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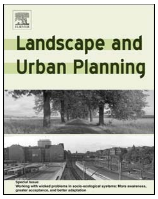

Research Paper

Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary

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ABSTRACT

Shading is shown to be one of the most effective strategies to mitigate urban heat stress, especially on a small scale. This paper presents an empirical study investigating the effectiveness of different means of shading—by sun sails and trees—to improve the local thermal environment during the summer. Three different urban settings were investigated through detailed human-biometeorological measurements in the Hungarian city of Pécs. Our study employed the accurate six-directional radiation measurement technique, and calculated Physiological Equivalent Temperature (*PET*) from the obtained data to assess outdoor thermal conditions. Our results indicate that in open urban squares trees can mitigate heat stress more effectively than low-hanging sun sails, installed right above the head of pedestrians. In the period of 9:00–16:00, the average *PET* reduction by trees and low sun sails was 9.0 °C and 5.8 °C, respectively. Sun sails, installed at higher elevation to shade an entire street canyon, and mature trees with dense canopy had more pronounced heat stress reduction ability, and were able to reduce the local *PET* by over 10 °C. Our study demonstrates the importance of detailed small-scale field measurements, the outcomes of which can be incorporated into climate-responsive urban design strategies with ease.

1. Introduction

Climate change is expected to bring rising temperatures and to increase the frequency and severity of extreme heat events in Central-Europe, and thus in Hungary (Kovats, Valentini, & Bouwer, 2014; Sábitz et al., 2015). Combined with the peculiar climate of cities—characterized by increased temperature and reduced ventilation—summertime heat waves are expected to have greater impacts in urban environments (EEA European Environment Agency, 2016). Taking into account that three quarter (73%) of the European population already lives in urban areas, and by 2050 this proportion is expected to rise over 80% (UN United Nations, Department of Economic and Social Affairs, Population Division, 2014), mitigating the impact of extreme heat events is one of the most important issues in urban planning. Without adaptation to heat waves, people will experience both deteriorating thermal comfort and decreasing work efficiency due to the increased heat stress. Additionally, heat stress intensification is expected to increase the mortality rates of urban dwellers—especially among the vulnerable groups, like infants, elderly people and those with cardio-vascular diseases (Ishigami et al., 2008).

Researches in the field of urban human-biometeorology demonstrated that radiation heat load, quantified as mean radiant temperature (T_{mrt}), is the main source of outdoor daytime heat stress in the summer (e.g. Ali-Toudert, Djenane, Bensalem, & Mayer, 2005; Mayer, Holst, Dostal, Imbery, & Schindler, 2008). Therefore, the prerequisite for heat stress mitigation in urban spaces is the reduction of T_{mrt}, which most effectively can be achieved by shading (Ali-Toudert & Mayer, 2006, 2007a, 2007b). Field measurements and simulation studies conducted in various climate zones (continental, arid, tropical) have shown that greater tree canopy coverage or higher street aspect ratio (that is, shading by buildings) are generally the most effective design strategies against urban heat stress (Emmanuel, Rosenlund, & Johansson, 2007; Holst & Mayer, 2011; Shashua-Bar, Pearlmutter, & Erell, 2011; Shashua-Bar et al., 2012). Studies from cities with temperate climate commonly found that shading delivers the greatest human-biometeorological improvement (Lee, Holst, & Mayer, 2013; Gál, 2015; Lee et al., 2014, 2016; O'Malley, Piroozfar, Farr, & Pomponi, 2015; Saneinejad, Moonen, & Carmeliet, 2014).

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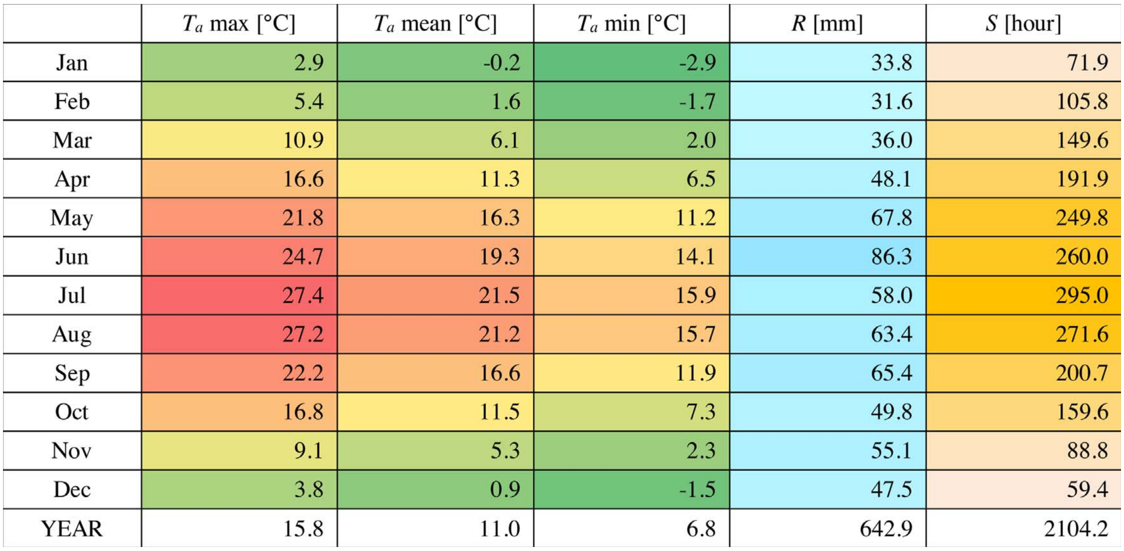
Table 1
Climate data of Pécs, Hungary (1981–2010, Pécs–Pogány Airport; data Source: HMS).



	T_a max [°C]	T_a mean [°C]	T_a min [°C]	R [mm]	S [hour]
Jan	2.9	-0.2	-2.9	33.8	71.9
Feb	5.4	1.6	-1.7	31.6	105.8
Mar	10.9	6.1	2.0	36.0	149.6
Apr	16.6	11.3	6.5	48.1	191.9
May	21.8	16.3	11.2	67.8	249.8
Jun	24.7	19.3	14.1	86.3	260.0
Jul	27.4	21.5	15.9	58.0	295.0
Aug	27.2	21.2	15.7	63.4	271.6
Sep	22.2	16.6	11.9	65.4	200.7
Oct	16.8	11.5	7.3	49.8	159.6
Nov	9.1	5.3	2.3	55.1	88.8
Dec	3.8	0.9	-1.5	47.5	59.4
YEAR	15.8	11.0	6.8	642.9	2104.2

Shading can be achieved by way of buildings (Ali-Toudert & Mayer, 2006, 2007a, 2007b; Ali-Toudert et al., 2005; Emmanuel et al., 2007; Holst & Mayer, 2011; Johansson, 2006; Mayer et al., 2008), by trees (Andrade & Vieira, 2007; Abreu-Harbich, Labaki, & Matzarakis, 2015; Kántor, Kovács, & Takács, 2016; Konarska, Lindberg, Larsson, Thorsson, & Holmer, 2014; Lee et al., 2013, 2016; Park, Hagishima, Tanimoto, & Narita, 2012; Shahidan, Shariff, Jones, Salleh, & Abdullah, 2010; Takács, Kiss et al., 2016; Takács, Kovács, Kiss, Gulyás, & Kántor, 2016), or by shading devices (Golden, Carlson, Kaloush, & Phelan, 2007; Middel, Selover, Hagen, & Chhetri, 2016; Swaid, 1992; Shashua-Bar et al., 2011; Saneinejad et al., 2014; Watanabe, Nagano, Ishii, & Horikoshi, 2014). Compared to the magnitude of heat stress reduction delivered by shading, heat stress reduction differences owing to the means of shading are rather small (Middel et al., 2016). In this regard, a handful of studies comparing the effect of different means of shading reported slightly greater increase in human thermal comfort conditions owing to tree-shading than either to buildings (Lee et al., 2013) or to shading devices (Shashua-Bar et al., 2011). Furthermore, the experimental study of Watanabe et al. (2014) found that buildings reduce the thermal heat stress slightly more than shading devices. In contrast, Golden et al. (2007) found that photovoltaic canopies accomplish greater surface temperature reductions (measured on the underlying pavements) than trees.

