ГЛАСНИК Српског географског друштва 102(2) 45-66
BULLETIN OF THE SERBIAN GEOGRAPHICAL SOCIETY 2022

Original scientific paper

UDC 551.524:911.375(497.113 Novi Sad)
https://doi.org/10.2298/GSGD2202045V

Received: September 19, 2022
Corrected: October 12, 2022
Accepted: October 14, 2022

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MICROMETEOROLOGICAL MEASUREMENTS AND BIOMETEOROLOGICAL SURVEY IN DIFFERENT URBAN SETTINGS OF NOVI SAD (SERBIA)

Abstract: Due to rapid urbanisation, urban microclimate research has become increasingly popular in the last decade. Significant variation in microclimate conditions can be created due to diversity in urban geometry and it can affect outdoor thermal comfort. Biometeorological measurements and survey were conducted in different urban settings (square, park, street) of the city of Novi Sad during a warm autumn day in October 2019. Air temperature, relative humidity, wind speed and globe temperature, but also outdoor thermal comfort indices such as Mean Radiant Temperature (T_{mrt}) and Physiological Equivalent Temperature (PET) were obtained for each location. The largest differences in the biometeorological conditions are noticed between the urban park and other urban areas. The maximum average value of T_a was at the city square with 27.9 °C, while in the urban park and street T_a were about 25 °C. The values of RH were the lowest at the city square. Globe temperature (T_g) had the highest values, on average, at the city square (about 40 °C), while the average values in the urban park and street were about 26–28 °C. The highest average PET values are registered at the city square (41.4 °C), followed by substantially lower average PET registered in urban park (27.1 °C) and urban street canyon (26.2 °C). The analysis showed that during about 70% of the time, urban dwellers experience extreme heat stress at the city square. Contrary to that, no extreme heat stress is noticed in urban park and street canyon.

Key words: thermal comfort, biometeorological measurements, biometeorological survey, urban park, Novi Sad, Serbia

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Introduction

In the past several years, increasing attention has been dedicated to the uncontrolled urbanisation and the consequences that it creates, which are especially related to outdoor thermal comfort (Fang et al., 2021). Urban heat islands (UHIs) often occur in densely populated cities (Lau et al., 2019) where conditions vary from thermal comfort to thermal stress (Johansson et al., 2018). By observing the situation in urban environments, data can be provided by enabling urban planners to form more pleasant urban areas (Milošević et al., 2021) which will encourage people to engage in outdoor activities (Fang et al., 2021).

Urban forms and structures modify the microclimate of cities (Holst & Mayer, 2011). Essentially, differences in air temperature can be dependent upon construction materials in cities, building structures and the amount of vegetation (Milošević et al., 2021). Urban areas are quite complex and they are composed of different urban forms (configurations of buildings), which may, in addition to different construction materials, create elements of the microclimate that can vary in space and time (Middel et al., 2016). Likewise, a number of other factors additionally contribute to the change of air temperature and other climatic elements within the local zones of a city. These can be the configuration of the street network (aspect ratio), parks (tree height and park distribution) affecting the areas surrounding the parks themselves, as well as city squares that are paved with different materials creating a higher temperature than it should be (Toparlar et al., 2018). It is important that urban planners have accurate information on how a particular urban landscape such as street canyons or city squares can affect the outdoor thermal comfort and form an urban microclimate (Lehnert et al., 2021).

Urban design can impact the outdoor thermal comfort through the sky view factor (SVF), aspect ratio, coverage and height of buildings that provide shading and reduce airflow (Lau et al., 2019). These factors can aggravate outdoor thermal comfort and it can be assigned to the solar radiation that penetrates the urban streets affecting the mean radiant temperature (T_{mrt}) (Jamei et al., 2016). T_{mrt} is significantly lower in the streets with N-S direction, than in the streets with E-W orientation, which are longer exposed to solar radiation. Furthermore, vegetation in urban parks can provide a cooling effect through shading, evapotranspiration and air flow (Lau et al., 2019). Also, vegetation can be planted within urban streets and squares to provide cooling effect where thermal stress is the most common (Thorsson et al., 2017). Beneath the vegetation, the air flow tends to be reduced, especially close to the buildings or in dense urban locations where thermal indices such as Physiological Equivalent Temperature (PET) may be higher (Lindberg & Grimmond, 2011). The main reason for reducing levels of discomfort in cities is shading (vegetation or buildings) which leads to a remarkable reduction in PET. Likewise, the aspect ratio has a huge role in PET where narrow urban streets provide better shading effect for people on sidewalks than in case of streets that are wide (Jamei et al., 2016).

It is very important to investigate human biometeorological conditions that can be perceived at different locations in the city (street, square, park). Questionnaire survey can be used to examine the relationship between thermal perception of citizens and outdoor thermal conditions. Therefore, these structured interviews can deal with some personal factors (age, activity level, clothing, time spent outdoors), personal sensations of meteorological elements (air temperature, relative humidity, wind, radiation) and comfort level on the measurement location (Zeng & Dong, 2015). Biometeorological survey is an appropriate solution for understanding the outdoor thermal comfort conditions and to obtain the subjective thermal sensation of pedestrians (Lau et al., 2019).

In this research, the analysis of quantitative data obtained from biometeorological survey and measurements within the city of Novi Sad will be performed. By comparing the values of air temperature, relative humidity, wind speed and globe temperatures in locations such as streets, squares and city parks, the microscale biometeorological differences can be obtained and quantified.

