	34.7	38.4
Max	39.0	37.7	38.9	49.9	44.0	49.7	50.5	52.4	58.0	1.6	1.4	1.6	75.4	47.4	74.8	53.2	42.4	54.4	47.2	39.3	48.9
Min	28.8	26.8	26.0	31.0	28.7	26.2	29.8	29.5	33.0	0.0	0.0	0.0	31.0	29.9	26.2	30.9	27.8	26.5	29.8	27.4	26.5
Range	10.2	10.9	12.9	18.9	15.3	23.5	20.7	22.9	25.0	1.6	1.4	1.6	44.4	17.5	48.5	22.3	14.6	27.9	17.4	11.9	22.4
St Dev	1.8	2.6	3.2	4.4	3.1	6.7	3.4	4.3	4.8	0.4	0.3	0.4	11.3	4.2	13.3	5.5	3.5	7.9	4.2	2.9	6.2

NOTE: Abbreviations of measurement locations are as follows: D - Downtown, P - Park, R - Riverside.

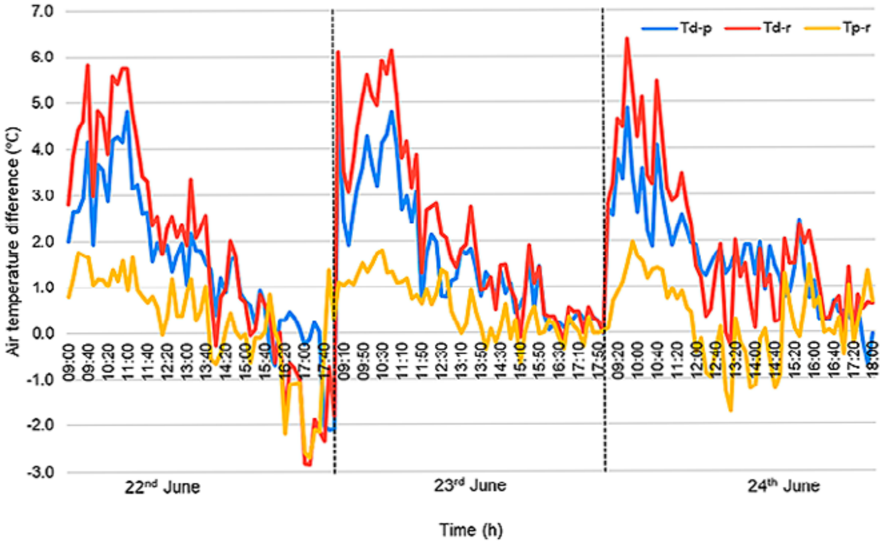

Figure 4. Temporal variation of T_a in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: $T_{d\text{-}p}$ represents air temperature difference between downtown and urban park; $T_{d\text{-}r}$ represents air temperature difference between downtown and riverside; and $T_{p\text{-}r}$ represents air temperature difference between urban park and riverside

ing on the characteristics of green areas, such as size of the urban park. Heat reduction potential of trees also depends on the location of trees and is species specific (Morakinyo et al., 2020). Tan et al. (2016; 2017) also indicated that the cooling effect of urban trees is highly associated with Sky View Factor of the location. Urban cool islands can also occur in densely built urban areas during the daytime in summer due to shadowing and it was typically around –1 °C in Szeged and –2 °C in Novi Sad (Lelovics et al., 2016). The river cooling effect also has an important role in reducing urban heat through evaporation and transfer of sensible heat, as shown by Park et al. (2019). The study of Jacobs et al. (2020) showed that afternoon air temperatures was reduced by a maximum of 0.6 °C in the surrounding spaces of urban water bodies in the Netherlands. Our study showed that the riverside location was most of the time cooler compared to other locations (downtown and urban park) during the summer daytime (Figure 4).

Relative Humidity

The highest average *RH* values are observed near the river (41.4%), followed by urban park (39.0%). In contrast, the lowest average *RH* was noticed in city center (35.7%). The highest maximum and minimum *RH* values are also registered near the river, thus leading

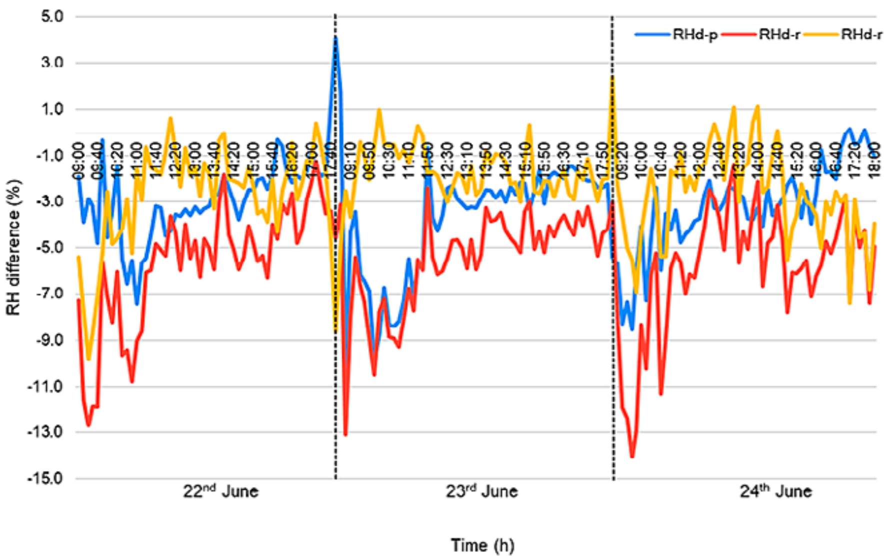

Figure 5. Temporal variation of *RH* in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: $RH_{d\text{-}p}$ represents relative humidity difference between downtown and urban park; $RH_{d\text{-}r}$ represents relative humidity difference between downtown and riverside; and $RH_{p\text{-}r}$ represents relative humidity difference between urban park and riverside

to larger range and standard deviation of *RH* at this location (Table 4).

Temporal variation of RH shows prominent differences between the locations during the morning hours (Figure 5). For example, city center in the morning had up to 14% lower RH compared to the riverside and up to 10% lower *RH* compared to the urban park. As the day progresses, *RH* differences are less prominent between the locations. The least prominent differences in *RH* occur between riverside and urban park, although the river location had higher *RH* values during most of the day (Figure 5).

Results from previous studies showed that lower humidity and urban dry island (UDI) often occurs in densely urbanized areas in summer daytime and during heat wave in Novi Sad, Serbia (Dunjić et al., 2021). Similar results were obtained in Ghent, Belgium, where the lowest *RH* was noticed at the urban location during heat wave, while the highest *RH* was reached at the rural location (Top et al., 2020). Yang et al. (2017) also pointed that *RH* decreases with the increase in urbanization.