Owing to the increasing availability of numerical simulation models, a growing number of studies have assessed the human-biometeorological impact of shading by means of both trees and buildings over the past decade (Égerházi, Kovács, & Unger, 2013; Égerházi, Kántor, & Gál, 2013; Fröhlich & Matzarakis, 2013; Huttner, Bruse, & Dostal, 2008; Konarska et al., 2014; Lindberg, Holmer, & Thorsson, 2008; Lindberg & Grimmond, 2011; Lau, Lindberg, Rayner, & Thorsson, 2015; Lee, Mayer, & Chen, 2016; Thom, Coutts, Broadbent, & Tapper, 2016; Zölch, Maderspacher, Wamsler, & Pauleit, 2016). In contrast, very few studies evaluated the influence of shading devices (Saneinejad et al., 2014; Swaid, 1992), despite commonly being considered as sun-protection alternatives to the former two. Among the field experiments evaluating the human-biometeorological impact of trees and urban geometry, only a limited number (Holst & Mayer, 2011; Kántor et al., 2016; Lee et al., 2013, 2014; Mayer et al., 2008) utilized the six-directional radiation measurement technique, which is regarded as the most accurate radiation measurement method for outdoor human-biometeorological studies (Höppe, 1992; Kántor & Unger,2011; Thorsson, Lindberg, & Holmer, 2007). From the breath of citation above and from the quality of research some numerical simulation study conveys (many simulation studies lack validation), it is evident that there is a research gap that calls for more empirical human-biometeorological studies to assess the effect of shading devices on heat stress and thermal comfort conditions. Such research will not only deliver high-quality field measurement data, but will have the ability to compliment and correct the findings of numerical simulation studies on the subject.

The aim of this study is to assess the human-biometeorological impact of shading in a Central-European city during summer daytime and to compare the effectiveness of different types of shading (trees and sun sails) in reducing heat stress in different urban settings (square and street). In order to achieve this, human-biometeorological field measurements were conducted at three locations in Pécs, Hungary. During these measurements, human-biometeorological parameters influencing the energy balance of the human body were recorded (that is radiant flux densities, air temperature, wind speed and humidity). The Physiological Equivalent Temperature (*PET*; Mayer & Höppe, 1987) was used to assess the level of heat stress pedestrians experience. Differences between different urban settings were discussed, and the cooling effect of different means of shading was analyzed.

2. Methods

2.1. Study areas

The city of Pécs is located in the Carpathian Basin in the south-west part of Hungary. It is one of the most important educational, cultural and art center of Hungary, and functions as the administrative and economic center of Baranya County. The elevation of the city varies from 120 m up to 250 m. The northern part of Pécs is bordered by the slopes of the 400–600 m high Mecsek Hills, while the southern end of the city is rather plain. Pécs has rich historical heritage and the country's first university was also founded here. In 2010, the city received the 'European Capital of Culture' title. The honorary title brought extensive socio-economic development to the city, the part of which the most frequented walking streets and urban squares were renewed. The official weather station of Pécs, run by the Hungarian Meteorological Service (HMS), is located 10 km south from the city center at the Pécs-Pogány Airport (46°00′N, 18°14′E, 200 m above sea level). It records long-term weather data (Table 1). The climate of the area is characterized with four distinct seasons and with the average annual air temperature (T_a) of 11 °C. The precipitation (R) is low and evenly distributed over the year. Monthly sunshine duration (S) is less than 100 h

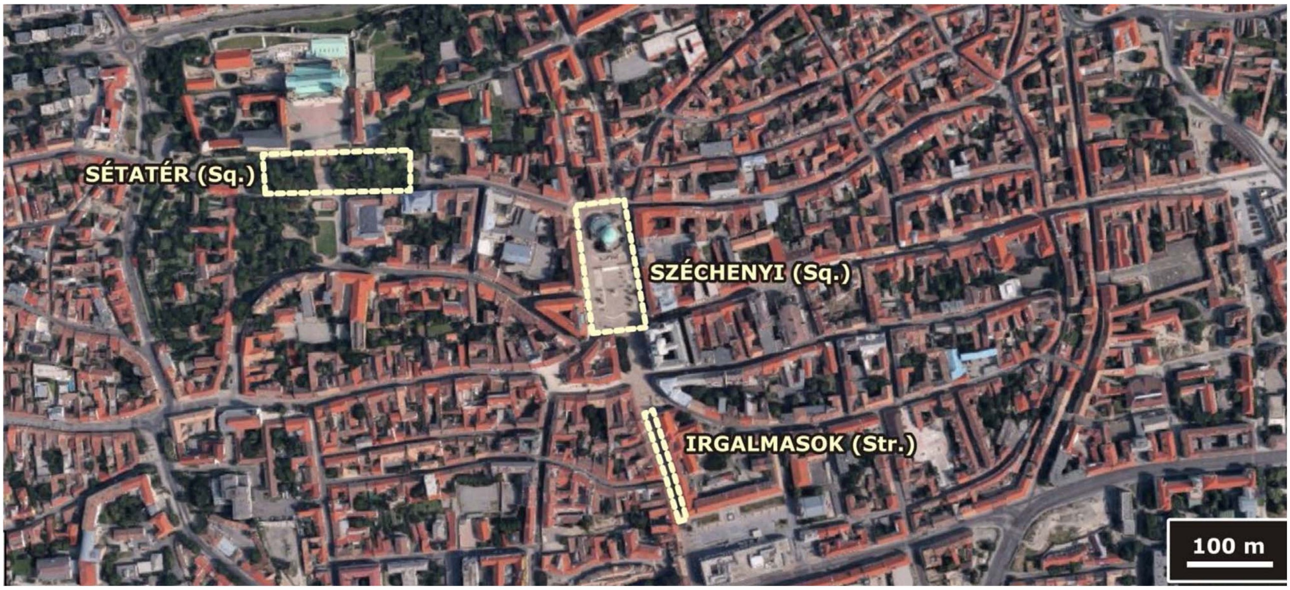


Fig. 1. Study areas in the historical downtown of Pécs, Hungary.

from November to January, while it is over 200 h from May to September. The lowest mean T_a occurs in January (-0.2 °C) and the highest in the mid and late summer months. In July and August, the minimum T_a is generally around 16 °C, the mean T_a is above 21 °C, and the maximum T_a is above 27 °C.

Three sites, located in different urban settings of downtown Pécs, were selected for this study, namely: Széchenyi Square, Irgalmasok Street, and Sétatér Square. The first two sites sit amidst the revitalized parts of the city, while the latter is located near the renewed Cella Septichora Visitor Center, which attracts large number of tourists every year. All the three study sites are within the historical downtown of the city (Fig. 1) and are part of the designated pedestrian zone. They play an important role in the daily life of local residents. Despite being hot spots for tourism, the activity of visitors is strongly influenced by the thermal conditions at these places.

Széchenyi Sq. is the main public square of Pécs with well-known historical and architectural attractions. The main rectangular part of the square is 50 m wide and 150 m long with a slight southward slope. It is surrounded by 3–4 storey buildings typical for dense Central-European city centers. As part of its full renovation, the square received a smooth, light-colored granite pavement. The major part of the area is exposed to the sun with only a handful of small, ornamental honey locust (*Gleditsia triacanthos*) trees in the middle and a couple of greater silver lindens (*Tilia tomentosa*) along the eastern and western sides. Beside these trees, only two small clusters of sun sails offer protection against the sun. They are installed over a few benches at a relatively low elevation of about 2 m.