The following tasks were performed:

- A comprehensive analysis of biometeorological (air temperature, relative humidity, wind speed, globe temperature, T_{mrt} and PET) conditions in different local urban environments (square, street, park) during warm autumn day.
- Biometeorological survey of the local population at the selected measurement sites in Novi Sad and gathering of their sensation votes regarding biometeorological parameters.
- Conclusion on obtained results and provision of information for urban climate and urban design of the city.

Study area, data and methods

Study area

Novi Sad is the second largest city in the Republic of Serbia. It has about 102 km2 of built-up and urban green and blue areas and a population of about 361,000 people in 2019 (Statistical Office of the Republic of Serbia, 2022). The city is located on a flat terrain of the Pannonian Plain with the absolute elevation between 72 m and 80 m (Geletič et al., 2019). It is a Central European city (45°16`N, 19°50`E) (Figure 1) with complex and heterogeneous urbanisation due to its historical and contemporary development patterns. Accordingly, the city can be divided in seven built-up ‘local climate zones’ (LCZs) (Lelovics et al., 2016) based on Stewart and Oke’s (2012) classification (Šećerov et al., 2015). To the south of the city is the low-lying Fruška Gora Mountain covered by forest and separated from the urban area by Danube River; to the north, west and east of the city is arable land (Fricke et al., 2020) with small patches of deciduous forests.

Novi Sad has a C_{fb} climate (temperate climate, fully humid, warm summers, with at least four months of average T_a above 10 °C) based on the Köppen-Geiger climate classification system (Kottek et al., 2006). The mean monthly T_a is from 0.2 °C (January) to 21.9 °C (July), while the mean annual precipitation is 647.3 mm (climate normal period 1981-2010). Increasingly warm and hot weather is noticed throughout the year in Novi Sad, not just during the summer months. For example, autumn months show increasing temperatures when compared to the previous climate normal period (1961-1990) (Republic Hydrometeorological Service of Serbia, 2021). The autumn of 2019 was an extremely warm autumn in the history of meteorological measurements in Serbia with three broken records: 1) Autumn 2019 is the hottest autumn in Serbia ever; 2) October 2019 was the warmest October in the history of meteorological measurements in Serbia according to the maximum air temperature; and 3) November 2019 was the hottest November in the history of meteorological measurements in Serbia. In addition, 2019 was the hottest year in Serbia since 1951 (Republic Hydrometeorological Service of Serbia, 2019). As the microclimate measurements are most frequently performed during hot or cold seasons, there is a research gap on the microclimate conditions during transition seasons, such as autumn. That is why we have selected to perform the measurements and survey during the hottest period of an autumn day in order to fill this research gap.

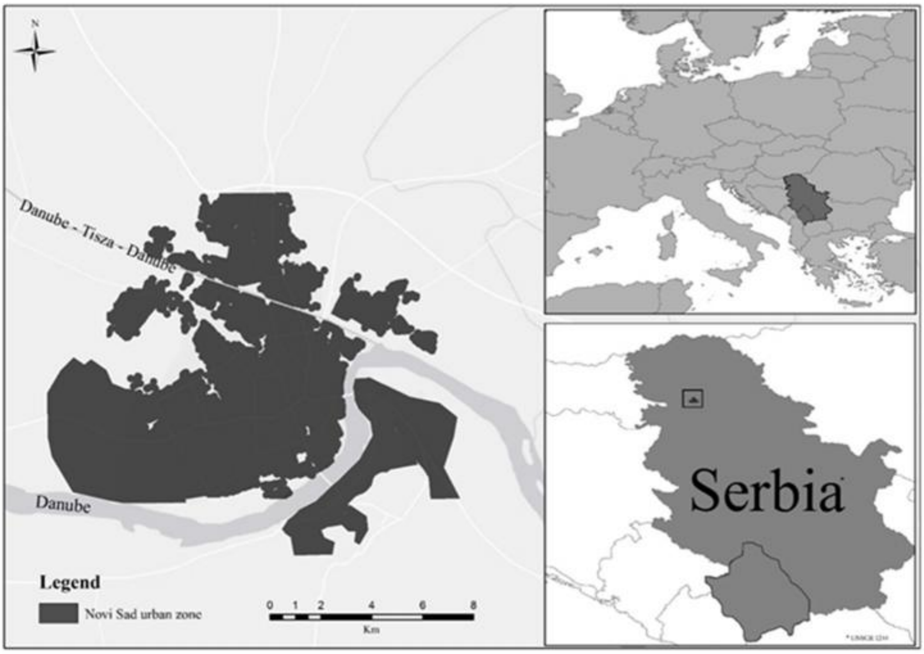


Figure 1. Novi Sad urban area (left) and its location in Serbia and Europe (right). Source: Milošević et al. (2021)

Methods

Micrometeorological measurements

Three urban sites were selected for micrometeorological measurements and OTC survey in Novi Sad: 1) Liberty Square – the main square in the city, 2) Mite Ruzica Street – small, urban street canyon in the pedestrian zone of the city centre and 3) Danube park – small urban park in the pedestrian zone near the city centre. All three sites are located in Old Town district in the city centre and are close to each other. For example, Liberty Square is about 150 m away from Mite Ruzica Street and about 450 m away from Danube Park (Figure 2). The locations are at about 80 m a.s.l.