Wind speed

During the measurement period, v were low at all locations (0.6-0.7 m s^{-1}) (Table 4). There were no significant v differences between the locations as the measurement period was characterized with sunny and calm weather. Urban park had only a slightly lower *v*. As the differences in v were not significant between the locations, we did not provide a detailed analysis of wind speed in Banja Luka.

In general, air movement in the built-up environment is reduced in comparison to rural areas (Arnfield, 2003) or it can be locally increased by urban canyon effect. More open urban sites in Ghent, Belgium, had highest v, especially during daytime compared to less open locations, such as urban parks (Top et al., 2020). Nevertheless, local climate change adaptation in cities must account for the synergies between regional air temperature and wind (Oliveira et al., 2021b).

Globe temperature

The highest values of T_g are measured at downtown which, on average, has 4 °C higher T_g values compared to riverside and 7.7 °C compared to urban park (Table 4). Also, in the downtown are registered highest maximum and minimum T_g values. The urban park is the most comfortable urban area during the measurement period with lower average T_g compared to the riverside.

Temporal variations of T_g show that substantial intra-urban differences occur in the period from 10 AM to 2 PM when downtown is substantially hotter with up to 14-15 °C higher T_g compared to urban park and riverside (Figure 6). In the morning hours, urban park is slightly warmer compared to riverside. On the contrary, as the day progresses towards the afternoon, riverside becomes warmer compared to urban park and downtown. This suggests that riverside location was in the shade before noon, however, was sunlit and directly irradiated during the late afternoon. These results highlight the key role of radiation in the spatial and temporal variability of thermal exposure in moderate-climate urban areas during summer days (Geletič et al., 2021). Nevertheless, it must be noted that smaller black globes commonly used in Kestrel

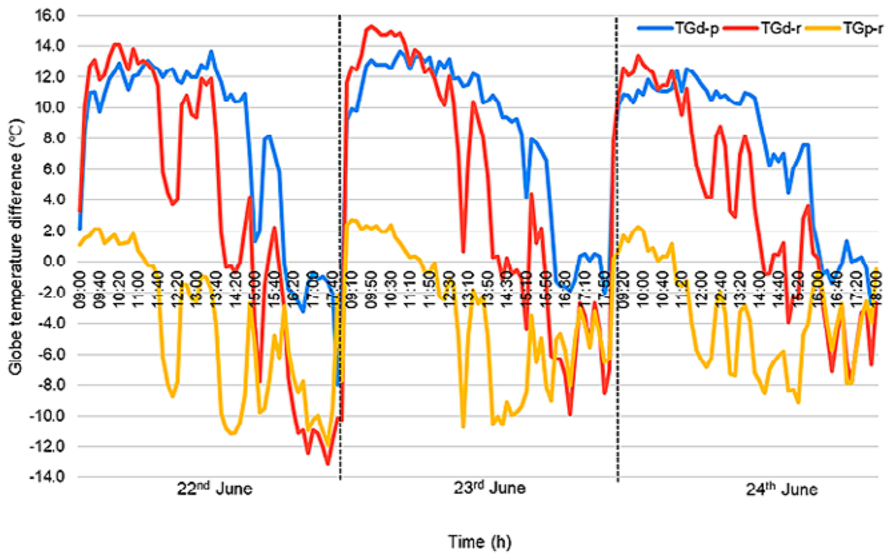

Figure 6. Temporal variation of T_g in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: TG_{d-p} represents globe temperature difference between downtown and urban park; TG_{d-r} represents globe temperature difference between downtown and riverside; and TG_{p-r} represents globe temperature difference between urban park and riverside

Heat Stress Trackers tend to overestimate T_g in the sun due to the globe overheating (Kántor & Unger 2011; Middel et al. 2016).

Calculated outdoor thermal comfort conditions

Mean Radiant Temperature

The most intensive intra-urban differences were registered for T_{mrt} values. On average, downtown had T_{mrt} of 55.6 °C, followed by riverside with T_{mrt} of 50.2 °C. On the contrary, urban park had substantially lower average T_{mrt} of 39.7 °C. Thus, urban park was able to mitigate average T_{mrt} by about 16 °C and 10 °C compared to downtown and riverside, respectively. The maximum T_{mrt} peaked over 70 °C in downtown and at the riverside, while it remained below 50 °C in urban park (Table 4).

Temporal variation of 10-minute T_{mrt} values indicate that downtown has substantially higher T_{mrt} values compared to riverside and urban park throughout the day. Around noon, city center has about 35 °C higher T_{mrt} compared to urban park and riverside (Figure 7). Nevertheless, in the period 4-6 PM, riverside becomes the warmest part of the city with substantially higher T_{mrt} compared to downtown and urban park. It can be also noticed that in the morning hours until about 11 AM, urban park has higher T_{mrt} compared to riverside. These changes in T_{mrt} values between the locations indicate the influence of the shading effect that varies over time depending on the urban design at each location.

The parameter governing OTC on warm, clear-sky days is radiation and its effect on OTC is accounted for by T_{mrt} (Gál and Kántor, 2020). Spatial and temporal variation of T_{mrt} is driven by exposure to solar and longwave radiation, which depends on local patterns of shading, *v*, air humidity and T_a (Aminipouri et al., 2019). In Ghent, Belgium, the largest intra-urban differences in T_{mrt} are registered in summer with on average a 7.0 °C higher T_{mrt} at more urbanized location compared to the urban park (Top et al., 2020). Although daytime T_{mrt} can reach an extreme level at exposed locations (65–75 °C), mature shade trees can reduce it to 30–35 °C in Szeged, Hungary (Kántor et al., 2018). Trees in Tempe, Arizona, USA, were also able to reduce afternoon T_{mrt} up to 33.4 °C (Middel and Krayenhoff, 2019). The results from our study are in accordance with the results from Szeged and Tempe as trees in urban park in Banja Luka, Bosnia and Herzegovina, decreased T_{mrt} up to 37.5 °C around noon during hot summer day (Figure 7). T_{mrt} varies substantially between locations throughout the day for all seasons in Tempe, Arizona, USA. This variability is mainly driven by the availability or absence of shade that impacts the incoming shortwave radiation (Crank et al., 2020). Another study from Middel et al. (2021) showed that not all shade is the same in terms of decreasing T_{mrt}. That study showed that during the day, at solar noon, and peak T_a, shade from urban form reduced T_{mrt} most effectively, followed by trees and lightweight structures in the City of Tempe (USA). However, it must be noted that many issues can arise due to slow response times, shape, inaccuracies in material properties and assumptions, and color (albedo, emissivity) inconsistencies between sensors used to obtain T_{mrt} (Vanos et al., 2021).