The second study area, Irgalmasok Str. is a nearly N-S oriented street canyon aligned by 2–3 storey buildings with small shops, bakeries, restaurants and a small hospital. Running directly into Széchenyi Sq., this street is one of the busiest pedestrian streets of Pécs. It has the same ground cover as Széchenyi Sq. The northern segment of the street lacks shading from trees or devices, while the southern part is more-or-less shaded by sun sails, fixed at about 7 m (at the height of the second storey). The distribution of the shading devices is uneven: some areas are more or less open to the sky, while others are fully obstructed.

The third study area is the E-W oriented Sétatér Sq. With UNESCO world heritage sites in the neighborhood, such as the Cella Septichora and the Early Christian Necropolis, it is one of Pécs's hot spots for tourism. It has a tree-lined stone walkway comprising of mature horse chestnut trees (*Aesculus hippocastanum*) and some additional shading trees, such as linden (*Tilia spp*), in their vicinity. The selected site is approximately 170 m × 20 m in size. The square has abundant shading and is the venue of several cultural and gastronomic events like the Sétatér Fest and the Pécs Days, attracting many local and foreign visitors.

2.2. On-site measurements

Human-biometeorological measurements were conducted at the three selected sites on three late-summer days (on August 9th, 14th and September 3rd, 2016). Measurements started at 9:00 and lasted till 16:00 or 17:00. The three sites experience shading by different means and are located within different urban setting. In order to study the effectiveness of different types of shading in mitigating heat stress, multiple observation points were selected at these sites.

At Széchenyi Sq., three survey points were selected within 20 m from each other to compare the effectiveness of shading by trees with sparse canopy and small leaves, and by sun sails located right above the head of pedestrians (as shown in Fig. 2):

- P1: in the middle of the square, without shading, Sky View Factor (*SVF*): 0.834;
- P2: under one of the free-standing honey locust (*Gleditsia triacanthos*) trees, *SVF*: 0.188;
- P3: under one of the artificial sun shades, *SVF*: 0.068.

At Irgalmasok Str., two survey points were selected approximately 40 m from each other to investigate the shading effect of sun sails installed over an entire street (as illustrated in Fig. 3):

- P1: northern end of the street, without sun sails, *SVF*: 0.416;
- P2: southern end of the street, sheltered by sun sails, *SVF*: 0.014.

At Sétatér Sq., two survey points were selected within 20 m distance from each other to investigate the shading efficiency of a large group of mature trees with large leaves and dense canopy (as shown in Fig. 4):

- P1: located in the center of the square, which was exposed to the sun during the mid-hours of the day, *SVF*: 0.600;
- P2: located under the canopy of mature horse chestnut trees (*Aesculus hippocastanum*), *SVF*: 0.015.

Two tailor-made mobile stations were used to monitor human-biometeorological parameters affecting the energy balance of the human body, as shown in Fig. 5. Both stations were equipped with Vaisala WXT

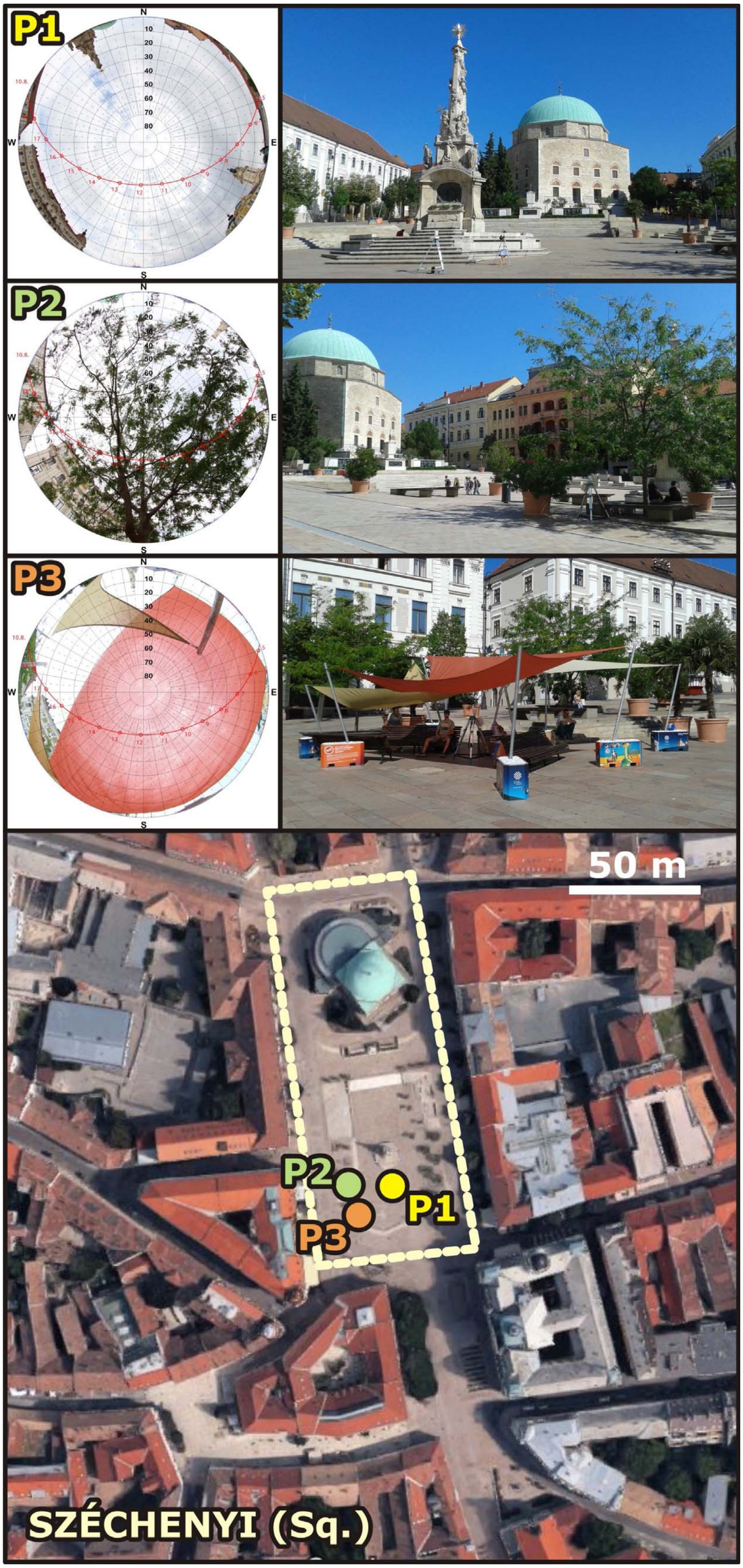


Fig. 2. Survey points at Széchenyi Square.

