DOI:10.28974/idojaras.2024.1.7

IDŐJÁRÁS

Quarterly Journal of the HungaroMet Hungarian Meteorological Service
Vol. 128, No. 1, January – March, 2024, pp. 121–141

Thermal assessments at local and micro scales during hot summer days: a case study of Belgrade (Serbia)

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(Manuscript received in final form January 11, 2023)

Abstract— Increasing thermal risk in cities is endangering the health and well-being of urban population and is driven by climate change and intensive urbanization. Therefore, if we plan to enlarge the capacities of cities to be more climate resilient in the 21st century, more detailed monitoring of urban climate on local and micro scales is needed. For this research we performed two microclimate measurement campaigns in urban area of Belgrade, during hot summer days in 2021. In total, five measurement sites were chosen in different urban designs and different local climate zones (LCZs). For thermal monitoring (air temperature – Ta and globe temperature – Tg) the Kestrel heat stress tracker sensor with 1-min measurement resolution was used, but we used 10-min average values. Obtained results showed distinct thermal differences (up to 7 °C on average) between densely built-up areas and green areas. Differences between built-up LCZs are lower with values from 2 to 4 °C. Important part of this research was microclimate monitoring on sites within the same LCZ (intra-LCZ variability). Results showed that shadows and short- and longwave radiation play a paramount role in thermal variability. Direct and reflected radiations on one measurement site increased Ta up to 6 °C and Tg up to 12 °C when compared to other measurement site (in a similar urban design), which was in the shadow.

Key-words: urban climate, temperature values, local climate zone; microclimate condition, urban design; city

1. Introduction

Numerous studies argued that different thermal conditions are driven by various urban designs, both on local scale (*Lehnert et al.,* 2021a) and microscale (*Middel* and *Krayenhoff,* 2019). Urban areas, characterized with predominant impervious surfaces and surface roughness, have higher thermal signal, lower evaporation, and a general disbalance in radiation and convection efficiency. Thus, urbanization directly affects temperature (air and surface), air humidity, wind speed, solar radiation, and other meteorological parameters, creating a city-specific urban climate. Furthermore, based on the modified pervious natural surfaces and the artificialization processes, thermoradiative and energetic processes are altered in cities (*Manoli et al.,* 2019). Based on the mentioned geometric/surface and thermal/radiative properties in cities, *Stewart* and *Oke* (2012) created a climate-based local climate zone (LCZ) classification system for urban and non-urban areas in order to standardize the research framework for thermal observations and assessments. Using LCZ concept, the heat load assessment could be performed at local scale that corresponds to areas (from hundreds of square meters to several kilometers on a horizontal scale) with uniform surface cover, urbanization structure, building materials, traffic, and human activities (*Stewart* and *Oke*, 2012). However, thermal differences can be uncovered on microscale, i.e., on sites that are located in the same LCZ, not only in different LCZs (*Shi et al.,* 2016; *Skarbit et al.,* 2017; *Quanz et al.,* 2018; *Shi et al.,* 2018; *Milošević et al.,* 2022a).

Climate projection outcomes displaying more frequent and severe heat waves (HWs) in Europe as a consequence of climate change (*Fischer* and *Schär,* 2010*; Jacob et al.,* 2018*; Geletič et al.,* 2020), and that will continue to occur during the 21st century (*Leconte et al.,* 2020; *IPCC,* 2021). According to previous publications, HWs in summer periods are generally connected with negative effects on public health in cities based on intensive outdoor thermal loads (*Tong et al.,* 2021*; Tuholske et al.,* 2021), but some results show potential positive influence of HWs in winter time in European regions that characterized with highly urbanized and populated areas/cities (*Macintyre et al.,* 2021). A combination of intense HWs and single hot days in summer and urbanization process in cities will modify urban thermal conditions more than the climate in rural/non-urbanized environments (*Oke et al.,* 2017). As a consequence, these urban-rural and intra-urban thermal differences will be intensified during intense HW periods and single hot days in summer.

The global climate change impacts force the cities to be more climate-resilient and climate-adaptable, and this task is of paramount importance (*Jänicke et al.,* 2021). Therefore, in situ and mobile measurements of climate conditions on the local and micro scales help to understand the climate processes and apply resilient/adaptable measures in cites. Previous research papers already highlighted the importance of urban networks and mobile measurements, e.g., *Konstantinov* *et al.* (2018), *Dian et al.* (2019), *Šećerov et al.* (2019), *Lehnert et al.* (2021b), *Skarbit et al.* (2017), *Alonso* and *Renard* (2020) and *Milošević et al.* (2022a; 2022b).

Belgrade's urban heat island (UHI) and outdoor thermal comfort (OTC) indices have been identified so far in relation to the surrounding cities (*Milovanović,* 2015; *Milovanović et al.,* 2020), or based on offical meterological station datasets (*Pecelj et al.,* 2021; *Lukić et al.,* 2021). However, this study presents the first micrometeorological measurement campaigns that were performed in Belgrade (capital of Serbia), during hot summer days in 2021, in diverse urban environments. This kind of climate monitoring can be valuable for future climate-sensitive urban design and planning strategies. Based on that, the main goals of this research are as follows: a) monitoring of micrometeorological conditions in diverse urban environments, such as densely built-up areas, industrial areas, urban or forest parks, during hot summer days; b) detailed spatial and temporal analysis of thermal conditions (air temperature – *Ta* and globe temperature – *Tg*, which is a measure of the heat stress in district sunlight) obtained from the field measurements; and c) discussion of obtained thermal condition results in Belgrade in order to contribute to better climate change adaptation.