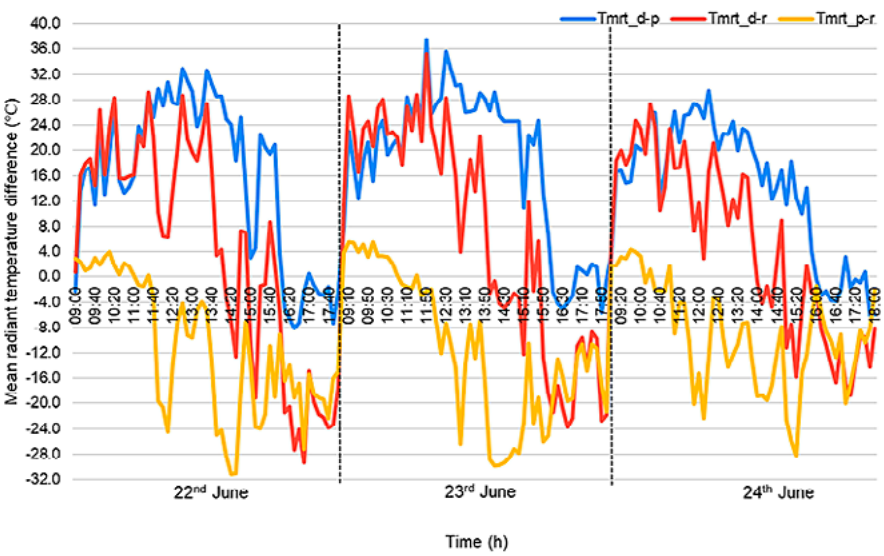

Figure 7. Temporal variation of T_{mrt} in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: $T_{mrt\_d\text{-}p}$ represents Mean Radiant Temperature difference between downtown and urban park; $T_{mrt\_d\text{-}r}$ represents Mean Radiant Temperature difference between downtown and riverside; and $T_{mrt\_p\text{-}r}$ represents Mean Radiant Temperature difference between urban park and riverside

PET

The highest average PET values are registered in downtown (45.6 °C), followed by riverside (41.5 °C). On the contrary, the lowest average PET values were registered in urban park (36.7 °C) (Table 4). This indicates that downtown and riverside were under extreme heat stress conditions, while strong heat stress conditions prevailed in urban park (see Table 2).

Temporal variation of PET showed similar results as T_{mrt}. In other words, downtown has substantially higher PET values compared to riverside and urban park throughout the day. In the period 2-4 PM, downtown has about 17 °C higher PET values compared to urban park and riverside and these differences decrease towards the late afternoon (Figure 8). In the period 4-6 PM, riverside becomes the most thermally uncomfortable part of the city with more than 10 °C higher PET compared to downtown and urban park. This is possibly a consequence of direct solar radiation at riverside in the afternoon, while downtown and urban park are in shade from buildings and trees, respectively. It can be also noticed that in the morning hours, urban park has higher PET compared to river location.

Previous studies have shown that during the daytime, the highest thermal loads are present in more urbanized areas, while the most comfortable are areas with dense trees (Milošević et al., 2016). Kovács and Németh (2012) found that compact midrise zone of Budapest has average PET values higher by 3 °C when compared to the suburban areas with more greenery. Similar to our results, higher PET values were obtained for built zones in Oberhausen (Germany) during the hot days (Tamax > 30 °C) when compared to sparsely built and dense trees zones (Müller et al. 2014). During the daytime period of heat waves, the urban park in Ghent, Belgium, was the most comfortable area because it was able to effectively mitigate heat stress compared to more urbanized locations (Top et al., 2020). In other words, citizens experienced extreme heat stress during daytime of heat waves with highest average PET reached at the semi-open downtown location in Ghent; on the contrary, the urban park had a 4.4 °C lower mean daytime PET when compared to the downtown (Top et al., 2020). The differences in OTC values in Czech cities confirm substantial cooling associated with high vegetation (trees), while the measurable cooling effect of low vegetation was negligible and quite low around water fountains, spray fountains, and misting systems (Lehnert et al., 2021b). The maximum PET in our study peaked over 50 °C in downtown and at riverside (see Table 4). Similar maximum PET values were also obtained in Ghent downtown and industrial areas (Top et al., 2020), as well as in compact midrise area of Szeged, Hungary (Unger et al., 2018).

Frequency analysis (%) of different grades of physiological stress (see Table 2) in downtown, urban park and riverside is shown in Figure 9. It can be concluded that downtown and riverside are under the impact of extreme heat stress during majority of the day (72% in downtown and 57% at riverside). On the contrary, only 6% of the time in urban park is characterized with the extreme heat stress (Figure 9). In urban park, moderate and strong heat stress occurs during majority of the time (in total 91%). The frequency analysis

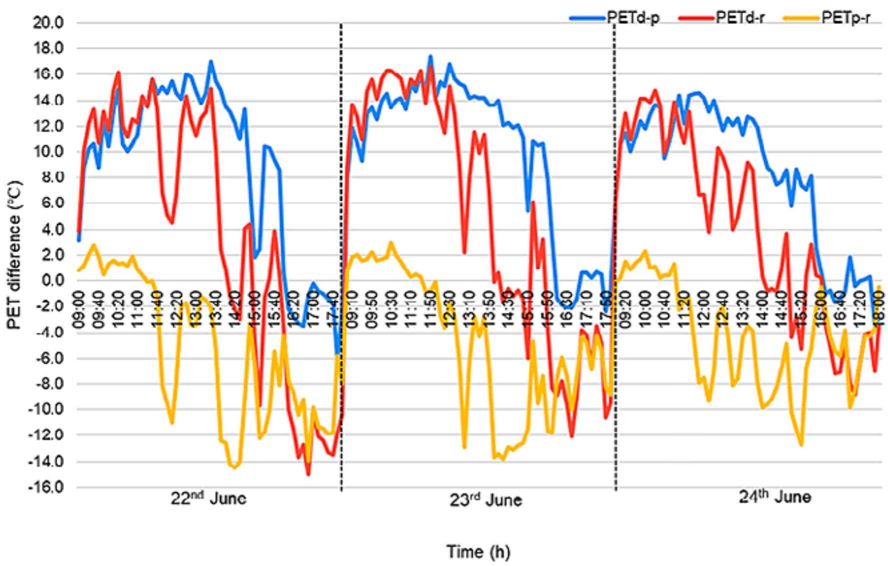

Figure 8. Temporal variation of PET in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: $PET_{d\text{-}p}$ represents Physiologically Equivalent Temperature difference between downtown and urban park; $PET_{d\text{-}r}$ represents Physiologically Equivalent Temperature difference between downtown and riverside; and $PET_{p\text{-}r}$ represents Physiologically Equivalent Temperature difference between urban park and riverside