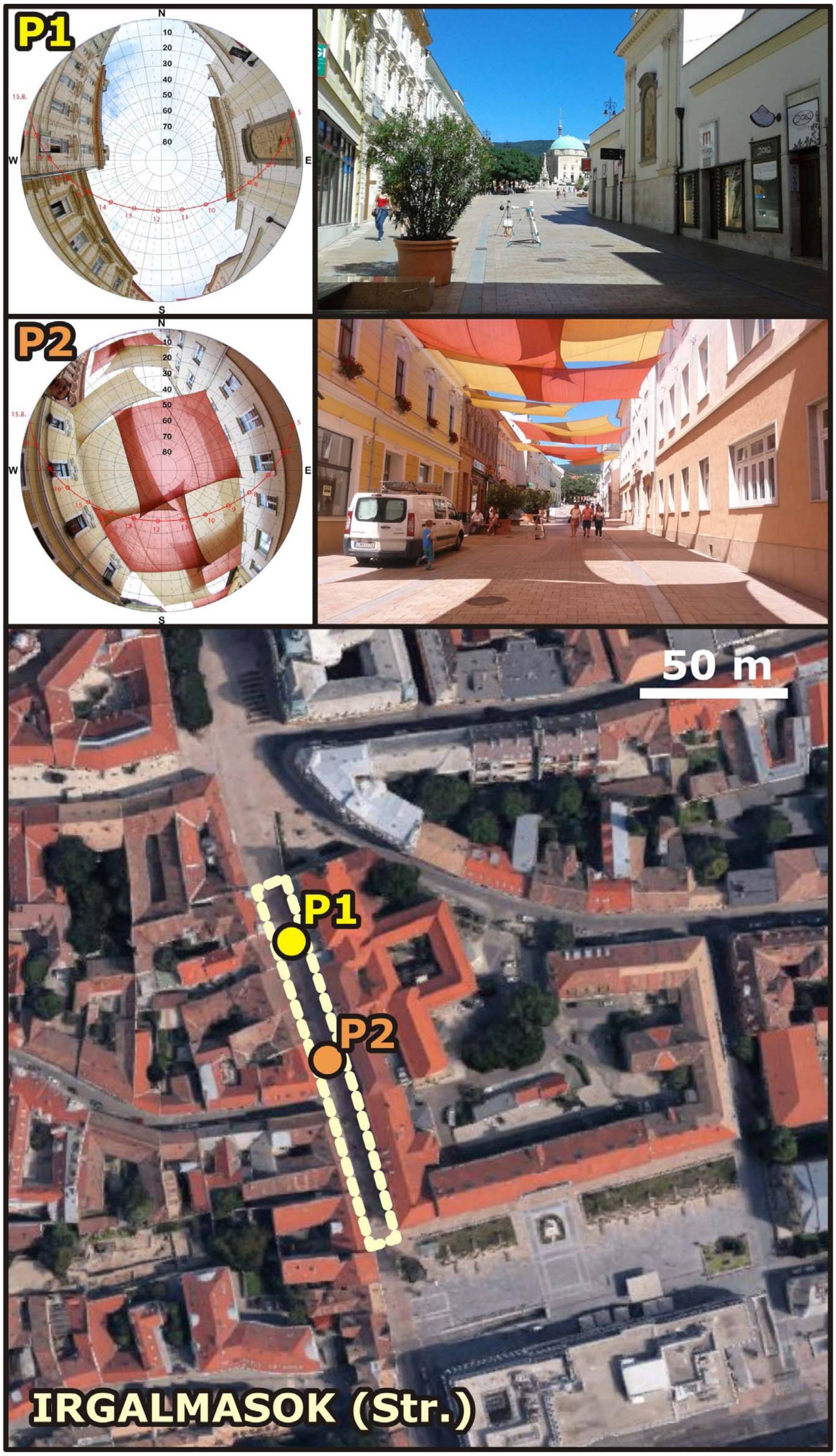


Fig. 3. Survey points at Irgalmasok Street.

520 weather transmitter to record air temperature (T_a [°C]), relative humidity (*RH* [%]) and wind speed (v [m/s]). They were also equipped with a rotatable Kipp & Zonen net radiometer (consisting of two pyranometers and two pyrgeometers) to monitor the 3D radiant environment—i.e. to record short-wave and long-wave radiation flux densities from six perpendicular directions (K_i, L_i [W/m^2], i: up, down, east, west, south, north). One of the stations was equipped with CNR 1, and the other with CNR 4 type radiometer.

Using telescopic tripods, the instruments were mounted 1.1 m above ground level, corresponding to the recommended elevation for human-biometeorological measurements (Mayer, 1993). The stations can be quickly installed and easily moved around, which is advantageous during outdoor mobile measurements. Such was the case at Széchenyi Sq. measurements, where one station remained at the middle location (P1) for the entire measurement period, while the other one was relocated at 15-min intervals between P2 and P3 locations. In the case of the other two measurement sites, the stations remained at the selected locations and recorded the human-biometeorological conditions of the ‘open’ (P1) and the ‘shaded’ (P2) locations simultaneously.

As mentioned above, the net radiometers are connected to the main

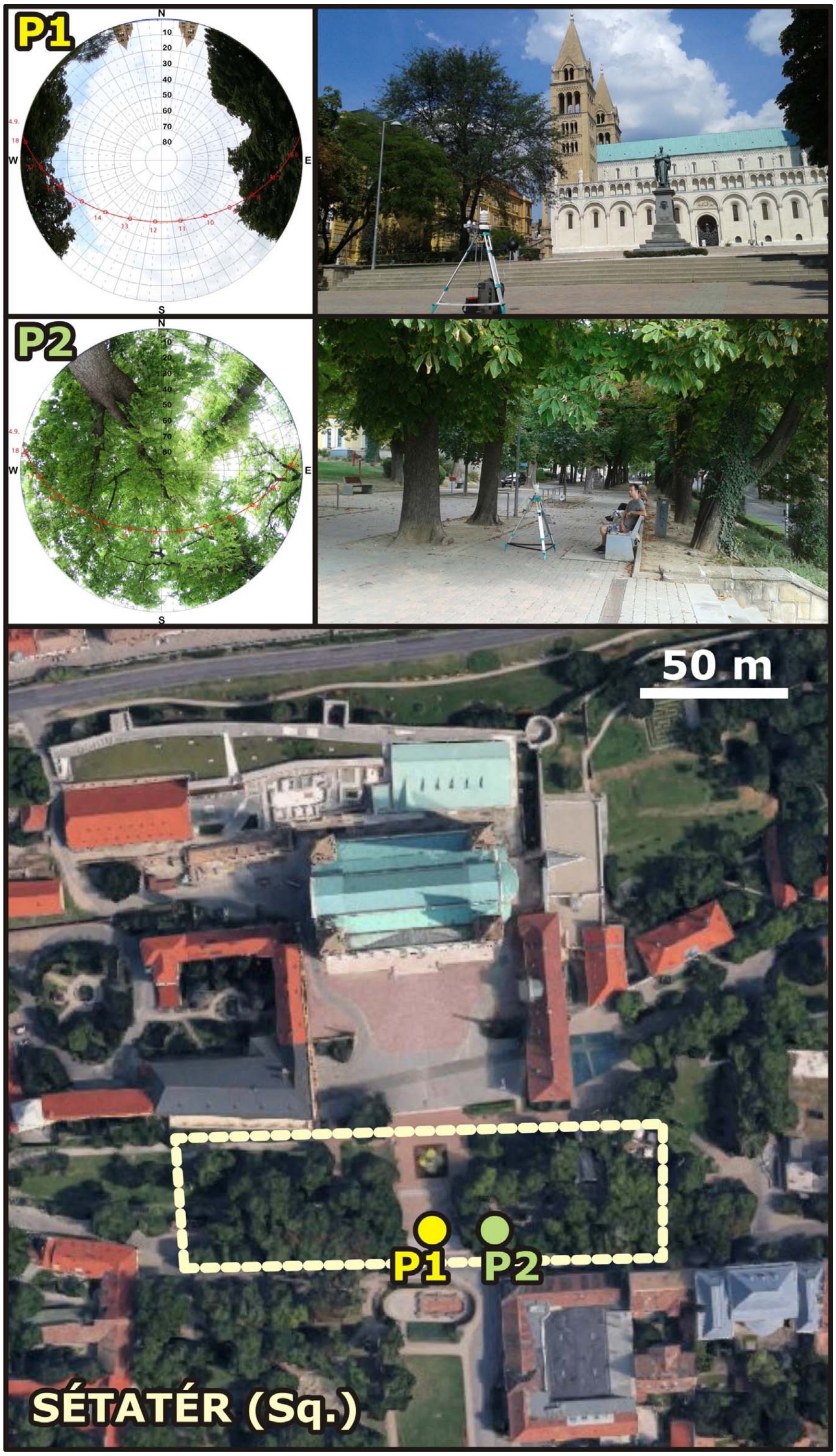


Fig. 4. Survey points at Sétatér Square.

Fig. 5. Human-biometeorological stations equipped with Vaisala WXT520 weather transmitters and Kipp & Zonen CNR1 (left photo) and CNR4 (right photo) net radiometers.

Table 2
PET-ranges for different levels of thermo-physiological stress (according to Matzarakis & Mayer, 1996).