Figure 2. The investigated area in Novi Sad with locations of micrometeorological measurements: 1) Liberty Square; 2) Mite Ruzica Street; and 3) Danube Park. Source: Google Earth

Liberty square is the main square in the City of Novi Sad. It is located in the city downtown, in the pedestrian area. The square is concrete and impervious with small tress only in the north-west direction. It is surrounded with low-rise, historical buildings with one to four stories. The highest building on the square is The Name of Mary Church. It is located in the northeast direction. Because of the lack of high buildings and trees, the Liberty square is characterized by lack of shadows and intense solar radiation. There are numerous benches on the edges of the square in all directions, except for the west direction where is located the entrance to the City Hall. This is the most frequently used square in the city. Liberty square can be seen in Figure 3.

Figure 3. Liberty square in the City of Novi Sad.

Mite Ruzica Street is a small pedestrian street in the city centre of Novi Sad. It is only 150 m away from the Liberty Square with one smaller square in between. The street is concrete and impervious with no trees, surrounded by 3-4 stories high buildings. The street is oriented in the NE-SW direction, so the street is in building shadows during most of the day and is a good representative of the urban street canyon. This street is filled with cafes with outdoor sitting area. When there are no shadows, majority of cafes have sun sails and use them to create shadows when solar radiation is intense. Photos and street view of this location can be seen in Figure 4.

Figure 4. Mite Ruzica Street in the City of Novi Sad

Danube Park is a small urban park in the pedestrian zone near the city centre. There are over 600 individual trees and 7.000 decorative plants in the park, with 250 different plant species. Deciduous trees include plane trees (some are over 100 years old), Lombardy poplar, silver linden, European nettle tree, hazelnut, birch, maple, horse-chestnut and pedunculate oak, which is under protection, while evergreen trees are black pine, Thuja, cypress, and fir. Decorative plants include white poplar, pond cypress, cherry plum, Turkish hazel, pyramidal oak and numerous shrubs. The park covers an area of 3.96 ha (9.8 acres), of which green area occupy 2.2 ha (5.4 acres). In the park is located one small and shallow pond which is mostly inhabited by ducks, turtles and a couple of swans. On the edges and inside the park are numerous benches under or near the tree canopies. This is the favourite urban park and one of the city's symbols. Photos and street view of this park can be seen in Figure 5.

Figure 5. Danube Park in the City of Novi Sad

Micrometeorological measurements were conducted at the above-mentioned three sites in the downtown area of the City of Novi Sad on 22nd October 2019 in the period 11 AM to 3 PM. These sites included square, street and park. Field work conditions were hot with maximum daily T_a of about 28 °C, no precipitation, low cloud cover, low wind speed, and intense solar radiation (more details in Section Results and Discussion - Background weather).

Kestrel 5400 Heat Stress trackers were used for micrometeorological measurements. We have measured air temperature, relative humidity, wind speed and globe temperature at 1.1 m height, which is the centre of gravity of the human body for standing subjects. All instruments comply with ISO 7726 (1998) standards for sensor measurement range and accuracy (Table 1). Measured values were averaged into 10-minute means for the statistical analysis. Furthermore, the instruments were deployed at least 15 minutes before the start of the measurement in order to allow the sensors to equilibrate to the atmospheric conditions. Pictures from the measurement campaign are provided in Figures 3-5.

Table 1. Sensor specifications and measurement height for stationary observations

Sensor	Variables	Range	Accuracy (±)	Height (m)
Kestrel 5400	Air temperature	-29 °C to 70 °C	0.5 °C	1.1
	Relative humidity	10% to 90%	2%	
	Globe temperature	-29 °C to 60 °C	1.4 °C	
	Wind speed	0.6 to 40 m/s	Larger of 3% of reading, least significant digit of 20 mft/min	

Estimation of biometeorological indices

Analysis of OTC conditions is based on the calculated values of Mean Radiant Temperature (T_{mrt}) and Physiologically Equivalent Temperature (PET). T_{mrt} was calculated based on the measured values of T_g, T_a and v as follows (Thorsson et al., 2007):

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

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

We calculated 10-minute average PET values for all sites in RayMan model (Matzarakis et al. 2007; Matzarakis et al. 2010) based on the calculated values of T_{mrt}, measured T_a, RH, v, and values for personal characteristics. The obtained values were assessed 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

Biometeorological survey

OTC surveys were performed at each site and 398 questionnaires were obtained after final quality control (about 130 questionnaires at each location). The OTC survey is based on the questionnaire designed by the Institute of Future Cities from Hong Kong (see Lau et al 2019 for more details) and was slightly edited for Novi Sad. The questionnaire consists of 19 questions related to the personal characteristics of the respondents (e.g., height, weight), their perceptions of the environment, etc. For more details, see the questionnaire design in Supplementary files.

Results and Discussion

Background weather

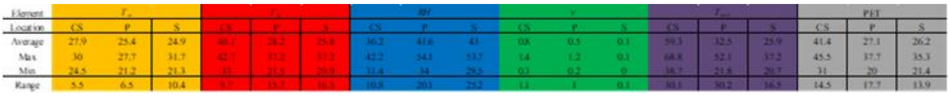
Air temperature, relative humidity, wind speed and solar radiation for 22nd October 2019 are obtained from the automatic weather station located on the roof (36 m height) of the Faculty of Sciences in Novi Sad. The weather was warm with a maximum T_a of about 28 °C and a minimum of about 14 °C. The average daily T_a was about 21 °C and the weather conditions resembled a standard warm summer day. Furthermore, it can be noticed that relative humidity was 40-50% during the daytime, and it started to increase during the night time. Wind speeds were lower (0.8 m/s on average), the maximum solar radiation reached 440 Wm^{-2}, and there was no precipitation. Accordingly, the weather was favourable for the development of micrometeorological differences inside the city.