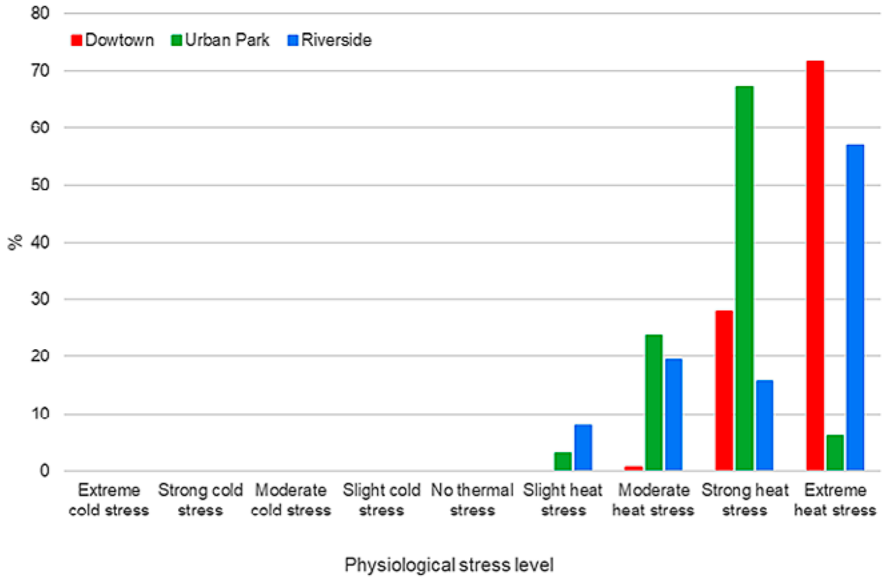

Figure 9. Frequency analysis (%) of different grades of physiological stress (based on PET values) at locations in Banja Luka in period 22-24 June 2021 (measurement period 9-18 h CEST)

revealed that the urban park in Ghent, Belgium, also experienced three to four times less frequent extreme heat stress compared to the downtown areas. This shows the importance of shading to improve the OTC for pedestrians during daytime (Top et al., 2020). The most built-up zones of Brno, Czech Republic, were also registered as the most uncomfortable areas of the city (Geletič et al., 2018).

mPET

The highest average mPET values are noticed in downtown (41.4 °C), followed by riverside (38.4 °C). On the contrary, the lowest average mPET are noticed in urban park (34.7 °C) (Table 4). This indicates that extreme heat stress is registered in downtown, strong heat stress at riverside and moderate heat stress in urban park (see Table 2). When compared to PET, mPET results indicated that modification in the original PET index led to the decrease in the physiological stress level by one category at riverside (from extreme to strong heat stress) and in urban park (from strong to moderate heat stress).

Temporal variation of mPET showed that maximum differences between downtown and other loca-

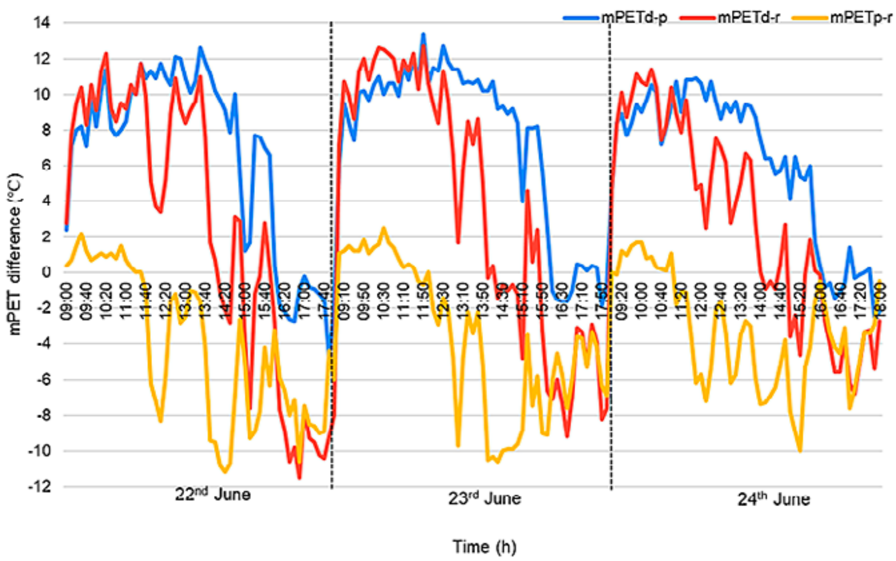

Figure 10. Temporal variation of mPET in Banja Luka (Bosnia and Herzegovina) in the period 22-24 June 2021 (measurement period 9-18 h CEST). NOTE: $mPET_{d-p}$ represents modified Physiologically Equivalent Temperature difference between downtown and urban park; $mPET_{d-r}$ represents modified Physiologically Equivalent Temperature difference between downtown and riverside; and $mPET_{p-r}$ represents modified Physiologically Equivalent Temperature difference between urban park and riverside

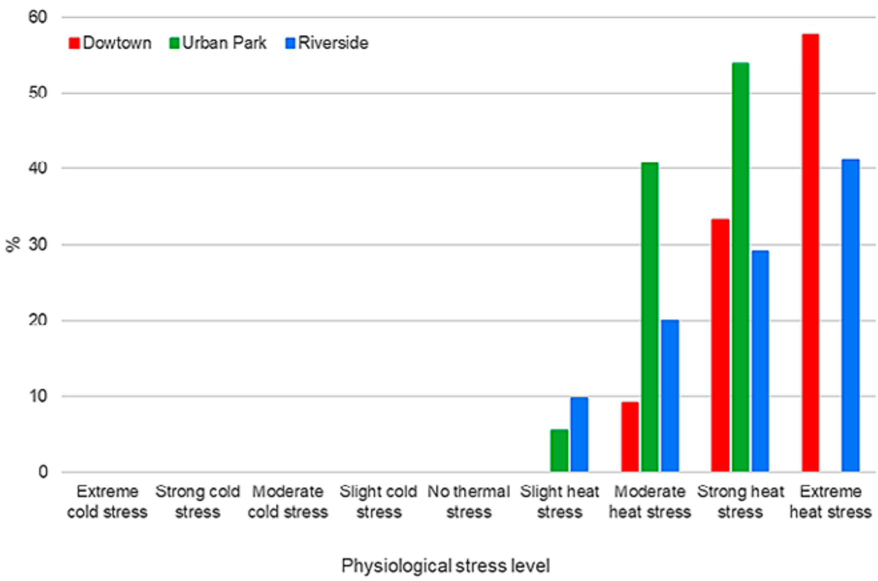

Figure 11. Frequency analysis (%) of different grades of physiological stress (based on mPET values) at locations in Banja Luka in period 22-24 June 2021 (measurement period 9-18 h CEST)

tions were somewhat smaller (up to 13 °C) when compared to PET differences (which were up to 17 °C) (Figure 10). Substantial higher mPET in downtown prevailed until 2-3 PM. Afterwards, riverside had higher mPET values compared to other locations as it was sunlit in the afternoon. Only in the morning period, urban park had slightly higher mPET compared to riverside. It probably continues during most of the night, as suggested by Geletič et al. (2021).