PET range [°C]	Level of thermal stress
41 <	extreme heat stress
35 – 41	strong heat stress
29 – 35	moderate heat stress
23 – 29	slight heat stress
18 – 23	no thermal stress
13 – 18	slight cold stress
8 – 13	moderate cold stress
4 – 8	strong cold stress
< 4	extreme cold stress

body of the station through a rotatable arm that allows the measurement of K_i and L_i from six perpendicular directions. Typically, in the first position, the arm of the net radiometers is set to face south. In this position, the two pyranometers and two pyrgeometers measure K_i and L_i separately from the upper and from the lower hemisphere (K_u, K_d, L_u, L_d). After three minutes, the net radiometers are rotated manually to the second position where the sensors face east and west (K_e, K_w, L_e, L_w). After another 3-min interval, the arms are turned 90° to measure the radiation flux densities coming from south and north (K_s, K_n, L_s, L_n). Considering the seven- and eight-hour-long measurement periods of our field surveys, this procedure entailed hundreds of rotations for both stations. Taking into account the response time of the sensors, as well as the time delays due to the rotation, the first K_i and L_i records following a rotation are always removed. Additionally, in the case of the Széchenyi Sq. where one of the stations was relocated every 15 min, the first three-minute data following the relocation is also omitted to record representative conditions of the new thermal environment.

2.3. Applied human-biometeorological assessment

The most important human-biometeorological parameter, the mean radiant temperature (T_{mrt} [°C]) was calculated from the measured 6-direction radiation flux densities. The calculations are based on the equation proposed by Höppe (1992):

$$\mathrm{T_{mrt}} = \sqrt[4]{\frac{\sum_{i=1}^{6} \mathrm{W_i} \times (\mathrm{a_k} \times \mathrm{K_i} + \mathrm{a_l} \times \mathrm{L_i})}{\mathrm{a_l} \times \sigma}} - 273.15 \qquad (1)$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/(m^2 K^4)), w_i is a direction-dependent weighting factor and a_k and a_l are the absorption coefficients of the human-biometeorological reference person regarding the short and long-wave radiation domain, respectively (Höppe, 1992). In urban human-biometeorological studies, a subject in standing position is most frequently considered (Höppe, 1992; Mayer, 1993). Accordingly, w_i is set to 0.06 for the two vertical and 0.22 for the four horizontal directions. Besides, a_k is assumed to be 0.7 and a_l to be 0.97, both referring to an ordinarily clothed Caucasian subject (Höppe, 1992; Kántor & Unger, 2011).

In order to express the comprehensive effect of the various micro-meteorological variables (T_a, VP, v, T_{mrt}) on the human body, *PET* (Höppe, 1999; Mayer & Höppe, 1987; Matzarakis, Mayer, & Izomon, 1999) was calculated with the help of the RayMan software (Lee & Mayer, 2016; Matzarakis, Rutz, & Mayer, 2007). *PET* is based on a simple idea of converting the actual bioclimatic condition to a fictive indoor bioclimatic condition that causes the same thermo-physiological reactions in the human body as the complex outdoor environment. The indoor reference environment is described with the following thermal parameters: $T_{mrt} = T_a$, $v = 0.1$ m/s and 12 hPa vapor pressure. Following the conversion, the obtained *PET* values can be interpreted as the air temperatures ($PET = T_a$) of the indoor reference environment in which the human body—assumed to be performing light activity with additional 80 W heat production and to be wearing light clothing with 0.9 clo insulation—would experience thermal conditions equivalent to those measured outdoors and characterized by the recorded T_a, T_{mrt}, v and VP values (Höppe, 1999).

From the several recent human-biometeorological indices*, PET* was selected for this study for several reasons. First, it describes the effect of the thermal environment on the human body by means of the commonly used dimension of temperature (°C), which facilitates the interpretation of the results. Second, *PET* is one of the most popular outdoor human comfort indices, which can be used for the assessment of both hot and cold conditions (Höppe, 1999; Mayer & Höppe, 1987). Finally, *PET* is used world-wide to analyze the thermal environment of cities, both at local and micro-scales, and is frequently used to investigate the effect of urban shading (see Ali-Toudert & Mayer, 2006, 2007a, 2007b; Charalampopoulos, Tsiros, Chronopoulou-Sereli, & Matzarakis, 2013; Gómez, Pérez Cueva, Valcuende, & Matzarakis, 2013; Gulyás, Unger, & Matzarakis, 2006; Holst & Mayer, 2011; Hwang, Lin, Cheng, & Lo, 2010; Kántor et al., 2016; Lee et al., 2013, 2014, 2016; Lin, Matzarakis, & Hwang, 2010; Mayer et al., 2008; Shashua-Bar et al., 2011; Streiling & Matzarakis, 2003). As shown in Table 2, the thermo-physiological stress categories assigned to particular *PET* ranges by Matzarakis & Mayer (1996) were adopted for the interpretation of the results. This *PET* categorization is valid for specific values of internal heat production due to human activity (80 W) and of heat resistance of clothing (0.9 clo) (Matzarakis, Mayer, & Izomon, 1999).

3. Results

3.1. Background weather

The measurement days are characterized by warm and mainly sunny weather conditions. According to the hourly data of the official meteorological station of Pécs, located about 10 km to the south of the measurement sites, the daily mean T_a was above 20 °C and the daily maximum T_a was above 25 °C on each day (Fig. 6a–c). The highest maximum T_a of 28.2 °C occurred on September 3rd, which is followed by 26.8 °C and 25.4 °C on August 9th and 14th, respectively. The daily average *VP* (Fig. 6d–f) was somewhat higher on August 9th and 14th (16 hPa) and lower on the last day (15.7 hPa). The global radiation was stronger on the first two measurement days with a daily maximum above 1100 W/m^2 and with a daily global radiation sum above 2500 kJ/m^2 (Fig. 6a-b). The daily sum of global radiation was only 1900 kJ/m^2 on the last measurement day: partly because of the smaller sun elevation angles and the fewer daylight hours, and partly due to the intermittent clouds in the afternoon (Fig. 6c). On August 9th, the synoptic wind speed (measured at 10 m above ground level) was higher, ranging from 2 to 3 m/s during the investigated period (between 9:00 and 16:00) (Fig. 6d). On the other days, the wind remained somewhat weaker, varying between 0.3 and 2.9 m/s on August 14th and between 0.3 and 2.4 m/s on September 3rd (Fig. 6e-f).

3.2. Field measurement at Széchenyi Sq

The first measurement was conducted at Széchenyi Sq. on August 9th, 2016 from 9:00 to 16:00. At the center of the square, T_a rose continuously from 25 °C to 29 °C (P1; Fig. 7a). T_a was 1 °C lower under the small tree (P2) and 0.7 °C lower under the low-hanging sun sails (P3) on average. During the measurement period, *RH* was low with an average value around 35% and slightly fluctuated between 31% and 40% at P1 (Fig. 7b). It was ca. 2.6% and 1.9% higher at P2 and P3, respectively. Because *RH* depends on T_a, Fig. 7c presents the observed humidity differences on the basis of vapor pressure (*VP*). The daily minimum *VP* occurred around 13:00. During our filed experiment, *VP* values at the three locations remained close to each other with less than 0.2 hPa difference. Similarly, the *v* values fluctuated between 1.0 m/s