Micrometeorological measurements

Air temperature

The highest average T_a was recorded at the square (27.9 °C), while the value in the urban park and urban street was about 25 °C (Table 3). Extreme temperatures (T_{max} and T_{min}) showed substantial differences between the urban locations. T_{max} reached the highest value in the urban street (31.7 °C), while T_{min} had the highest value at the square (24.5 °C). In the urban park, T_{max} and T_{min} were the lowest, indicating the potential of urban park to mitigate temperature extremes. The urban street had the largest temperature range (10.4 °C), thus indicating the impact of surrounding buildings on the occurrence of shaded or sunlit areas in the street, which impacted T_a.

Table 3. The 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 different urban environments of Novi Sad (Republic of Serbia) on October 22, 2019 (measurement period 11-15 CET). NOTE: Abbreviations of measurement locations are: CS – city square, P - Park, S – Street



Element	T_a			T_g			RH			v			T_{mrt}			PET		
Location	CS	P	S	CS	P	S	CS	P	S	CS	P	S	CS	P	S	CS	P	S
Average	27.9	25.4	24.9	40.1	28.2	25.8	36.2	41.6	41	0.8	0.5	0.1	59.3	32.5	25.9	41.4	27.1	26.2
Max	30	27.7	31.7	42.7	37.2	37.2	42.2	54.1	53.7	1.4	1.2	0.1	68.8	52.1	37.2	45.5	37.7	35.3
Min	24.5	21.2	21.3	33	21.5	20.9	31.4	34	29.5	0.3	0.2	0	38.7	21.8	20.7	31	20	21.4
Range	5.5	6.5	10.4	9.7	15.7	16.3	10.8	20.1	23.2	1.1	1	0.1	30.1	30.2	16.5	14.5	17.7	13.9

The most noticeable T_a difference (about 8 °C) occurred between the city square and the urban park and street during the first measuring hour (11-12 h) (Figure 6). Thereafter, T_a differences between the city square and other locations began to decrease, with urban street having a lower T_a compared to the city square and the urban park because it is located in the shadows of buildings. The substantial increase in T_a in the street happened around 2 p.m. due to street exposure to direct sunlight, leading to T_a increase inside the street compared to city square and urban park. The urban park had a lower temperature compared to the city square during the whole measurement, while compared to the urban street, it had a lower value of T_a only after 2 p.m.

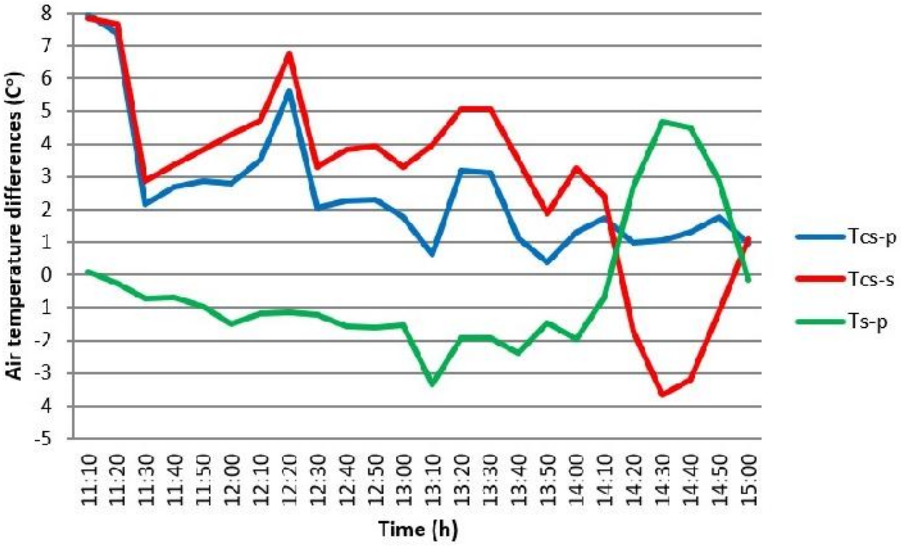


Figure 6. The temporal variation of T_a differences in Novi Sad (Republic of Serbia) on 22nd October 2019 (measurement period 11-15h CET). NOTE: T_{cs-p} represents the difference in air temperature between the city square and the urban park; T_{cs-s} represents the difference in air temperature between the city square and the urban street; and T_{s-p} represents the difference in air temperature between the urban street and the urban park.

Our results are generally in line with other intra-urban micrometeorological studies. For example, in Beijing (China) the difference in T_a between the park (vegetation) and the street (buildings) was about 1.24 °C during daytime (Kuang, 2020), while in Novi Sad the average T_a difference between these two locations was less severe (only about 0.4 °C). These differences may vary because of the measurement period, urban form or even the human activities during the day. Another study based on intra-urban analysis in Venice have shown that the higher values of T_a were observed in areas that have large amounts of impenetrable surfaces where there are no trees or tall building that can provide shadows (Peron et al., 2015). Urban areas that can provide shadows mostly have lower temperature during daytime, i.e., urban park in Ghent (Belgium) where the differences between this area and downtown are about 1 °C. Thus, the highest T_a was recorded in downtown, where it is prone in creating heat stress. Unlike the centre, the streets of Ghent have a tendency in creating cold stress, which is a consequence of lower temperatures during daytime (Top et al., 2020) because of the shadowing effect. The study in Banja Luka has shown that urban area without shadowing effects (buildings, trees) such as downtown has a higher temperature than, for example, urban park of about 1.6 °C (Milošević et al., 2022a). The variation between the urban parks and the streets may be different during daytime and night time. In Tokyo, the difference in T_a between squares and parks until noon was about 1.5 °C (Ichinose et al., 1999), while in Novi Sad the average temperature difference between these locations was about 2.4 °C.