Frequency analysis (%) of different grades of physiological stress at locations in Banja Luka based on mPET values is shown in Figure 11. Extreme heat stress levels are prevailing in downtown (58%) and at riverside (41%). Nevertheless, this is a decrease in the frequency of extreme heat stress occurrence by 14% in downtown and by 16% at the riverside when compared to PET frequencies at these locations. In addition, strong heat stress is dominating in urban park (54%), which is a decrease of about 13% when compared to frequency of this heat stress level based on PET values. This indicates that clothing variability brought by mPET calculation in the RayMan model can lower the heat stress levels at studied locations.

Results from Pecelj et al. (2021) showed the applicability of PET and mPET indices as indicators of biothermal conditions necessary in urban planning, public health systems, tourism and recreation purposes. Increase in frequency and intensity of heat waves and hot weather are direct consequences of climate change with a higher risk for urban populations due to UHI effect. Reducing urban overheating is thus a priority as well as identifying the most vulnerable locations and people to establish targeted and coordinated public health policies (Alonso & Renard, 2020b). For this purpose, a continued monitoring and improvement of heat intervention is needed due to projected changes in frequency, duration, and intensity of heat events combined with shifts in demographics, making heat a major public health issue now and in the future (Sheridan & Allen, 2018).

Conclusions

Up to now, OTC research from Bosnia and Herzegovina mainly focused on the examination of climate potential for tourism development (Dunjić, 2019). Our study investigated OTC conditions in Banja Luka and confirmed conclusions from previous studies that showed the importance of small-scale micrometeorological measurements, the outcomes of which can be incorporated into climate-responsive urban design (Kántor et al., 2018b; Milošević et al.; 2022).

Nevertheless, detailed spatial and temporal climate data from diverse urban environments is often lacking in urban planning process and practice. This study showed that diverse urban environments (downtown, urban park, riverside) have diverse biometeorological conditions during hot summer days in Banja Luka, Bosnia and Herzegovina. Downtown area is the hottest area with up to 5-6 °C higher air temperatures compared to urban park and riverside. More importantly, downtown area has up to 35 °C higher T_{mrt}, up to 17 °C higher PET and up to 13 °C higher mPET compared to urban park and riverside. This shows that the local population is more often under extreme heat stress in the downtown than in other more natural locations such as urban park and riverside. Of all the locations, urban park is the most comfortable with 9 °C lower average PET compared to downtown and 5 °C lower average PET compared to riverside. When mPET is used, the differences are smaller, but the urban park remains the most comfortable urban area. The highest RH is noticed at the riverside, while urban dry island occurs in the downtown due to lack of vegetation and abundance of impermeable surfaces. Riverside has somewhat lower average T_a during summer daytime compared to urban park which is likely due to the combined effect of river cooling and tree shading near the river in Banja Luka. This kind of research based on field measurements during extreme heat conditions can provide detailed temporal and spatial climate information for the local authorities and guide their efforts in mitigating extreme heat at the right place and at the right time.

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References

Allen, M. J., & Sheridan, S. C. (2018). Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. *International journal of biometeorology,* 62(1), 57-67. https://doi.org/10.1007/s00484-015-1117-4

Alonso, L., & Renard, F. (2020a). A new approach for understanding urban microclimate by integrating complementary predictors at different scales in regression and machine learning models. *Remote Sensing*, 12(15), 2434. https://doi.org/10.3390/rs12152434

Alonso, L., & Renard, F. (2020b). A comparative study of the physiological and socio-economic vulnerabilities to heat waves of the population of the Metropolis of Lyon (France) in a climate change context. *International Journal of Environmental Research and Public Health,* 17(3), 1004. https://doi.org/10.3390/ijerph17031004

Aminipouri, M., Rayner, D., Lindberg, F., Thorsson, S., Knudby, A.J., Zickfeld, K., Middel, A. & Krayenhoff, E.S. (2019). Urban tree planting to maintain outdoor thermal comfort under climate change: The case of Vancouver's local climate zones. *Building and Environment,* 158, 226-236. https://doi.org/10.1016/j.buildenv.2019.05.022

Anderson, V., Leung, A.C., Mehdipoor, H., Jänicke, B., Milošević, D., Oliveira, A., Manavvi, S., Kabano, P., Dzyuban, Y., Aguilar, R. & Agan, P.N. (2021). Technological opportunities for sensing of the health effects of weather and climate change: a state-of-the-art-review. *International Journal of Biometeorology*, 65, 779-803. https://doi.org/10.1007/s00484-020-02063-z

Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology: a Journal of the Royal Meteorological Society*, 23(1), 1-26. https://doi.org/10.1002/joc.859

Arsenović, D., Lehnert, M., Fiedor, D., Šimáček, P., Středová, H., Středa, T., & Savić, S. (2019a). Heatwaves and mortality in Czech cities: A case study for the summers of 2015 and 2016. *Geographica Pannonica*, 23(3), 162-172. https://doi.org/10.5937/gp23-22853

Arsenović, D., Savić, S., Lužanin, Z., Radić, I., Milošević, D., & Arsić, M. (2019b). Heat-related mortality as an indicator of population vulnerability in a mid-sized Central European city (Novi Sad, Serbia, summer 2015). *Geographica Pannonica,* 23(4), 204-215. https://doi.org/10.5937/gp23-22680

Atanasova, N., Castellar, J.A., Pineda-Martos, R., Nika, C.E., Katsou, E., Istenič, D., Pucher, B., Andreucci, M.B. & Langergraber, G. (2021). Nature-Based Solutions and Circularity in Cities. *Circular Economy and Sustainability*, 1, 319-332. https://doi.org/10.1007/s43615-021-00024-1

Bajšanski, I. V., Milošević, D. D., & Savić, S. M. (2015). Evaluation and improvement of outdoor thermal comfort in urban areas on extreme temperature days: Applications of automatic algorithms. *Building and Environment*, 94, 632-643. https://doi.org/10.1016/j.buildenv.2015.10.019

Bokwa, A., Geletič, J., Lehnert, M., Žuvela-Aloise, M., Hollósi, B., Gal, T., Skarbit, N., Dobrovolný, P., Hajto, M.J., Kielar, R., Walawender, J.P., Šťastný, P., Holec, J., Ostapowicz, K., Burianová, J., & Garaj, M. (2019). Heat load assessment in Central European cities using an urban climate model and observational monitoring data. *Energy and Buildings,* 201, 53-69. https://doi.org/10.1016/j.enbuild.2019.07.023

Castellar, J.A.C., Popartan, L.A., Pueyo-Ros, J., Atanasova, N., Langergraber, G., Säumel, I., Corominas, L., Comas, J., & Acuna, V. (2021). Nature-based solutions in the urban context: Terminology, classification and scoring for urban challenges and ecosystem services. *Science of The Total Environment,* 779, 146237. https://doi.org/10.1016/j.scitotenv.2021.146237

Castillo, A., Correa, E., & Cantón, M. (2021). Microclimatic Behavior of Sustainable Urban Schemes Proposed for Hillside Areas Versus Existing Neighborhoods in the Metropolitan Area of Mendoza, Argentina. *Geographica Pannonica.* DOI: 10.5937/gp25-30532 (In press)