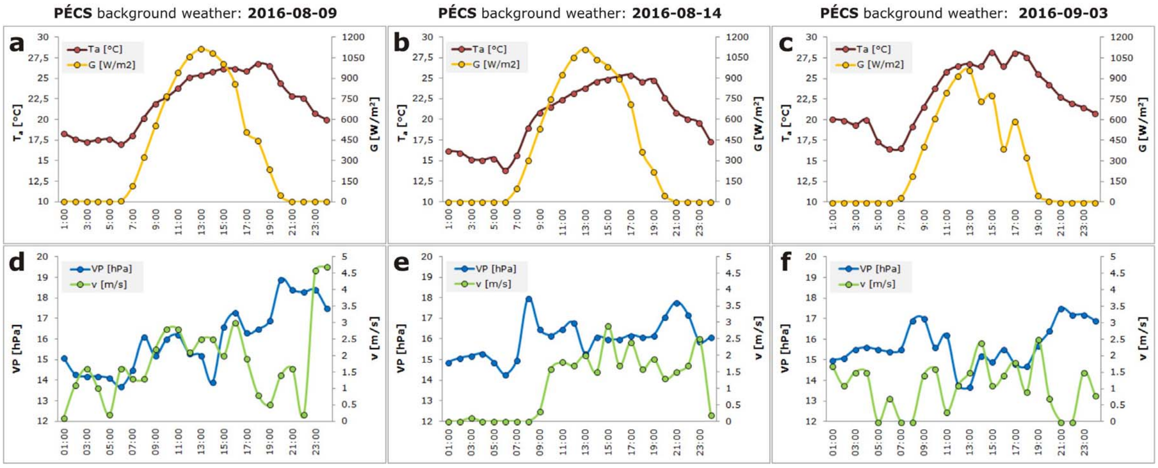


Fig. 6. Weather conditions on the measurement days at Pécs-Pogány Airport (data Source: Ákos Németh, HMS).

and 1.5 m/s at all survey points (Fig. 7d), with rather small differences between them. The similarities between the observed conditions at these locations are both due to their spatial proximity and the relatively small spread of the shading structures at P2 and P3.

In contrast to the above parameters, greater differences are recorded in the case of T_{mrt} (Fig. 7e), and consequently, in the case of *PET* (Fig. 7f). At P1, T_{mrt} remained above 50 °C during the field experiment except for a brief period around 13:20 when a small cloud obstructed the sun. After that, T_{mrt} reached 60 °C and remained above it for the remaining part of the observation period. It was also found that the small tree (at P2) reduced T_{mrt} by 18.2 °C on average, while the reduction by the sun sail (at P3) was only 11.4 °C (note: values when the cloud obstructed the sun were omitted from the analysis). Consequently, the mean *PET* difference between P1 and P2 is 9.0 °C and between P1 and P3 is 5.8 °C (Fig. 7f). In terms of heat stress categories, this reduction means that the small tree can decrease heat stress by two categories, while the sun sail by only one.

Detailed analysis of the radiation flux densities (Fig. 7g–r) revealed that the T_{mrt}– and *PET*-reduction potential of different means of shading are primarily attributable to differences in solar radiation transmission: the canopy of the selected tree obstructs more radiation (K_u) than the sun sail (Fig. 7g). As a consequence, they kept the ground surface cooler, which in turn decreased the amount of emitted heat from the ground (L_d) in the afternoon compared to that under the sun sail (Fig. 7n). Besides K_u, notable differences can be observed between K_s, K_e, K_w components as well when comparing different shading solutions (Fig. 7i–k). It should be noted that although both tree and sun sail reduced short-wave radiation flux densities considerably, compared to the open survey point, the overhead shading structures increased the incoming long-wave component from the upper hemisphere (L_u). From this point of view, tree canopy is more beneficial, as it results in lower incoming L_u than the overhead sun sail (Fig. 7m).

3.3. Field measurement at Irgalmasok Str

The second measurement was conducted within the street canyon of Irgalmasok Str. on August 14th, 2016 between 9:00 and 16:00. During this period, T_a was lower than during the first measurement, and increased continuously from 20 °C to 27 °C (Fig. 8a). The T_a values of the unshaded northern and the shaded southern street sections remained rather close with an average difference of 0.2 °C. The T_a curves were especially close during the first and last hours of the measurement period when buildings shadowed the human-biometeorological stations. When the exposed survey point at the northern end of the street (P1) received direct sunlight, it became 0.4 °C warmer than P2. Air humidity differences between the survey points were greater compared to the first measurement: *RH* was 2.4% and *VP* was 0.55 hPa higher in the shaded southern end of the street (P2; Fig. 8b-c). This difference can be partially explained by the potted oleanders in the vicinity of the instrument and also by the reduced convective water vapor losses due to the confined environment of P2. The v values remained around 1 m/s, and similarly to previous observations, differences between the measurement points remained insignificant (Fig. 8d).

For the survey point P1, the instrument was exposed to direct sunlight from ca. 9:30 to ca. 13:45 (Fig. 8g–k), which resulted in high T_{mrt} values of 54–61 °C (Fig. 8e). During this period, the mean T_{mrt} difference between the sunny and the shaded measurement points (P1–P2) was ca. 27° C. This is mainly attributable to the reduction of incoming short-wave radiation from the upper hemisphere and from east and south as well (Fig. 8g, i and k). (The western short-wave radiation component would have also had an impact on these differences, if buildings would not have obstructed the sun in the afternoon). Due to the reduced solar exposure of the ground and the adjacent building facades, the heat emitted by them (long-wave radiation from the lower hemisphere and from the lateral directions) remained somewhat lower in the case of the sun sail than at the exposed location (Fig. 8n–r). On the other hand, sun sails increased slightly the incoming long-wave radiation flux densities from the upper hemisphere (Fig. 8m).

As a result of all radiation components and their modifications due to the presence of the sun sails, the T_{mrt} difference between the shaded and the unshaded locations was greater in the first hour of the measurement and decreased from 31 °C to 23 °C continuously (Fig. 8e). After 14:00, when the adjacent buildings begin to cast shadow to the street, the T_{mrt} of P1 dropped considerably. Nevertheless, the prolonged effect of warmer surfaces (pavement and masonry walls) at the exposed location remained evident as T_{mrt} values at P1 stayed 7.5 °C higher than at P2.

Fig. 8f illustrates the integrated effect of the observed thermal parameters by *PET*. The results indicate the defining role of solar radiation in human thermal balance during sunny conditions. At P1, *PET* increased rapidly during the first half hour of the measurement period. Thereafter, it remained in the strong heat stress category until the buildings shaded the measurement point. During the last two hours of the measurement, conditions remained on the margin between moderate and slight thermal stress levels. Under the sun sails, at P2, *PET* increased smoothly from 19 °C to 29 °C and conditions without heat stress remained until 11:00 when slight heat stress occurred. During the last two hours, the *PET* curve of P2 followed that of P1 by 3.0 °C lower on average. During the whole measurement period, the average *PET* difference was 9.4 °C, and it reached 13.0 °C when calculated for the sun-exposed hours only (9:30–13:45). These *PET* differences suggest that high-mounted sun sails are able to reduce severe heat stress levels by 2–3 categories.