Relative humidity

Similar values of RH are noticed in urban park and urban street (about 41-43%). Unlike these locations, the lowest average RH was registered at the square (36.2%). Extreme values, such as RH_{max} and RH_{min}, were registered in the urban park and street canyon, respectively.

Following the results, it can be noticed that in the first measuring hour (11-12h) value of RH has been lower about 15-20% at the city square than in the urban street or park (Figure 7). Furthermore, RH in the urban street started to decrease at 2 p.m., which is the consequence of rising T_a in the street. As a result, the city square had higher value of RH than the urban street during the following hour. After that, RH in the urban street started to increase and once more had the higher value of RH than the city square. Moreover, the urban street had a slightly higher values of RH in relation to the park in the first measurement hours, whilst in the last measurement hours are noticed higher values of RH in the urban park than in the urban street.

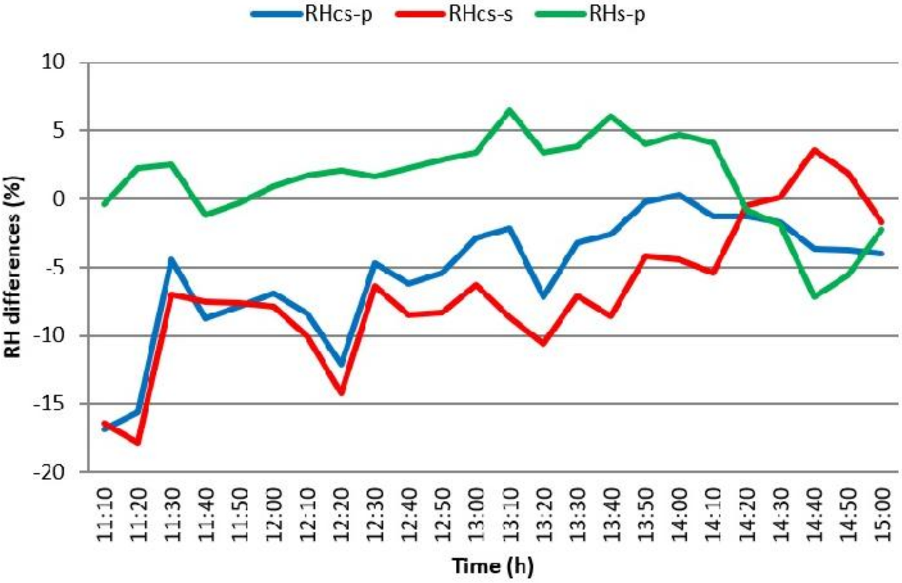


Figure 7. The temporal variation of RH differences in Novi Sad (Republic of Serbia) on 22nd October 2019 (measurement period 11-15h CET). NOTE: RH_{cs-p} represents the difference in RH between the city square and the urban park; RH_{cs-s} represents the difference in RH between the city square and the urban street; and RH_{s-p} represents the difference in RH between the urban street and the urban park.

Relative humidity shows variation during the day between different urban locations. For example, the average value of RH during October in Beijing (China) in the park is about 54% in the afternoon, while at the city square, RH was lower (43%). Thus, the difference in RH between locations was about 11% during the daytime, but as the day went on, the differences became more pronounced (20%) (Kuang, 2020). A similar observation can be seen in the city of Novi Sad. The average RH during the day has a higher value in the urban park than at the city square. However, it is slightly lower than the RH in the urban street. Previous research in Banja Luka leads to similar results, where the lowest value of the RH is also observed at the city square (35.7%), while in the urban park the value is slightly higher (39%). Additionally, the biggest differences of about 10-15% occurred between the city square and the urban park and the river in Banja Luka in the first measuring hours

(Milošević et al., 2022a), while in Novi Sad the differences between city square and other urban areas were more than 16-17%. Furthermore, study in Ghent, Belgium, shows that during daytime, values of RH were mostly higher in areas with larger amount of vegetation of about 7.6% compared to the city square (Top et al. 2020).

Wind speed

Average wind speed (v) in these urban locations was below 1 m s^{-1}. During the day, the weather was calm, warm and sunny, with no substantial variations in v throughout the day of measurement. The lowest wind speed was observed in the street, while the highest was observed at the city square (Table 3). The measurement results show that the maximum v was recorded at the city square (1.4 m/s^{-1}) at 14:30 h. The urban street had the lowest v values, where the average wind speed was about 0.1 m/s^{-1}. In the street canyon, v can be extremely low due to urban geometry and configuration. The combination of the low wind speed and the high temperature in the city leads to a dissatisfying cooling effect and a lack of airflow in the urban canyon. Deficiency of wind or even low wind speed can result in creating an outdoor thermal stress (Dimoudi et al., 2013).

Globe temperature

Globe temperature (T_g) had the highest values, on average, at the city square (about 40 ^oC), while the average values in the urban park and street were about 26–28 ^oC (Table 3) due to shadowing effects of trees and buildings, respectively. It can be noticed that the average T_g was lower in urban street than in the urban park, which suggests that building shade was more successful in lowering T_g compared to tree shade in an urban park. T_g maximum and minimum values were also the highest at the city square. Nevertheless, the urban street had the highest T_g range of about 16.3 ^oC due to shifting between sunlit and shaded areas in the street.