2. Research area, materials and methods

2.1. Description of research area

Belgrade is a capital city of the Republic of Serbia located in Southeast Europe (*Fig. 1*). City coordinates are 44°49`N and 20°27`E, with an average absolute elevation of about 117 m. The urban area of 3 222 km^2 has a population of about 1.6 million people. The downtown and its nearest surrounding are characterized by densely built-up urban design. Towards the suburban areas, there are more detached multi-storey buildings and one-storey houses with higher ratio of green areas. There are forest parks on the southern and northeastern parts of the urban area (*Fig. 1*). Obviously, a strongly modified climate and significant thermal differences between Belgrade urban area and its natural surroundings can be expected.

Belgrade has a *Cfa* climate (*Milovanović et al.,* 2017) according to the Köppen-Geiger climate classification system (*Kottek et al.,* 2006). During the 1991–2020 period, the mean annual temperature was 13.2 °C, the mean annual maximum temperature was 18.2 °C, the mean annual minimum temperature was 9.1 °C, and the mean annual precipitation is 698.9 mm (*Republic Hydrometeorological Service,* 2022).

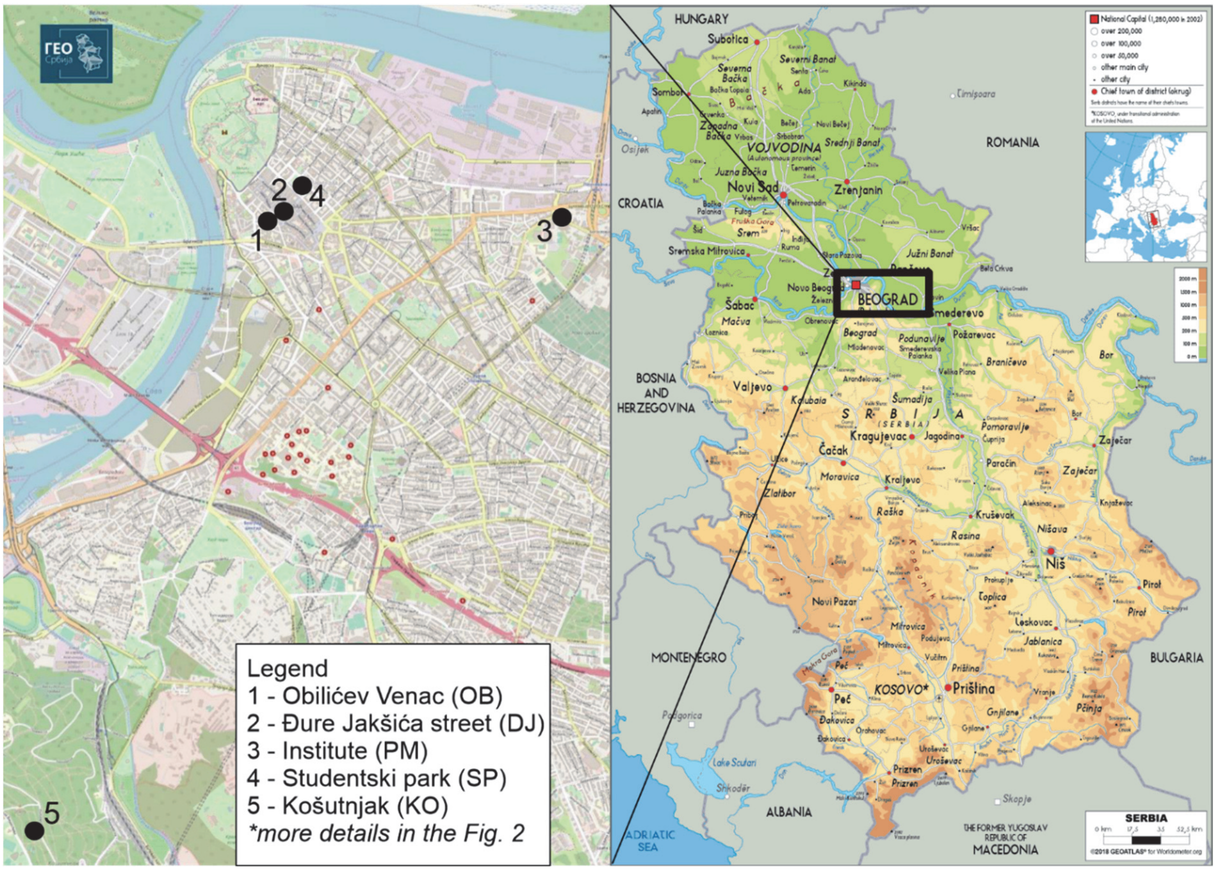

Fig. 1. Locations of micrometeorological measurement campaigns in summer 2021, and position of Belgrade in Serbia. Source of maps: *https://a3.geosrbija.rs/* (urban map of Belgrade) and *https://www.worldometers.info/img/maps/serbia_physical_map.gif* (Serbia/Europe).