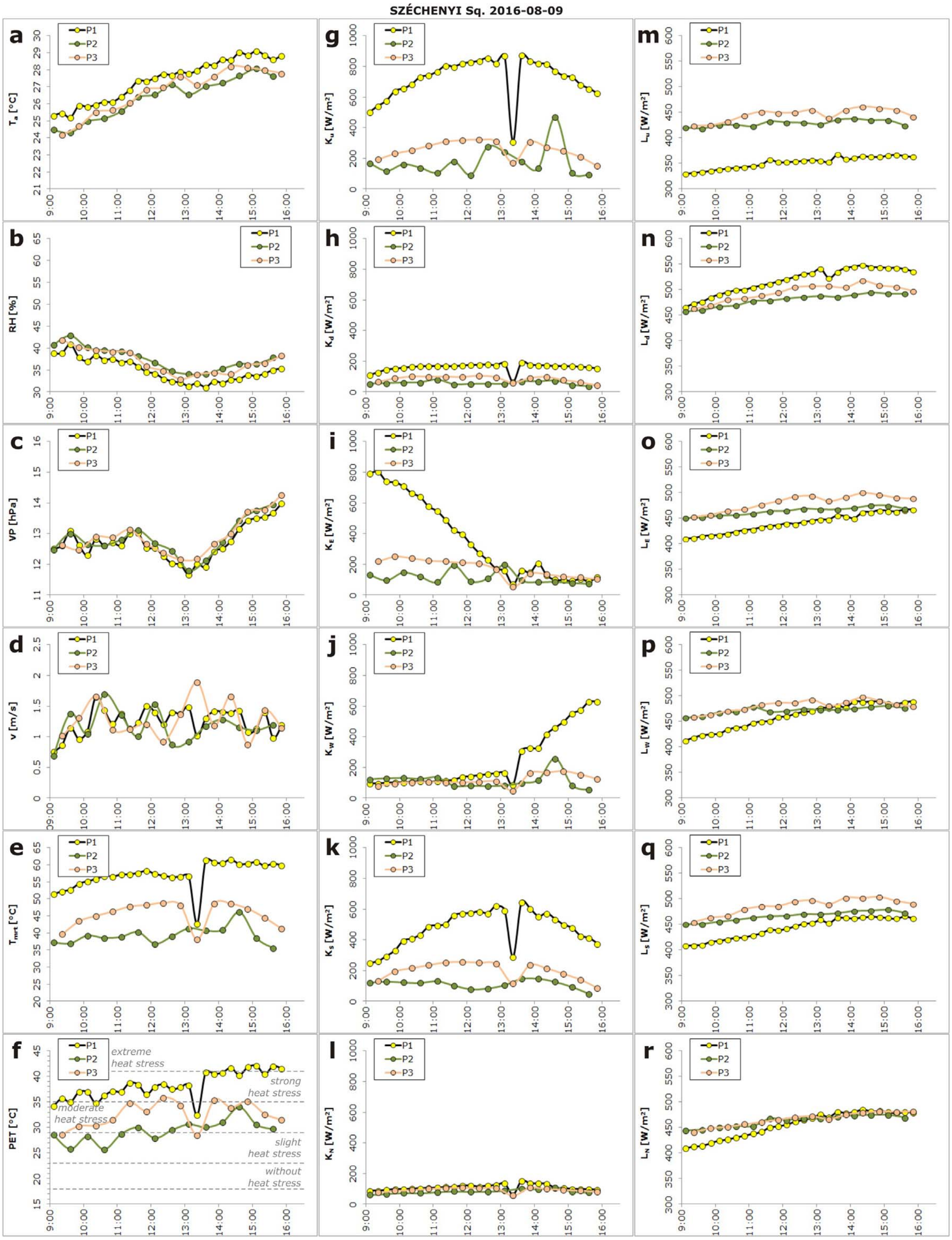


Fig. 7. Small-scale human-biometeorological conditions at Széchenyi Sq. on 2016-08-09 (P1: open point in the middle, P2: under a small free-standing tree with sparse canopy, P3: under a low sun sail).

3.4. Field measurement at Sétatér Sq

The third measurement was conducted on the E-W oriented promenade of the Sétatér Sq. on September 3rd, 2016 between 9:00 and 17:00. The daily maximum T_a occurred in the late afternoon and reached 29 °C (Fig. 9a). During the first observation hour, the T_a difference between the two measurement points was close to zero. However, as P1 became exposed to direct solar radiation, its T_a increased sharply. The average T_a difference between P1 and P2 for the measurement period was 0.75 °C. Due to the spatial proximity of the two measurement points, air humidity difference remained rather small: under the mature horse chestnut trees (P2) *RH* was only 1.8% and *VP* only 0.05 hPa higher than at the open section of the square (P1; Fig. 9b and c). Similarly to the previous two measurements, v fluctuated around 1 m/s (between 0.5 and 1.5 m/s) and the average v difference between the measurement points was only 0.16 m/s (Fig. 9d).

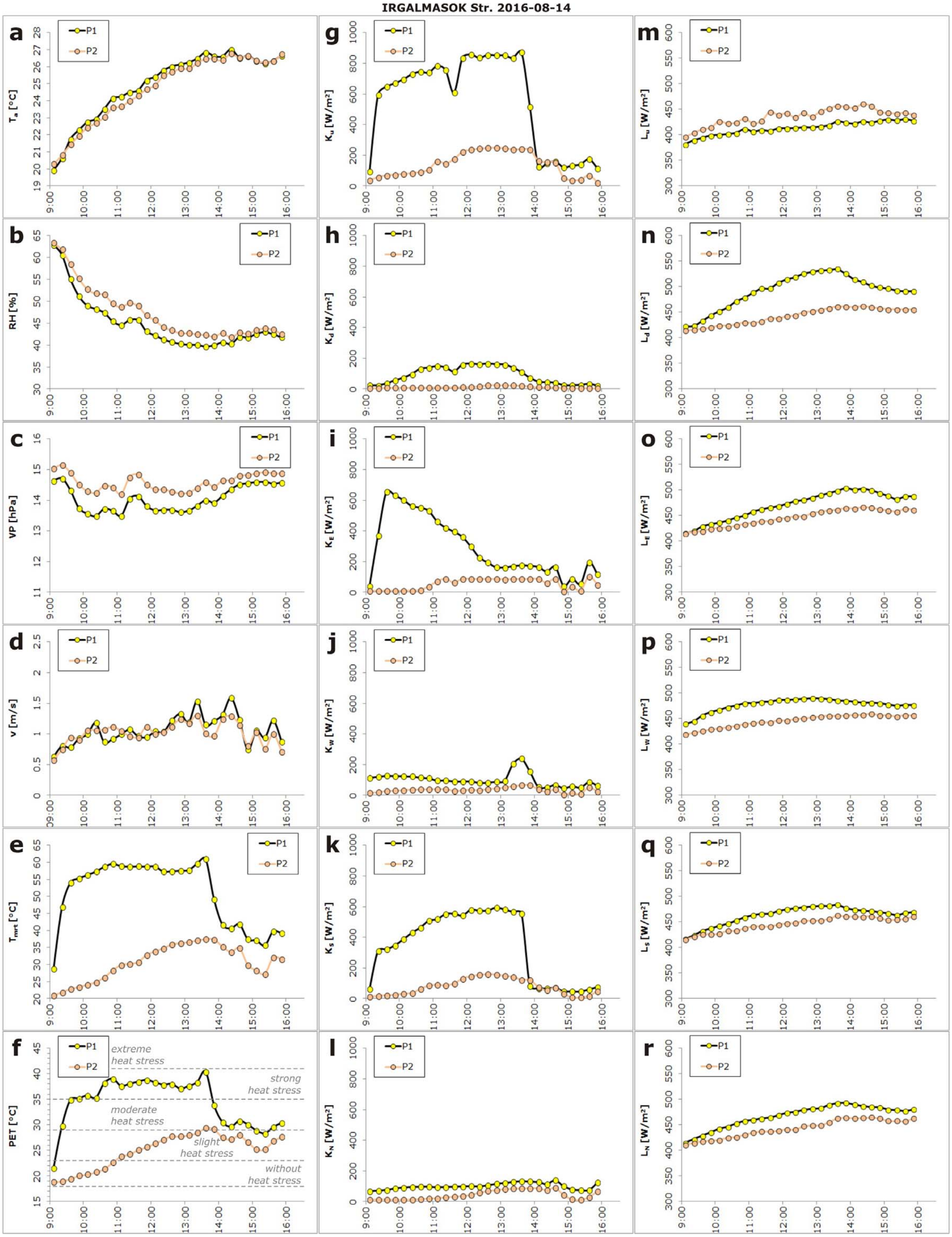


Fig. 8. Small-scale human-biometeorological conditions at the S-N oriented Irgalmasok Str. on 2016-08-14 (P1: without artificial shading, P2: under high-mounted sun sails).