The measurement results obtained in the city of Novi Sad show that the highest T_g differences (about 15-19 ^oC) were noticed in the first measurement hours between the city square and the urban park and street (Figure 8). After 2 p.m., T_g differences started to decrease and at 3 p.m. it reached the value of about 4-6 ^oC between the urban areas. According to the results, it can be noticed that urban square had higher T_g compared to other locations throughout the measurement period. In addition, urban street had lower T_g compared to urban park until about 2 p.m. due to shadowing effects of buildings. After 2 p.m., the street was sunlit and T_g values were higher compared to urban park. Likewise, a similar study of the city of Banja Luka has shown that the T_g differences were the highest between downtown and other urban locations in the period from 10 a.m. to 2. p.m. (about of 14-15 ^oC). Furthermore, T_g on the riverside started to increase and became warmer than the urban park or downtown, this is probably due to the irradiation later in the afternoon (Milošević et al., 2022).

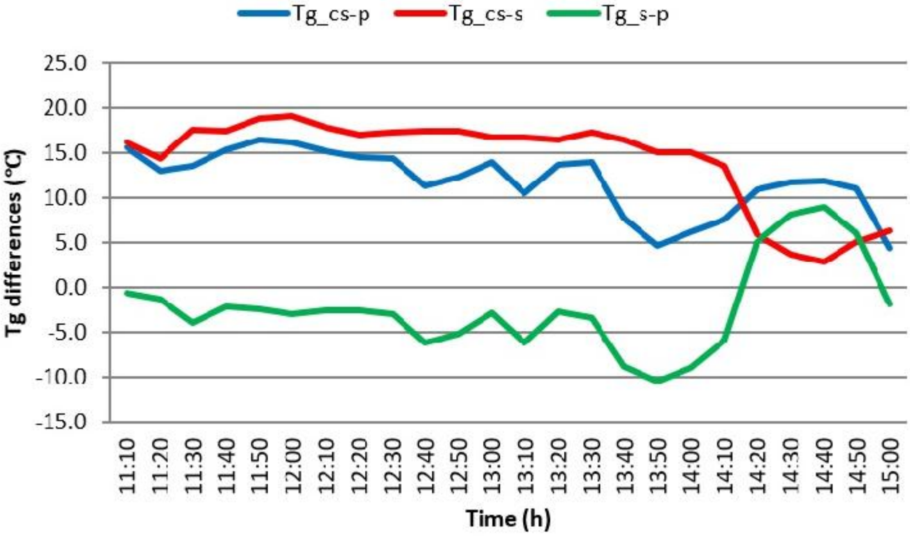


Figure 8. The temporal variation of T_g in Novi Sad (Republic of Serbia) on 22nd October 2019 (measurement period 11-15h CET). NOTE: T_g_cs-p represents the difference in globe temperature between the city square and the urban park; T_g_cs-s represents the difference in globe temperature between the city square and the urban street; T_g_s-p represents the difference in globe temperature between the urban street and the urban park.

Calculated outdoor thermal comfort conditions

Mean Radiant Temperature

The highest average T_{mrt} of 59.3 °C was noticed at the city square, followed by urban park (32.5 °C) and urban street (25.9 °C) (Table 3). In addition, the city square had the highest extreme values of T_{mrt}. The urban street had lowest extreme values of T_{mrt} due to the shadowing effects of buildings which was present most of the time.

Temporal variation of 10-minute T_{mrt} values shows that the city square has substantially higher T_{mrt} values compared to the urban street and the urban park throughout the measurement period. Between 11 a.m. and 2 p.m., the city square had about 20-40 °C higher T_{mrt} compared to the urban park and the urban street (Figure 9). Urban park had higher T_{mrt} compared to urban canyon from the morning until 2 p.m. as this is the period when urban canyon is in the shadows of the buildings. After 2 p.m., the street canyon is sunlit and registers higher T_{mrt} compared to the urban park.

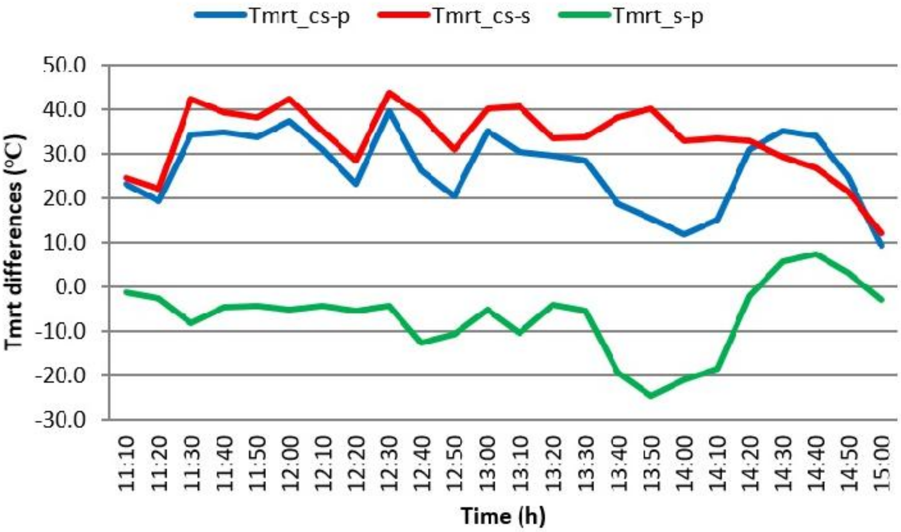


Figure 9. The temporal variation of T_{mrt} in Novi Sad (Republic of Serbia) on 22nd October 2019 (measurement period 11-15h CET). NOTE: T_{mrt}_cs-p represents the difference in T_{mrt} between the city square and the urban park; T_{mrt}_cs-s represents the difference in T_{mrt} between the city square and the urban street; T_{mrt}_s-p represents the difference in T_{mrt} between the urban street and the urban park.