2.2. Measurement locations and datasets

Micrometeorological monitoring has been performed through organization of two measurement campaigns in the urban area of Belgrade. Measurement campaigns were performed on June 18 and August 23, 2021 on five locations with different urban environments (*Fig. 2*). Both measurement campaigns were realized on hot summer days, i.e., during intensive HW periods. The HW period is defined as period with minimum three consecutive days with maximum temperature 5 °C or more comparing to average for this part of the year. In our case, in Belgrade, the average *Ta* is 22.0 °C in June and 24.0 °C in August (*Republic Hydrometeorological Service,* 2022), so days with maximum temperature of 29 °C or higher can be considered as adequate. Selected hot summer days, for our research, were characterized with maximum daily air temperature higher than 30 °C, no precipitation, low cloud cover, low wind speed, and intense solar radiation. Measurement campaigns were conducted at five sites with different urban designs: 1) Obilićev Venac (OV) is characterized by an open square with combination of pavement and green area with trees, and surrounded by densely built-up area that is equivalent to LCZ 2 according to *Stewart* and *Oke* (2012) classification system of local climate zones (LCZs). This location is a popular pedestrian and relaxation area in the city; 2) Đure Jakšića street (DJ) is an urban canyon street with multi-storey buildings on both sides and without green areas. The street is 100% covered by artificial surfaces and oriented northeast-southwest. This location is part of LCZ 2 and is a very intensive pedestrian corridor; 3) Institute for Biological Research „Siniša Stanković" (PM) is characterized by the combination of parking lots and green areas (on microlevel) and surrounded by light industrial buildings and residential areas. This measurement location is a synergy between LCZ 8 and LCZ 3; 4) Studentski park (SP) is characterized by an urban park with scattered trees (LCZ B). This park is about 200 m long and with width of about 100 m (based on Google Earth data). The central part of the park is an open square, while other parts of the park are a combination of green areas with trees and pedestrian footpaths. This park is surrounded by densely built-up areas that represent LCZ 2; and 5) Košutnjak (KO) presents a forest park in the suburban area with dense trees (LCZ A), and this location is characterized by 100% of pervious surfaces and green areas. Locations SP and KO are popular relaxation areas. Locations of measurement sites are presented in *Fig. 1* and *Fig. 2*, and more microenvironmental characteristics of each site are shown in *Table 1*.

Table 1. Basic descriptions of the microenvironment around the five measurement locations

Date of measurement	**Name of location**	**Abbreviation of location**	**Latitude (N) longitude (E)**	**Altitude (m)**	**Urban area feature**	**LCZ**
June 18 /August 23, 2021	Obilićev Venac	OV	44°48'59"; 20°27'18"	113	downtown; densely built	2
August 23, 2021	Đure Jakšića street	DJ	44°49'02"; 20°27'23"	116	downtown; densely built	2
June 18, 2021	Institute for Biological Research „Siniša Stanković"	PM	44°49'03"; 20°29'12"	94	industrial; residential	8_3
August 23, 2021	Studentski park	SP	44°49'09"; 20°27'29"	111	downtown; urban park	B
June 18, 2021	Košutnjak	KO	44°46'10"; 20°25'43"	220	outskirt; forest park	A

LCZ – local climate zone classification (based on *Stewart* and *Oke,* 2012)