Chen, Y. C., & Matzarakis, A. (2018). Modified physiologically equivalent temperature—Basics and applications for western European climate. *Theoretical and applied climatology,* 132(3), 1275-1289. https://doi.org/10.1007/s00704-017-2158-x

Crank, P. J., Middel, A., Wagner, M., Hoots, D., Smith, M., & Brazel, A. (2020). Validation of seasonal mean radiant temperature simulations in hot arid urban climates. *Science of the Total Environment,* 749, 141392. https://doi.org/10.1016/j.scitotenv.2020.141392

Cugnon, G., Caluwaerts, S., Duchêne, F., Hamdi, R., Termonia, P., Top, S., & Vergauwen, T. (2019). Climate sensitivity to land use changes over the city of Brussels. *Geographica Pannonica*, 23(4), 269-276. 10.5937/gp23-24214

Dian, C., Pongrácz, R., Incze, D., Bartholy, J., & Talamon, A. (2019). Analysis of the urban heat island intensity based on air temperature measurements in a renovated part of Budapest (Hungary). *Geographica Pannonica*, 23(4), 277-288. https://doi.org/10.5937/gp23-23839

Dunjić, J. (2019). Outdoor thermal comfort research in urban areas of Central and Southeast Europe: A review. *Geographica Pannonica*, 23(4), 359-373. https://doi.org/10.5937/gp23-24458

Dunjić, J., Milošević, D., Kojić, M., Savić, S., Lužanin, Z., Šećerov, I., & Arsenović, D. (2021). Air Humidity Characteristics in "Local Climate Zones" of Novi Sad (Serbia) Based on Long-Term Data. *ISPRS International Journal of Geo-Information*, 10(12), 810. https://doi.org/10.3390/ijgi10120810

Fischer, E. M., & Schär, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature geoscience*, 3(6), 398-403. https://doi.org/10.1038/ngeo866

Gál, C. V., & Kántor, N. (2020). Modeling mean radiant temperature in outdoor spaces, A comparative numerical simulation and validation study. *Urban Climate*, 32, 100571. https://doi.org/10.1016/j.uclim.2019.100571

Gál, T., Mahó, S. I., Skarbit, N., & Unger, J. (2021). Numerical modelling for analysis of the effect of different urban green spaces on urban heat load patterns in the present and in the future. *Computers, Environment and Urban Systems,* 87, 101600. https://doi.org/10.1016/j.compenvurbsys.2021.101600

Geletič, J., Lehnert, M., Savić, S., & Milošević, D. (2018). Modelled spatiotemporal variability of outdoor thermal comfort in local climate zones of the city of Brno, Czech Republic. *Science of the total environment*, 624, 385-395. https://doi.org/10.1016/j.scitotenv.2017.12.076

Geletič, J., Lehnert, M., & Jurek, M. (2020). Spatiotemporal variability of air temperature during a heat wave in real and modified landcover conditions: Prague and Brno (Czech Republic). *Urban Climate*, 31, 100588. https://doi.org/10.1016/j.uclim.2020.100588

Geletič, J., Lehnert, M., Krč, P., Resler, J., & Krayenhoff, E. S. (2021). High-resolution modelling of thermal exposure during a hot spell: a case study using PALM-4U in Prague, Czech Republic. *Atmosphere*, 12(2), 175. https://doi.org/10.3390/atmos12020175

Jacob, D., Kotova, L., Teichmann, C., Sobolowski, S. P., Vautard, R., Donnelly, C., Koutroulis, A.G., Grillakis, M.G., Tsanis, I.K., Damm, A., & Sakalli, A. (2018). Climate impacts in Europe under+ 1.5 C global warming. *Earth's Future*, 6(2), 264-285. https://doi.org/10.1002/2017EF000710

Jacobs, C., Klok, L., Bruse, M., Cortesão, J., Lenzholzer, S., & Kluck, J. (2020). Are urban water bodies really cooling?. *Urban Climate*, 32, 100607. https://doi.org/10.1016/j.uclim.2020.100607

Jamei, E., Seyedmahmoudian, M., Horan, B., & Stojcevski, A. (2019). Verification of a bioclimatic modeling system in a growing suburb in Melbourne. *Science of the total environment,* 689, 883-898. https://doi.org/10.1016/j.scitotenv.2019.06.399

Jänicke, B., Milošević, D., & Manavvi, S. (2021). Review of User-Friendly Models to Improve the Urban Micro-Climate. *Atmosphere*, 12(10), 1291. https://doi.org/10.3390/atmos12101291

Kántor, N., & Unger, J. (2011). The most problematic variable in the course of human-biometeorological comfort assessment—the mean radiant temperature. *Central European Journal of Geosciences,* 3(1), 90-100. https://doi.org/10.2478/s13533-011-0010-x

Kántor, N., Chen, L., & Gál, C. V. (2018b). Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary. *Landscape and urban planning*, 170, 241-255. https://doi.org/10.1016/j.landurbplan.2017.09.030

Kántor, N., Gál, C. V., Gulyás, Á., & Unger, J. (2018). The impact of façade orientation and woody vegetation on summertime heat stress patterns in a central European square: comparison of radiation measurements and simulations. *Advances in Meteorology*, 2018. https://doi.org/10.1155/2018/2650642

Konstantinov, P., Varentsov, M., & Esau, I. (2018). A high density urban temperature network deployed in several cities of Eurasian Arctic. *Environmental Research Letters*, 13(7), 075007. https://doi.org/10.1088/1748-9326/aacb84

Konstantinov, P., Shartova, N., Varentsov, M., & Revich, B. (2020). Evaluation of outdoor thermal comfort conditions in northern Russia over 30-year period: Arkhangelsk region. *Geographica Pannonica*, 24(4), 252-260. 10.5937/gp24-24738

Konstantinov, P., Tattimbetova, D., Varentsov, M., & Shartova, N. (2021). Summer thermal comfort in Russian big cities (1966-2015). *Geographica Pannonica*, 25(1), 35-41. doi: 10.5937/gp25-29440

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated, *Meteorologische Zeitschrift*, 15(3), 259–263. DOI: 10.1127/0941-2948/2006/013.

Kovács, A., & Németh, Á. (2012). Tendencies and differences in human thermal comfort in distinct urban areas in Budapest, Hungary. *Acta Climatologica et Chorologica*, 46, 115–124.

Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of the Total Environment*, 661, 337-353. https://doi.org/10.1016/j.scitotenv.2019.01.062

Langergraber, G., Castellar, J. A., Pucher, B., Baganz, G. F., Milosevic, D., Andreucci, M. B., Kearney, K., Pineda-Martos, R., & Atanasova, N. (2021). A framework for addressing circularity challenges in cities with nature-based solutions. *Water*, 13(17), 2355. https://doi.org/10.3390/w13172355

Leconte, F., Bouyer, J., & Claverie, R. (2020). Nocturnal cooling in Local Climate Zone: Statistical approach using mobile measurements. *Urban Climate*, 33, 100629. https://doi.org/10.1016/j.uclim.2020.100629

Lehnert, M., Brabec, M., Jurek, M., Tokar, V., & Geletič, J. (2021). The role of blue and green infrastructure in thermal sensation in public urban areas: A case study of summer days in four Czech cities. *Sustainable Cities and Society*, 66, 102683. https://doi.org/10.1016/j.scs.2020.102683

Lehnert, M., Tokar, V., Jurek, M., & Geletič, J. (2021b). Summer thermal comfort in Czech cities: measured effects of blue and green features in city centres. *International Journal of Biometeorology*, 65(8), 1277-1289. https://doi.org/10.1007/s00484-020-02010-y

Lelovics, E., Unger, J., Savić, S., Gál, T. M., Milošević, D., Gulyás, Á., Marković, V., Arsenović, D., & Gál, C. V. (2016). Intra-urban temperature observations in two Central European cities: a summer study. *Időjárás/Quarterly Journal of The Hungarian Meteorological Service*, 120(3), 283-300.

Liu, A., Xu, Q., Gao, J., Xu, Z., & Han, L. (2019). Improving schoolyard wind environments: Case studies in two schools in Nanjing. *Geographica Pannonica*, 23(4), 256-268. DOI: 10.5937/gp23-24183

Lukić, M., Filipović, D., Pecelj, M., Crnogorac, L., Lukić, B., Divjak, L., Lukić, A., & Vučićević, A. (2021). Assessment of Outdoor Thermal Comfort in Serbia's Urban Environments during Different Seasons. *Atmosphere*, 12(8), 1084. https://doi.org/10.3390/atmos12081084

Manavvi, S., & Rajasekar, E. (2021). Evaluating outdoor thermal comfort in "Haats"–The open air markets in a humid subtropical region. *Building and Environment*, 190, 107527. https://doi.org/10.1016/j.buildenv.2020.107527

Matzarakis, A., & Mayer, H. (1996). Another kind of environmental stress: thermal stress. *WHO newsletter*, 18, 7–10.

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International journal of biometeorology*, 51(4), 323-334. https://doi.org/10.1007/s00484-006-0061-8

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *International journal of biometeorology*, 54(2), 131-139. https://doi.org/10.1007/s00484-009-0261-0

Middel, A., Selover, N., Hagen, B., & Chhetri, N. (2016). Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. *International journal of biometeorology*, 60(12), 1849-1861. https://doi.org/10.1007/s00484-016-1172-5

Middel, A., & Krayenhoff, E. S. (2019). Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: Introducing the MaRTy observational platform. *Science of the total environment*, 687, 137-151. https://doi.org/10.1016/j.scitotenv.2019.06.085

Middel, A., Alkhaled, S., Schneider, F. A., Hagen, B., & Coseo, P. (2021). 50 Grades of Shade. *Bulletin of the American Meteorological Society*, 102(9), E1805-E1820. https://doi.org/10.1175/BAMS-D-20-0193.1

Milošević, D. D., Savić, S. M., Marković, V., Arsenović, D., & Šećerov, I. (2016). Outdoor human thermal comfort in local climate zones of Novi Sad (Serbia) during heat wave period. *Hungarian Geographical Bulletin*, 65(2), 129-137. https://doi.org/10.15201/hungeobull.65.2.4

Milošević, D. D., Bajšanski, I. V., & Savić, S. M. (2017). Influence of changing trees locations on thermal comfort on street parking lot and footways. *Urban forestry & urban greening*, 23, 113-124. https://doi.org/10.1016/j.ufug.2017.03.011

Milosevic, D., Dunjić, J., & Stojanović, V. (2020). Investigating micrometeorological differences between saline steppe, forest-steppe and forest environments in northern Serbia during a clear and sunny autumn day. *Geographica Pannonica*, 24(3), 176-186. https://doi.org/10.5937/gp24-25885

Milošević, D., Savić, S., Kresoja, M., Lužanin, Z., Šećerov, I., Arsenović, D., Dunjić, J., & Matzarakis, A. (2021). Analysis of air temperature dynamics in the "local climate zones" of Novi Sad (Serbia) based on long-term database from an urban meteorological network. *International Journal of Biometeorology*, 1-14. https://doi.org/10.1007/s00484-020-02058-w

Milošević, D., Middel, A., Savić, S., Dunjić, J., Lau, K., & Stojsavljević, R. (2022). Mask wearing behavior in hot urban spaces of Novi Sad during the COVID-19 pandemic. Science of the Total Environment (in press).

Morakinyo, T. E., Ouyang, W., Lau, K. K. L., Ren, C., & Ng, E. (2020). Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation-development and evaluation. *Science of the Total Environment*, 719, 137461. https://doi.org/10.1016/j.scitotenv.2020.137461

Müller, N., Kuttler, W., & Barlag, A. B. (2014). Counteracting urban climate change: adaptation measures and their effect on thermal comfort. *Theoretical and applied climatology*, 115(1), 243-257. https://doi.org/10.1007/s00704-013-0890-4

Nimac, I., Herceg-Bulić, I., Cindrić Kalin, K., & Perčec Tadić, M. (2021). Changes in extreme air temperatures in the mid-sized European city situated on southern base of a mountain (Zagreb, Croatia). *Theoretical and Applied Climatology*, 146(1), 429-441. https://doi.org/10.1007/s00704-021-03689-8

Oliveira, A., Lopes, A., Correia, E., Niza, S., & Soares, A. (2021a). An urban climate-based empirical model to predict present and future patterns of the Urban Thermal Signal. *Science of The Total Environment*, 790, 147710. https://doi.org/10.1016/j.scitotenv.2021.147710

Oliveira, A., Lopes, A., Correia, E., Niza, S., & Soares, A. (2021b). Heatwaves and summer urban heat islands: a daily cycle approach to unveil the urban thermal signal changes in Lisbon, Portugal. *Atmosphere*, 12(3), 292. https://doi.org/10.3390/atmos12030292

Paramita, B., & Matzarakis, A. (2019). Urban morphology aspects on microclimate in a hot and humid climate. *Geographica Pannonica*, 23(4), 398-410. DOI: 10.5937/gp23-24260

Park, C. Y., Lee, D. K., Asawa, T., Murakami, A., Kim, H. G., Lee, M. K., & Lee, H. S. (2019). Influence of urban form on the cooling effect of a small urban river. *Landscape and urban planning*, 183, 26-35. https://doi.org/10.1016/j.landurbplan.2018.10.022

Pearlmutter, D., Pucher, B., Calheiros, C.S., Hoffmann, K.A., Aicher, A., Pinho, P., Stracqualursi, A., Korolova, A., Pobric, A., Galvão, A. & Tokuç, A. (2021). Closing water cycles in the built environment through nature-based solutions: The contribution of vertical greening systems and green roofs. *Water*, 13(16), 2165. https://doi.org/10.3390/w13162165