During warm and clear sky days, radiation is governing OTC and its effect is accounted for by T_{mrt} (Gál and Kántor, 2020). Previous studies from Ghent, Belgium (Top et al., 2020), Szeged, Hungary (Kántor et al., 2018), Banja Luka, Bosnia and Herzegovina (Milošević et al., 2022a), Novi Sad, Serbia (Milošević et al., 2022b), and Tempe, Arizona, USA (Middel and Krayenhoff, 2019), showed that T_{mrt} is driven by exposure to solar and longwave radiation, with higher values registered at more urbanized and exposed locations. Another study from Middel et al., 2021 in the City of Tempe (USA) showed that shade from the urban form reduced T_{mrt} most effectively, followed by trees, which is also proved in our study.

PET

The highest average PET values are registered at the city square (41.4 °C), followed by substantially lower average PET registered in urban park (27.1 °C) and urban street canyon (26.2 °C) (Table 3). This shows that, on average, city square was the most uncomfortable study area due to extreme heat stress, while urban park and urban canyon were under slight heat stress (see Table 2). Temporal variation of PET values confirms this, as it shows that square had 15-20 °C higher PET values compared to other locations during the majority of the measurement period. Urban park and street canyon had similar values during the majority of the time due to shadowing by trees (in the park) or buildings (in the street), except in the afternoon when urban street was sunlit (Figure 10).

Previous studies showed that heat stress is more extreme in more urbanized locations than in more natural urban areas, such as suburbs, urban parks, river quays (Kovács and Németh, 2012; Muller et al. 2014; Milošević et al., 2016; Milošević et al., 2022a). For example, the urban park in Ghent, Belgium, was the most comfortable area as it was able to better mitigate heat stress compared to urbanized locations (Top et al., 2020). The substantial cooling related to high vegetation (trees) was also noticed in Czech cities by Lehnert et al. (2021), while Middel et al. (2021) showed that shadows from buildings were the most effective in mitigating the heat, which is confirmed also in this study.

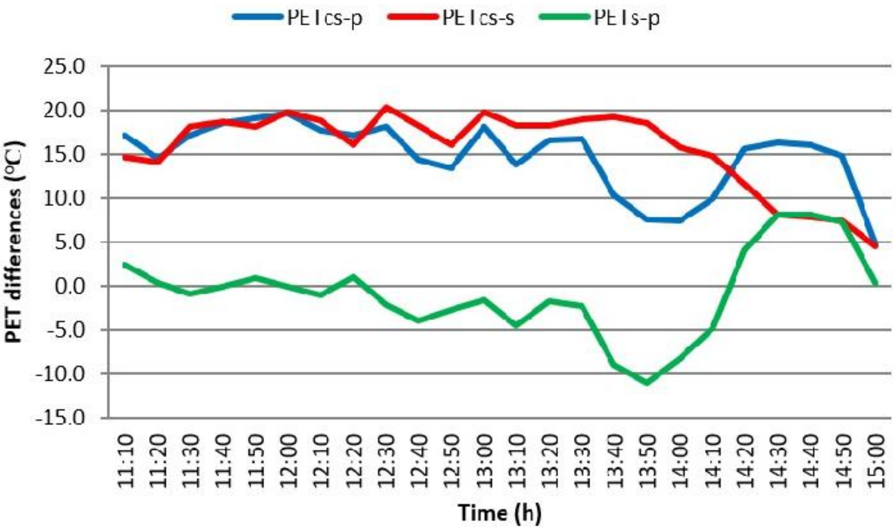


Figure 10. The temporal variation of PET in Novi Sad (Republic of Serbia) on 22nd October 2019 (measurement period 11-15h CET). NOTE: PET_cs-p represents the difference in PET between the city square and the urban park; PET_cs-s represents the difference in PET between the city square and the urban street; PET_s-p represents the difference in PET between the urban street and the urban park.

Frequency analysis (%) of different grades of physiological stress (Table 2) at the city square, urban park and urban street canyon is shown in Figure 11. The analysis showed that during about 70% of the time, urban dwellers experience extreme heat stress at the city square. Contrary to that, no extreme heat stress is noticed in urban park and urban street canyon. These locations are characterized with slight heat stress and comfortable conditions during the majority of the time, which makes them more suitable locations for outdoor activities of urban population during autumn warm days. It is also noticed that urban street canyon has slightly better OTC conditions due to urban form, i.e., it is in the shadows during the majority of the measurement period.