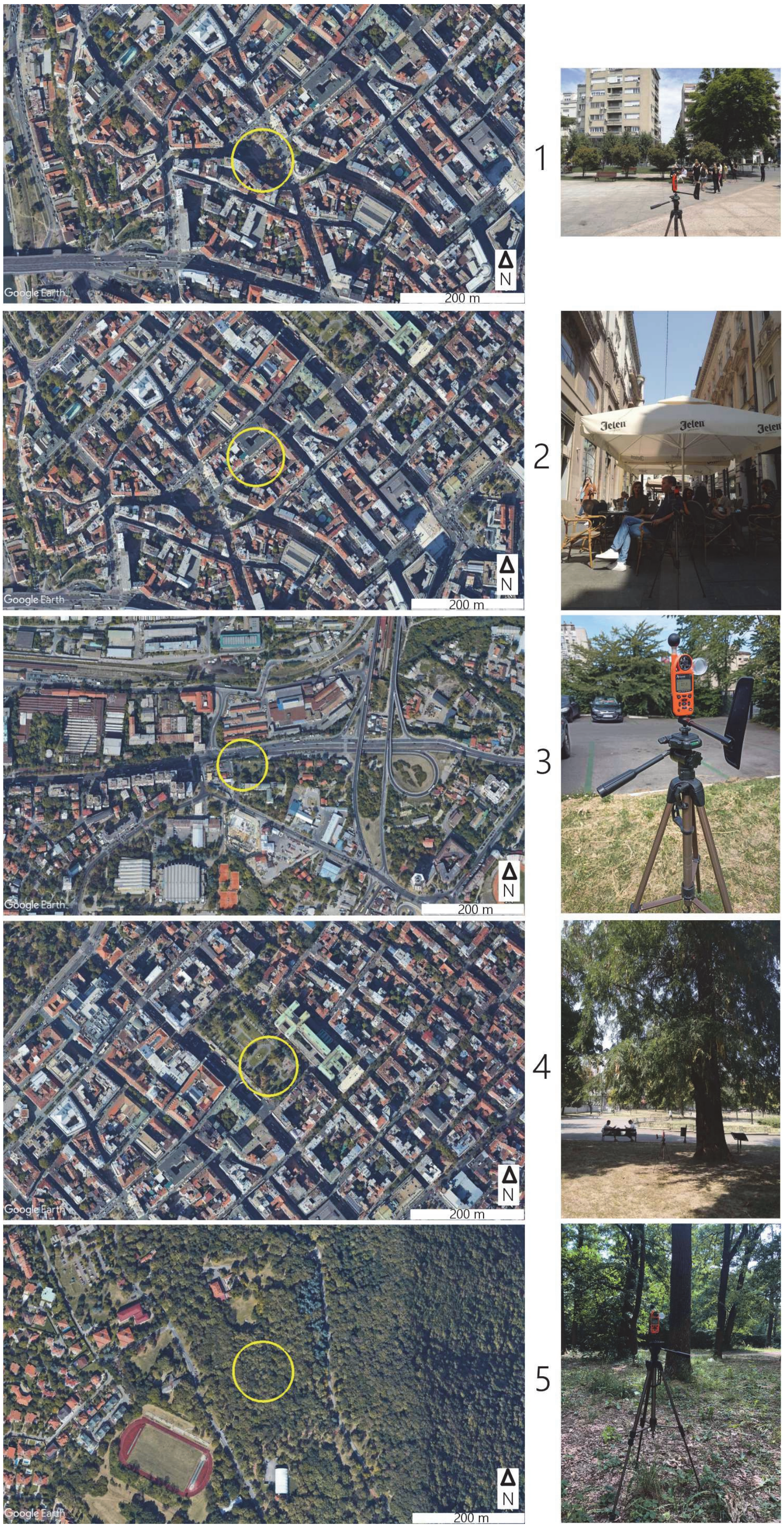

Fig. 2. Locations of micrometeorological measurements (performed on June 18 and August 23, 2021) in Belgrade (Serbia): (1) Obilićev Venac – OV; (2) Đure Jakšića street – DJ; (3) Institute for Biological Research „Siniša Stanković" – PM; (4) Studentski park – SP; and (5) Košutnjak - KO.

Measurement campaign on June 18 was performed from 12:00 to 18:00 in Central European Summer Time – CEST at three locations (OV, PM, and KO). On August 23, the measurements were conducted from 12:00 to 21:00 (CEST) at OV, DJ, and SP. The goal was to monitor thermal differences in various urban designs during the hottest parts of the day and during the sunset period, when the highest thermal differences are expected in different urbanization types.

Three Kestrel 5400 Heat Stress Tracker sensors (*Fig. 2*, *Table 2*) were used to obtain one-minute measurements of *Ta* – air temperature measured at 1.1 m from the surface (in °C) and *Tg* – globe temperature measured at 1.1 m from the surface (in °C), during both measurement campaigns. The *Tg* is referred as the globe temperature or black globe temperature and resembles the thermal values of surroundings, and that means that *Tg* simulates the thermal conditions felt by the human body (*available at: https://www.designingbuildings.co.uk/wiki/Globe_temperature*). For further statistical analysis, we used 10-minute average values of the measured variables. Usage of 10-minute average values of meteorological variables showed to be sufficiently frequent for this kind of urban thermal analysis (*Unger et al.,* 2018; *Milošević et al.,* 2022a; 2022b). The Kestrel Heat Stress Tracker sensors were deployed at least 15 minutes before the start of the measurement in order to allow the sensors to equilibrate to the atmospheric conditions. Furthermore, the equipment is calibrated in accordance with the manufacturer's specifications (*available at: https://kestrelinstruments.com/mwdownloads/download/link/id/14/*).

Table 2. Accuracy, resolution, and range of Kestrel 5400 Heat Stress Tracker sensors used for outdoor thermal condition measurements in Belgrade (Serbia)

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

Note: available at: https://kestrelinstruments.com/mwdownloads/download/link/id/14/

2.3. Statistical methods

The description of the measured data is given using central tendency and dispersion (mean value, standard deviation, absolute maximum, and absolute minimum values of *Ta* and *Tg* – *Table 3*). Daily fluctuations of measured variables in the period from 12:00 to 18:00 CEST and 12:00 to 21:00 CEST is shown graphically (*Fig. 3* and *Fig. 4*). We defined our research question as: Is there any significant difference between *Ta/Tg* values measured at different locations in Belgrade during the hot summer days? To test the null hypothesis H0 – there is no statistically significant difference between the *Ta* values measured at the mentioned locations; and H0 – there is no statistically significant difference between the *Tg* values measured at the mentioned locations; the one-way analysis of variance was used. Finally, following the results of the Levene test of homogeneity of variances, Hochberg and Games-Howell post-hoc tests were used to compare the values of the measured variables between possible pairs of locations. Those tests are considered appropriate if some of the assumptions for the application of one-way analysis of variance are not appropriate (*Tamhane,* 1979; *Stoline,* 1981; *Shingala and Rajyaguru,* 2015). To conduct the mentioned analysis, we used SPSS v. 14.

Table 3. Main statistical characteristics of air temperature (*Ta*) and globe temperature (*Tg*) in diverse urban environments of Belgrade (Serbia) during the measurement campaigns

Date of measurement	**Locations**	***Ta* (°C)**				***Tg* (°C)**			
		max.	**min.**	**aver.**	**st. dev.**	**max.**	**min.**	**aver.**	**st. dev.**
June 18, 2021	OV	34.7	26.8	30.8	1.9	48.5	35.4	42.5	3.3
	PM	36.1	29.6	32.6	1.7	50.3	34.1	42.6	3.8
	KO	29.4	25.8	27.8	0.9	37.6	26.9	29.5	1.3
August 23, 2021	OV	36.5	23.5	31.0	3.7	47.5	23.2	35.7	8.6
	DJ	40.6	25.4	32.1	3.8	49.1	25.6	34.1	6.9
	SP	33.4	23.6	30.3	3.1	39.1	23.7	31.6	4.0

max. – maximum; min. – minimum; aver. – average; st. dev. – standard deviation.