Pecelj, M., Matzarakis, A., Vujadinović, M., Radovanović, M., Vagić, N., Đurić, D., & Cvetkovic, M. (2021). Temporal Analysis of Urban-Suburban PET, mPET and UTCI Indices in Belgrade (Serbia). *Atmosphere*, 12(7), 916. https://doi.org/10.3390/atmos12070916

Popov, T., Gnjato, S., Trbić, G., & Ivanišević, M. (2018). Recent trends in extreme temperature indices in Bosnia and Herzegovina. *Carpathian Journal of Earth and Environmental Sciences*, 13(1), 211-224. DOI:10.26471/cjees/2018/013/019

Popov, T., Gnjato, S., & Trbić, G. (2019). Changes in extreme temperature indices over the Peripannonian region of Bosnia and Herzegovina. *Geografie*, 124(1), 19-40. https://doi.org/10.37040/geografie2019124010019

Ramadhan, T., Jurizat, A., Syafrina, A., & Rahmat, A. (2021). Investigating outdoor thermal comfort of educational building complex in urban area: A case study in Universitas Kebangsaan, Bandung city. *Geographica Pannonica*, 25(2), 85-101. DOI: 10.5937/gp25-30430

Republic Hydrometeorological Service of Republic of Srpska, Bosnia and Herzegovina (2021). Meteorological data from station Banja Luka. Available at: https://rhmzrs.com/

Savić, S., Marković, V., Šećerov, I., Pavić, D., Arsenović, D., Milošević, D., Dolinaj, D., Nagy, I. & Pantelić, M. (2018). Heat wave risk assessment and mapping in urban areas: case study for a midsized Central European city, Novi Sad (Serbia). *Natural hazards*, 91(3), 891-911. https://doi.org/10.1007/s11069-017-3160-4

Santamouris, M., Synnefa, A., & Karlessi, T. (2011). Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*, 85(12), 3085-3102. https://doi.org/10.1016/j.solener.2010.12.023

Sheridan, S. C., & Allen, M. J. (2018). Temporal trends in human vulnerability to excessive heat. *Environmental research letters*, 13(4), 043001. https://doi.org/10.1088/1748-9326/aab214

Skarbit, N., Stewart, I. D., Unger, J., & Gál, T. (2017). Employing an urban meteorological network to monitor air temperature conditions in the 'local climate zones' of Szeged, Hungary. *International Journal of Climatology*, 37, 582-596, https://doi.org/10.1002/joc.5023

Syafii, N. (2021). Promoting urban water bodies as a potential strategy to improve urban thermal environment. *Geographica Pannonica*, 25(2),113-120. https://doi.org/10.5937/gp25-30431

Tablada, A., De Troyer, F., Blocken, B., Carmeliet, J., & Verschure, H. (2009). On natural ventilation and thermal comfort in compact urban environments–the Old Havana case. *Building and Environment*, 44(9), 1943-1958. https://doi.org/10.1016/j.buildenv.2009.01.008

Tan, Z., Lau, K. K. L., & Ng, E. (2016). Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. *Energy and Buildings*, 114, 265-274. https://doi.org/10.1016/j.enbuild.2015.06.031

Tan, Z., Lau, K. K. L., & Ng, E. (2017). Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas. *Building and Environment*, 120, 93-109. https://doi.org/10.1016/j.buildenv.2017.05.017

Thorsson, S., Lindberg, F., Eliasson, I., & Holmer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 27(14), 1983-1993. https://doi.org/10.1002/joc.1537

Top, S., Milošević, D., Caluwaerts, S., Hamdi, R., & Savić, S. (2020). Intra-urban differences of outdoor thermal comfort in Ghent on seasonal level and during record-breaking 2019 heat wave. *Building and Environment*, 185, 107103. https://doi.org/10.1016/j.buildenv.2020.107103

Trbic, G. (2011) Екоклиматска рејонизација Перипанонског обода Републике Српска (Eco-climatological regionalisation of Peripanonian rim of Republika Srpka, Географско друштво Републике Српке, 2011, 1-189. (in Serbian)

Trbić, G., Popov, T., & Gnjato, S. (2017). Analysis of air temperature trends in Bosnia and Herzegovina. *Geographica Pannonica*, 21(2), 68-84. DOI: 10.18421/GP21.02-01

Unger, J., Skarbit, N., & Gál, T. (2018). Evaluation of outdoor human thermal sensation of local climate zones based on long-term database. *International journal of biometeorology*, 62(2), 183-193. https://doi.org/10.1007/s00484-017-1440-z

Unger, J., Skarbit, N., Kovács, A., & Gál, T. (2020). Comparison of regional and urban outdoor thermal stress conditions in heatwave and normal summer periods: A case study. *Urban Climate*, 32, 100619. https://doi.org/10.1016/j.uclim.2020.100619

Vanos, J. K., Rykaczewski, K., Middel, A., Vecellio, D. J., Brown, R. D., & Gillespie, T. J. (2021). Improved methods for estimating mean radiant temperature in hot and sunny outdoor settings. *International journal of biometeorology*, 65(6), 967-983. https://doi.org/10.1007/s00484-021-02131-y

Varentsov, M., Shartova, N., Grischenko, M., & Konstantinov, P. (2020). Spatial patterns of human thermal comfort conditions in Russia: Present climate and trends. *Weather, Climate, and Society*, 12(3), 629-642. https://doi.org/10.1175/WCAS-D-19-0138.1

Vecellio, D. J., Bardenhagen, E. K., Lerman, B., & Brown, R. D. (2021). The role of outdoor microclimatic features at long-term care facilities in advancing the health of its residents: An integrative review and future strategies. *Environmental research*, 111583. https://doi.org/10.1016/j.envres.2021.111583

Wang, X., Liu, F., & Xu, Z. (2019). Analysis of urban public spaces' wind environment by applying the CFD simulation method: A case study in Nanjing. *Geographica Pannonica*, 23(4), 308-317. https://doi.org/10.5937/gp23-24249

Webb, B. (2016). The use of urban climatology in local climate change strategies: a comparative perspective. *International Planning Studies*, 22(2), 68-84. https://doi.org/10.1080/13563475.2016.1169916

Yang, P., Ren, G., & Hou, W. (2017). Temporal–spatial patterns of relative humidity and the urban dryness island effect in Beijing City. *Journal of Applied Meteorology and Climatology*, 56(8), 2221-2237. https://doi.org/10.1175/JAMC-D-16-0338.1

Žiberna, I., Pipenbaher, N., Donša, D., Škornik, S., Kaligarič, M., Bogataj, L.K., Črepinšek, Z., Grujić, V.J. & Ivajnšič, D. (2021). The Impact of Climate Change on Urban Thermal Environment Dynamics. *Atmosphere*, 12(9), 1159. https://doi.org/10.3390/atmos12091159