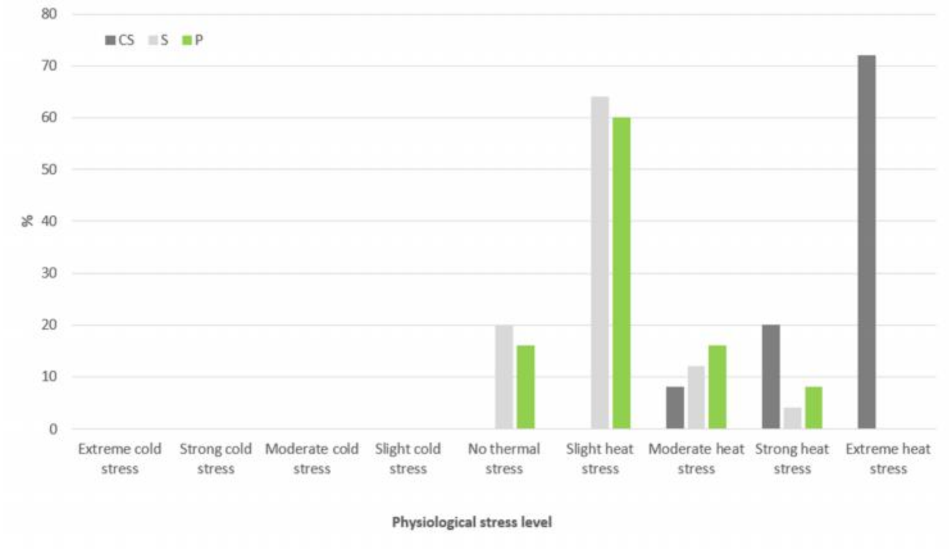


Figure 11. Frequency analysis (%) of different grades of physiological stress (based on PET values) at measurement locations in Novi Sad on 22nd October 2019 (measurement period 11-15h CET). CS - city square, S – urban street canyon, P – urban park

Subjective perceptions of microclimatic conditions

Subjective perception of microclimatic conditions by pedestrians was obtained using the questionnaire. The distribution of the subjective perception votes of temperature (TSV), humidity (HSV), wind speed (WSV), and solar radiation (SSV) is shown in Figure 12.

The results showed that the majority of TSVs was in “warm” category at the square and in urban park, while it was “neutral” in the urban street canyon. “Very hot” category was most frequent at the square, followed by street, while it was the least frequent in urban park. For the HSV categories, the most frequent was “neutral” at all locations with no substantial differences noticed between them. WSV categories showed that pedestrians most often feel “neutral” regarding wind at the square and in the street, while they felt “very stagnant” wind in the urban park. Results for the SSV categories showed the most diverse conditions felt by pedestrians, i.e., they felt “intense” solar radiation at the square, while it was “neutral” in the urban park and “weak” in the urban street.

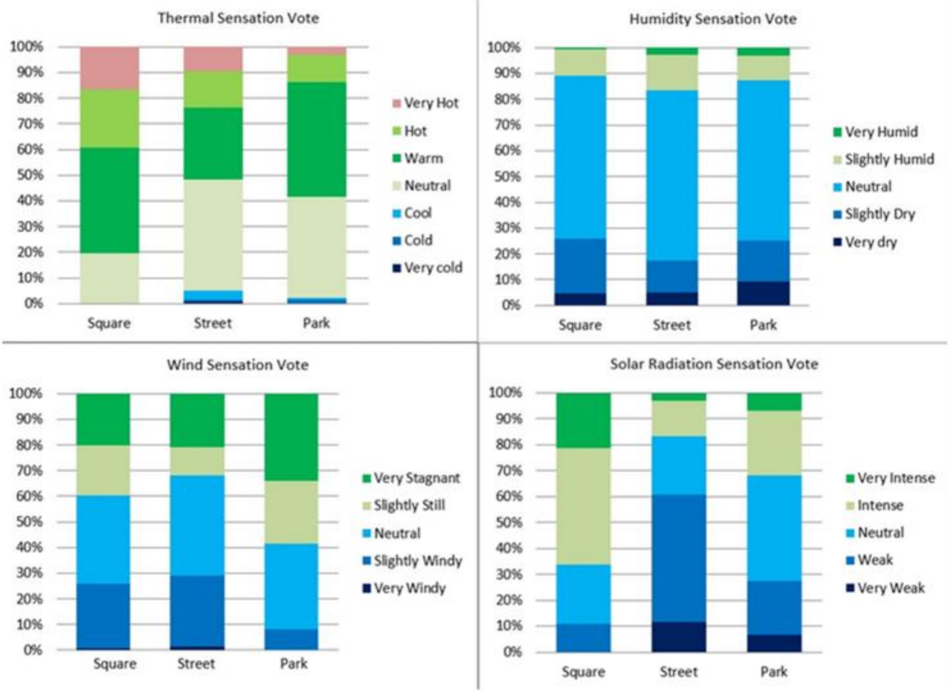


Figure 12. Proportion of TSVs, HSVs, WSVs and SSVs for measurement locations in the present study

Conclusion

Micrometeorological measurement and biometeorological survey were conducted in different urban settings (square, street, park) of Novi Sad. The research was implemented during a calm and warm day in October. Different values of micrometeorological elements occur between all three urban areas. The biggest differences in the average air temperature (T_a) were noticed between the city square on one side and the street and park on the other side. The reason for this may be the lack of vegetation at the city square, paving material at the square, while the street and the park were in the shade for most of the day. The lowest temperatures were recorded in the street, except for the period around 2 p.m. when the street was warmer than other measurement areas of the city due to direct sunlight. During the measurement in the period of 11 a.m. to 3 p.m., variations and changes in the values of the analysed climate elements were observed. The city square had the highest values of air temperature and solar radiation during the measurements, but also the highest wind speed compared to other areas, but the lowest value of relative humidity, thus the square was the place where thermal heat occurs most of the day. The biometeorological survey also revealed that urban dwellers can “feel” the difference in urban microclimate conditions at different urban locations, and it is recommended to continue with the usage of the biometeorological questionnaire in further research.

Acknowledgement: Research Funded by the Global Preparedness Centre of the American Red Cross. The research was also supported by a project (number 142-451-2557/2021-01) financed by the Autonomous Province of Vojvodina (regional government).

Conflicts of Interest: The authors declare no conflict of interest.

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