3. Results

3.1. Temperature measurements

During the two days measurement campaigns, the highest *Ta* values were recorded in the most densely built-up areas (OV, PM, DJ) and the lowest values were measured in green areas (KO and SP) (*Table 3*). The highest average *Ta* and *Tmax* values were measured in the compact mid-rise zone – LCZ 2 (OV, DJ) and large low-rise zone with small area and houses – LCZ 8_3 (PM). *Tmax* ranged from

34.7 °C (OV on June 18) to 40.6 °C (DJ on August 23). In the dense trees zone – LCZ A (KO – forest park) and scattered trees zone – LCZ B (SP – urban park), *Tmax* values are about 7 °C lower compared to the densely built-up zones (LCZ 2/LCZ 8_3). Similar tendencies are visible in the averaged *Ta* values, but with a smaller temperature difference (about 2 °C to 5 °C) between various LCZ types. Contrary to average *Ta* and *Tmax*, *Tmin* values are quite similar at all measurement locations, except the location PM. The *Tmin* is about 2 °C higher in PM in both measurement days, which can be explain with very intensive traffic in the morning in the industrial surroundings. The values of the standard deviation show 50% lower value at the location of KO (forest park) in relation to OV and PM (in June 18) and about 20% lower value at the location of SP (urban park) in relation to OV and DJ (in August 23) (*Table 3*).

Fig. 3 shows 10-minute *Ta* differences between measurement locations and provide detailed insights into the temporal variability of *Ta* in different urban designs in Belgrade. During the whole period of measurement (from 12:00 to 18:00, on June 18 CEST), *Ta* differences are positive when comparing densely built-up areas (OV and PM) with green area (KO). The highest intra-urban differences were recorded at 16:30 (8.7 °C) between PM and KO, and at 18:00 (7.1 °C) between OV and KO. Generally, the differences between OV/PM and KO constantly increased from 16:30 towards 18:00, but quite high differences can be also noticed before 15:30. The intra-urban comparison between LCZ 2 (OV) and LCZ 8_3 (PM) show lower *Ta* values on OV location during most of the time, with a few exceptions (*Fig. 3a*).

Temporal variability based on 10-minute *Ta* values during the measurement campaign on August 23 (from 12:00 to 21:00 CEST) present constantly higher values in the densely built-up area (LCZ 2) with locations OV and DJ, when compared to the urban park (SP). Only during the sunset and nighttime, the differences between OV and SP are negligible. The highest intra-urban differences are measured between DJ and SP, with differences higher than 7 °C (form 14:20 to 15:20), and OV-SP with the highest difference of 4.6 °C (at 12:30). The micro-location differences within the LCZ 2 zone (OV-DJ) show higher *Ta* values at OV location from 12:00 to 14:00, but during the rest of the measurement time, DJ location was warmer, particularly from 14:00 to 16:00 CEST (*Fig. 3b*).

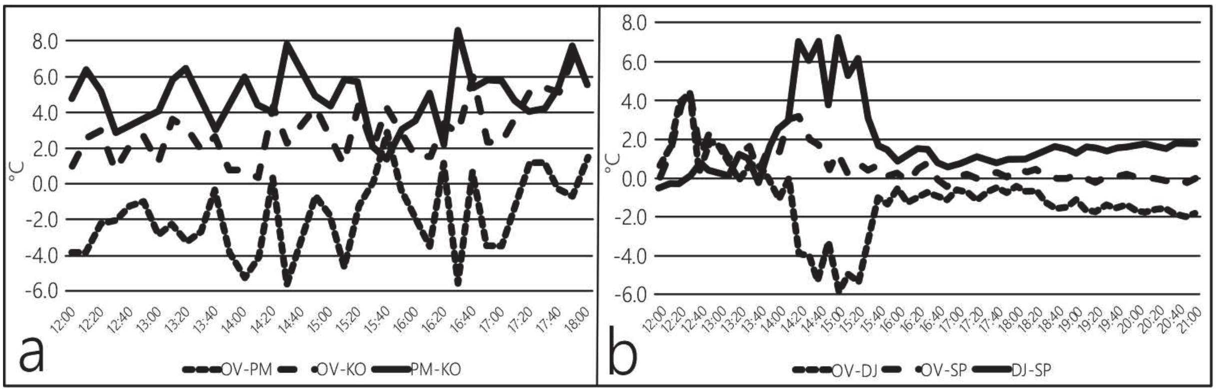

Fig. 3. Temporal variation of *Ta* in Belgrade (Serbia) during the measuring campaigns: (a) on June 18 – measurement time 12:00-18:00 CEST; and (b) August 23 – measuring time 12:00-21:00 CEST). The OV-PM – represents *Ta* differences between the diverse densely built-up types (LCZ 2/LCZ 8_3); OV-KO – represents *Ta* differences between the densely built-up type (LCZ 2) and forest park (LCZ A); and PM-KO – represents *Ta* differences between the densely built-up type (LCZ 8_3) and forest park (LCZ A).

The highest values of *Tg*, during both measurement campaigns are recorded at densely built-up zones (OV, PM, DJ), and the lowest values are noticed in forest and urban parks (KO and SP). The differences between built-up zones (OV, PM, DJ) and green areas (KO, SP) are from about 10 °C to 13 °C – *Tgmax*, about 2 °C to 9 °C – *Tgmin*, and about 4 °C to 13 °C – average *Tg*. The highest differences are recorded between densely built-up zones (LCZ 2/LCZ 8_3) and forest park (LCZ A) during the measurement campaign on June 18. Contrarily to that, significantly smaller differences were observed between compact mid-rise built-up zone (LCZ 2) and urban park (LCZ B) during the measurement campaign on August 23. The values of the standard deviation are three times lower in the forest park (KO), i.e., twice lower in the urban park (SP) compared to the urbanized parts of the city (*Table 3*).

Temporal variations of *Tg* (*Fig. 4*), during the measurement campaign on June 18 (*Fig. 4a*) show positive differences between OV/PM and KO during the whole measurement time, with a substantially hotter period between 14:00 and 15:30 CEST. During that time, *Tg* is higher from 12 °C to 17 °C in densely urbanized zones compared to the green area of forest park. Furthermore, *Tg* values are higher in large low-rise zone with small area of houses – LCZ 8_3 (PM) then in compact mid-rise zone – LCZ 2 (OV) during most of the measurement time (between 12:00 and 18:00). Only during a few short periods, *Tg* values are higher at OV location.

Fig. 4b presents *Tg* intra-urban differences during the measurement campaign on August 23 (form 12:00 to 21:00 CEST). On all three micro-locations (OV, DJ, and SP), after 16:00 CEST, *Tg* differences are around 0 °C (2 °C or less). On the other hand, significant differences between the densely built-up zone (OV and DJ) and urban park (SP) are recorded from 12:00 to 16:00, particularly in the period from 14:00 to 16:00. In these hours, locations in LCZ 2 are substantially hotter than the urban park with *Tg* differences up to 15 °C. Also, the interesting outcome is that DJ location has substantially higher *Tg* values compared to OV location in the period from 14:00 to 15:40. In the period between 12:00 and 14:00, OV location has noticeable higher *Tg* values compared to DJ location. In both cases, *Tg* differences are up to 12 °C.

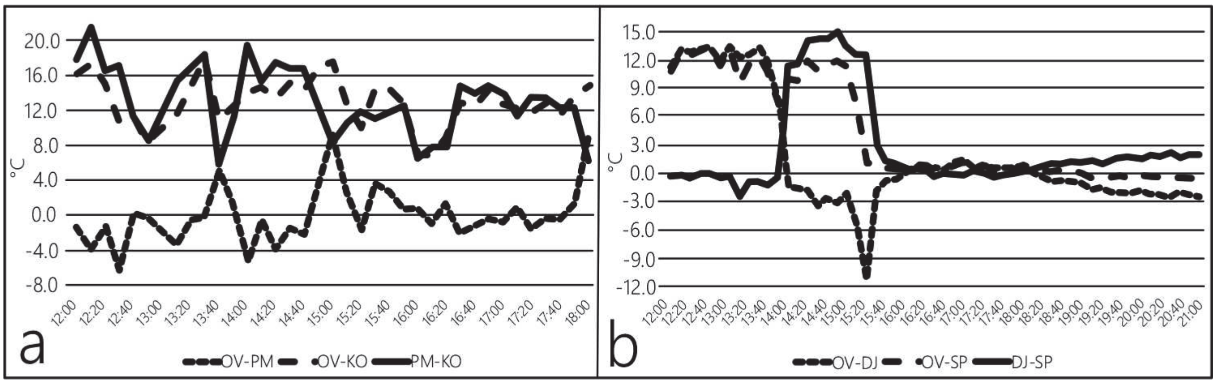

Fig. 4. Temporal variation of *Tg* in Belgrade (Serbia) during the measuring campaigns: (a) on June 18 – measurement time 12:00-18:00 CEST; and (b) on August 23 – measurement time 12:00-21:00 CEST). OV-DJ – represents *Tg* differences within the same densely built-up type (LCZ 2); OV-SP – represents *Tg* differences between the densely built-up type (LCZ 2) and urban park (LCZ B); and DJ-SP – represents *Tg* differences between the densely built-up type (LCZ 2) and urban park (LCZ B).

3.2. Statistical outcomes

To examine whether there is a statistically significant difference between *Ta* and *Tg* on all three locations during the measurement campaign on June 18, a one-way analysis of variance was applied. It was shown that there are statistically significant differences (r = 0.05) in *Ta* (*Table 4*) and *Tg* (*Table 5*) between the measurement locations.

Table 4. Results of the one-way analysis of *Ta* variance during the measurement campaign on June 18 (measurement time 12:00–18:00 CEST)

	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	432.486	2	216.243	88.210	0.000
Within groups	264.757	108	2.451		
Total	697.243	110			

df – degree of freedom; F – F-value; Sig. - significance

Table 5. Results of the one-way analysis of *Tg* variance during the measurement campaign on June 18 (measurement time 12:00–18:00 CEST)

	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	4039.694	2	2019.847	209.242	0.000
Within groups	1042.541	108	9.653		
Total	5082.234	110			

df – degree of freedom; F – F-value; Sig. - significance

Hochberg and Games-Howell post-hoc tests were used to determine which pairs of measurement locations had a statistically significant differences in *Ta* and *Tg*, respectively. These tests were chosen because the Levene test showed that there was no homogeneity of variance in the analyzed variables (*Table 6* and *Table 7*).

Table 6. Results of the Levene test of homogeneity of variance for *Ta* measured during the measurement campaign on June 18 (measurement time 12:00–18:00 CEST)

Levene statistic	**df1**	**df2**	**Sig.**
8.139	2	108	0.001

df1 and df2 – degreases of freedom; Sig. - significance

Table 7. Results of the Levene test of homogeneity of variance for *Tg* measured during the measurement campaign on June 18 (measurement time 12:00–18:00 CEST)

Levene statistic	**df1**	**df2**	**Sig.**
6.772	2	108	0.002

df1 and df2 – degreases of freedom; Sig. - significance

Regarding *Ta*, both tests showed that there are statistically significant differences between each of the pairs of locations (KO-OV; KO-PM, OV-PM), i.e., that *Ta* in KO is significantly lower than that in PM, i.e., OV, and that *Ta* on OV is significantly lower than that in PM (*Table 8*). In terms of *Tg*, there is a statistically significant difference only between KO and OV, i.e., KO and PM, where *Tg* value in KO is lower by about 12.8 °C than at PM and OV. The difference in *Tg* between PM and OV is negligible (0.027 °C) and not statistically significant (*Table 9*).

Table 8. Results of post-hoc tests for *Ta* measured during the measurement campaign on June 18 (measurement time 12:00–18:00 CEST)

Post-hoc test	**Location**	**Location**	**Mean difference (°C)**	**Std. error**	**Significance**
Hochberg	KO	PM	-4.784	0.36402	0.000
		OV	-3.000	0.36402	0.000
	PM	KO	4.784	0.36402	0.000
		OV	1.784	0.36402	0.000
Games-Howell	KO	PM	-4.784	0.319217	0.000
		OV	-3.000	0.344469	0.000
	PM	OV	1.784	0.420683	0.000

Significance values marked with grey areas are statistically significant.

Table 9. Results of post-hoc tests for *Tg* measured during the measurement campaign on June 18th (measurement time 12:00–18:00 h CEST)

Post-hoc test	**Location**	**Location**	**Mean difference (°C)**	**Std. error**	**Significance**
Hochberg	KO	PM	-12.784	0.698	0.000
		OV	-12.811	0.629	0.000
	PM	KO	12.784	0.698	0.000
		OV	-0.027	0.826	0.999
Games-Howell	KO	PM	-12.784	0.698	0.000
		OV	-12.811	0.629	0.000
	PM	OV	-0.027	0.826	0.999

Significance values marked with grey areas are statistically significant.

Analysis of variance for the measurement campaign on August 23 showed that there is a statistically significant difference in *Ta* and *Tg* between the measurement locations, i.e., OV, SP, and DJ (*Tables 10* and *11*). Furthermore, Levene test showed that there is a homogeneity of variance in *Ta*, while it is absent for *Tg* (*Tables 12* and *13*).

Table 10. Results of one-way analysis of *Ta* variance during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	90.703	2	45.352	3.570	0.030
Within groups	2058.109	162	12.704		
Total	2148.812	164			

df – degree of freedom; F – F-value; Sig. - significance

Table 11. Results of one-way analysis of *Tg* variance during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	514.521	2	257.261	5.627	0.004
Within groups	7406.473	162	45.719		
Total	7920.994	164			

df – degree of freedom; F – F-value; Sig. - significance

Table 12. Results of the Levene test of homogeneity of variance for *Ta* measured during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

Levene Statistic	**df1**	**df2**	**Sig.**
0.523	2	162	0.594

df1 and df2 – degreases of freedom; Sig. - significance

Table 13. Results of the Levene test of homogeneity of variance for *Tg* measured during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

Levene Statistic	**df1**	**df2**	**Sig.**
17.014	2	162	0.000

df1 and df2 – degreases of freedom; Sig. - significance

A statistically significant difference in *Ta* (1.8 °C) exists only between DJ and SP (*Table 14*). According to the Hochberg post-hoc test, a statistically significant difference in *Tg* exists only between OV and SP. However, according to the Games-Howell post-hoc test, there is a statistically significant difference between OV and SP, but also between DJ and SP (*Table 15*).

Table 14. Results of post-hoc tests for *Ta* measured during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

Post-hoc test	Location	Location	Mean difference (°C)	Std. error	Significance
Hochberg	OV	DJ	-1.109	0.680	0.281
		SP	0.691	0.680	0.671
	DJ	OV	1.109	0.680	0.281
		SP	1.800	0.680	0.026
Games-Howell	OV	DJ	-1.109	0.720	0.276
		SP	0.691	0.650	0.539
	DJ	OV	1.109	0.720	0.276
		SP	1.800	0.667	0.022

Significance values marked with grey areas are statistically significant.

Table 15. Results of post-hoc tests for *Tg* measured during the measurement campaign on August 23 (measurement time 12:00–21:00 CEST)

Post-hoc test	Location	Location	Mean difference (°C)	Std. error	Significance
Hochberg	OV	DJ	1.673	1.289	0.480
		SP	4.291	1.289	0.003
	DJ	OV	-1.673	1.289	0.480
		SP	2.618	1.289	0.126
Games-Howell	OV	DJ	1.673	1.483	0.499
		SP	4.291	1.280	0.004
	DJ	OV	-1.673	1.483	0.499
		SP	2.618	1.072	0.043

Significance values marked with grey areas are statistically significant.

4. Discussion and conclusions

Micrometeorological measurement campaigns performed in Belgrade during hot summer days confirmed general statement that different urban designs have specific thermal patterns. The obtained results showed that densely built-up areas with multi-storey buildings (OV and DJ locations), densely built-up areas with light industrial buildings and residential areas (PM location), and green areas with trees (SP and KO locations) have different thermal conditions during the day/evening/sunset hours, and in the most cases, these differences are statistically significant, as it was presented in results. Therefore, it can be concluded that the LCZ classification system created by *Stewart* and *Oke* (2012) based on different built-up and land cover types is appropriate method for thermal difference assessments in cities on the local scale.

Results from this study showed that temperature differences between densely built-up areas and green areas are about 7 °C, while differences between various built-up zones (LCZ 2 – LCZ 8_3) are about 2–4 °C. Previous studies focused on *Ta* showed that the highest *Ta* values are usually found in more urbanized areas of the city. For example, in Lisbon (Portugal), the more compact urban areas had the highest temperature conditions (*Oliveira et al.,* 2021), and in Banja Luka (Bosnia & Herzegovina), the downtown area with densely built-up design had highest thermal conditions in daytime and nighttime hours during the hot summer days (within HW period), when compared to urban park and riverside (*Milošević et al.,* 2022a). Research studies also analyzed urban shadows and green areas as elements that drive thermal conditions. *Lelovics et al.* (2016) recognized urban cool island with temperature lower by 1 °C (in Szeged, Hungary) or 2 °C (in Novi Sad, Serbia) in densely built-up zones during the summer days caused by shadowing conditions. Furthermore, urban parks that are close to/or within downtown areas could lower temperature conditions with up to 1 °C or more, that is noticed in Ghent (Belgium) (*Top et al.,* 2020). Therefore, a few research studies related of green infrastructures and its cooling potential in cities are published already. *Tan et al.* (2016; 2017) highlighted the impact of trees in Sky View Factor values, and some authors (*Morakinyo et al.,* 2020; *Gál et al.,* 2021) pronounced different spatial characteristics of green areas and content of species as elements that driving to cooler thermal conditions in hot periods. Also, we can conclude that hot summer days that occur within the heat wave periods represent higher concern based on general accumulation of heat during the consecutive hot summer days and obtained intensive outdoor thermal load (surplus of the heat) in built-up areas, as well as in rural/non-urbanized areas.

Our research also showed temperature differences between the locations in the same LCZ (OV and DJ locations), i.e., these outcomes emphasize that urban areas are characterized by specific thermal conditions on the microscale. OV and DJ locations are only 150 m away from each other, both are in the LCZ 2, but OV site is the open square with pavement and green area, while DJ is in a narrow street canyon with no green area (*Fig. 2*). During the measurement day, the OV site was sunny, while street canyon was in the shade from 12:00 to 14:00 CEST, which lead to higher *Ta* (about 4 °C) and *Tg* values (about 12 °C) on the OV site. Completely different thermal conditions at these two locations occur from 14:00 to 15.30 CEST. During this time, DJ site is entirely sunny, and the OV location is mostly in shadows because of trees and high buildings on the south part of the square. In this one and a half hour, the maximum measured *Ta* difference (DJ-OV) is 6 °C, and the maximum measured *Tg* difference is 12 °C. After 15.30 until the end of the measurement, both sites are in shadow, and differences are from

0 °C to 2–3 °C. These outcomes are in general in accordance with the results of *Geletič et al.* (2021), where is pronounced that direct and reflected radiation intensified thermal conditions in urban surroundings. On the other hand, we have to be aware of technical issues in Kestrel Heat Stress Trackers i.e., when the black globe is under direct radiation, this could lead to overestimation of *Tg* values (*Kántor* and *Unger,* 2011; *Middel et al.,* 2016). Intra-LCZ variability was analyzed by others, too, and *Skarbit et al.* (2017) found small differences (less than 1 °C) in Szeged (Hungary) between sites in LCZ 5, 6 and 9. *Shi et al.* (2018) confirmed thermal differences from LCZ 1 to LCZ 6 in Hong Kong, and the range is from 2 °C to 3 °C. *Quanz et al.* (2018) analyzed thermal conditions within LCZ 2_B and found that average daily differences are generally about 1 °C, but during clear, calm, and dry days, the daytime differences are rising about 3 °C.

During the same campaign in August, the results show that there are no differences of more than 3 °C between the OV/DJ locations and the SP site (urban park) in the period after 15:00 CEST. All three sites are in the shade after 15:00 CEST, but due to the green area in the urban park, lower values are expected. However, this is not the case, which may be due to several factors, such as the size of the park, which is approximately 100×200 m, characterized by scattered trees and urban environment around the park that is densely built-up (LCZ 2). Such a statement is in accordance with other studies that highlighted spatial characteristics of green areas as thermal conditions regulator (*Morakinyo et al.,* 2020; *Gál et al.,* 2021).

Finally, to prepare cities to be more resilient to climate change and heat risks, detailed thermal conditions monitoring on the microscale is needed, and therefore, further thermal assessments could be based on crowd-sourcing techniques using citizen weather stations (CWS), smart-phone records, web-based tools (*Fenner et al.,* 2017*,* 2019; *Venter et al.,* 2020), or purpose-designed mobile/portable instruments with specifically-numbered and high-accuracy sensors, particularly for radiation measurements (*Middel* and *Krayenhoff,* 2019; *Schnell et al.,* 2021). These kind of monitoring can contribute to achieving the SDGs (Sustainable Development Goals) within the Agenda 2030 through: a) raise awareness of heat load stress and to improve the public health care for vulnerable groups (under age or poverty groups) of the population in cities (SDG 3); b) contribute to a better implementation of climate-conscious urbanization that can improve the microclimate conditions, increase quality of life of the population, and adapt cities to climate change (SDG 11); and c) contribute to further adaptation to climate change, especially in urban areas where the microclimate and local climate are additionally modified due to the impact of urbanization (SDG 13). Obviously, the interaction of the process of "climate change-urbanization-urban climate" and its direct impact on the tendencies of atmospheric changes in cities should be incorporated into the development of climate action policies, as it becomes a serious issue in the twenty-first century (*Savić et al.,* 2022).

The potential shortcoming of this research can be defined in the number of days when measurements were taken, considering that during the summer of 2021, there were significantly more hot days. However, the two hot summer days that were analyzed in this study may well represent a realistic picture of the micro-scale thermal conditions in Belgrade, and each one must take into account both technical and human capacities when planning field measurements. The further development of these investigations will develop both on temporal and spatial levels, and it will be particularly interesting to implement a campaign of measurements in different urban micro conditions during tropical nights and to monitor the differences in thermal conditions.

Acknowledgements: This research was supported by the financial support of the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-47/2023-01/200125). We would like to thank the Institute for Biological Research "Siniša Stanković" for the location provided for field measurements.

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