The great variations in T_{mrt} (and in the K_i, components) during this day reveal more diversified sky conditions than during the others days (Fig. 9e, g–l). Indeed, while in the morning hours the sky remained clear, larger and smaller cumulus clouds arrived from North in the afternoon. This resulted in considerable dips in the T_{mrt}, K_u and K_w curves of P1, which was exposed to the sun from ca. 10:00 to ca. 15:30. The extended heat radiation from the warmed ground surface at P1 resulted in 5.6 °C higher T_{mrt} values than at P2, even when the point became shaded by the nearby horse chestnut trees. The average T_{mrt} reduction of the mature horse chestnut trees during the sunny hours was 21.4 °C (Fig. 9e). In the case of the shaded location of P2, the T_{mrt} curve lacked the monotonic increase observed at the sun sail-shaded street canyon case in the second measurement. Similarly to the observations at the second measurement with sun sails, the presence of tree canopy increased the amount of incoming long-wave radiation flux densities from the upper hemisphere slightly (Fig. 9m). However, the reduced warming from the ground surface due to shading resulted less long-wave radiation from the lower hemisphere (Fig. 9n).

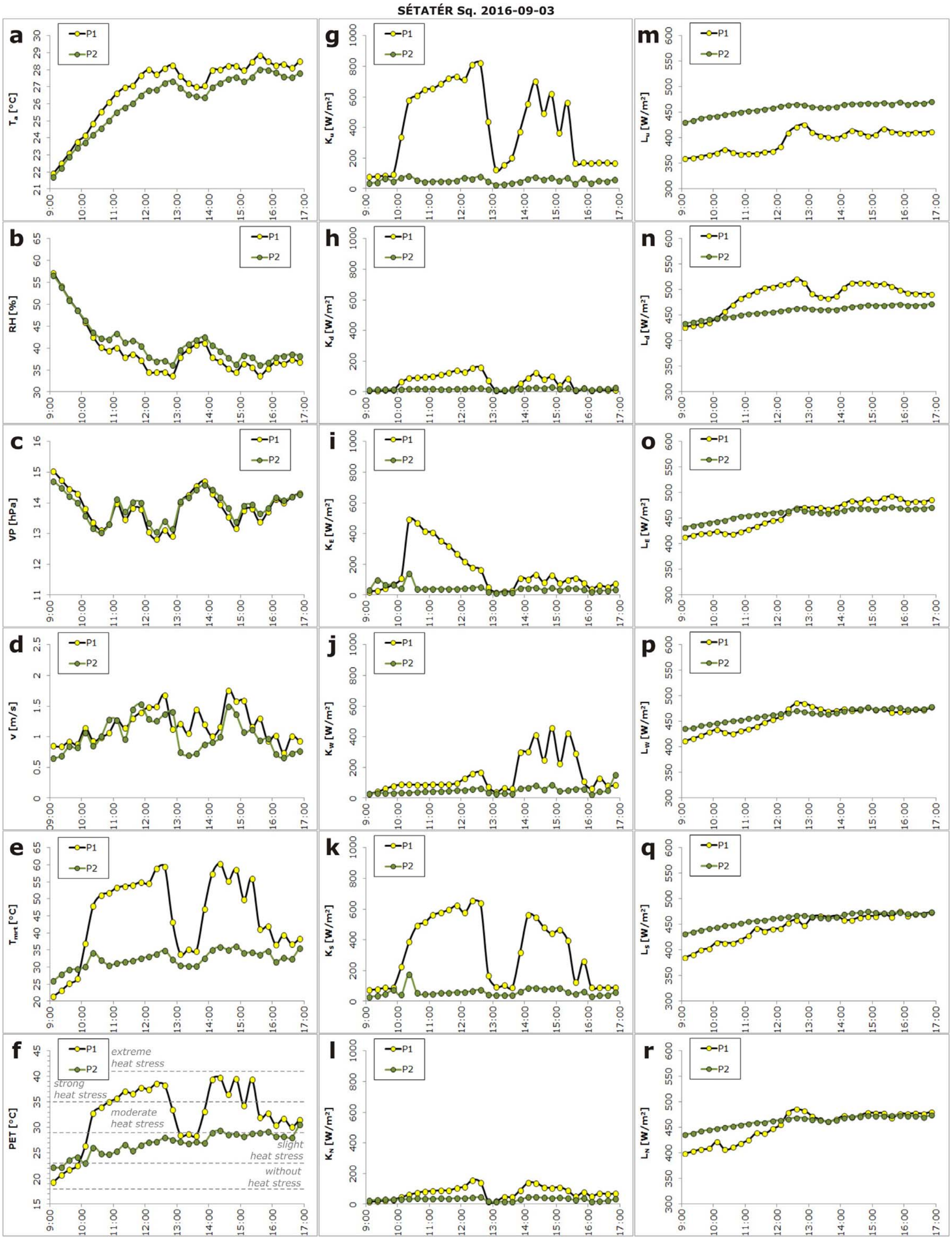


Fig. 9. Small-scale human-biometeorological conditions at Sétatér Sq. on 2016-09-03 (P1: middle point exposed to the sun, P2: under mature horse chestnut trees with dense canopy).

Similar to the other two measurements, the dominant role of radiation is evident from the *PET* curves (Fig. 9f), which are governed by T_{mrt} values. The sharp increase in P1's *PET* curve in the morning elevated heat stress level from the 'without heat stress' category to the 'moderate-strong' category. During the early afternoon, the sudden relapse in P1's *PET* curve is the result of an extensive cumulus cloud that reduced heat stresses to the 'slight' category. Thereafter, *PET* values increased steadily and fluctuated in the 'strong heat stress' domain until around 15:00 when the west-side trees began to cast shadow to the measurement point. Consequently, *PET* fell into the 'moderate heat stress' category. As a result of shading, the average *PET* difference between the two measurement locations was 5.7 °C during the measurements period. Whereas calculated for the sunny periods only, this reduction was 10.1 °C.

4. Discussions

Table 3 summarizes the findings of this study with regards to the

Table 3

Summary of the research findings (Note: colored cells are suggested to be used for international comparisons).

Investigation day	Background weather			Study area	Investigated shading solution	Human-biometeorological impact			Time frame
	T_a max [°C]	G max [W/m^2]	G sum [kJ/m^2]			ΔT_a [°C]	ΔT_{mrt} [°C]	ΔPET [°C]	
2016-08-09	26.8	1115	2517	**Széchenyi Sq.** (middle-sized open urban square)	Free standing **small tree** with small leaves and sparse canopy	-1.0	-18.2	-9.0	whole measurement period (9:00-16:00) (except the time around 13:20 when a small cloud obstructed direct irradiation)
					Sun sails right above the head of pedestrians	-1.0	-11.5	-5.8	
2016-08-14	25.4	1113	2520	**Irgalmasok Str.** (N-S oriented street canyon)	**Sun sails** over a street at higher elevation	-0.2	-20.1	-9.4	whole measurement period (9:00-16:00)
						-0.4	-27.0	-13.0	when clouds and buildings haven't obstructed direct irradiation into the street (ca. 9:30-13:40)
						-0.1	-7.5	-3.0	prolonged effect of previously irradiated and warmed surfaces (after 14:10)
2016-09-03	28.2	963	1895	**Sétatér Sq.** (E-W oriented promenade)	Group of **mature trees** with large leaves and dense canopy	-0.7	-12.6	-5.7	whole measurement period (9:00-17:00)
						-1.0	-21.4	-10.1	when clouds and trees haven't obstructed direct irradiation into the open point (10:20-12:40)
						-0.6	-5.6	-2.5	prolonged effect of previously irradiated and warmed surfaces (after 15:40)

impact of different shading solutions on the reduction of main human-biometeorological measures in °C. The table indicates the background weather conditions in terms of daily maximum temperature and global radiation as well, which are of importance for the development of micro-scale differences of the radiative environment (T_{mr}) and thus, of human thermal comfort (*PET*). The three investigated sites exhibited different human-biometeorological characteristics in terms of heat stress mitigation owing to the differences in the means of shading and also due to the differences in urban settings.

For the first measurement at Széchenyi Sq. on August 9th, people were exposed to more severe heat stress levels with 34–42 °C *PET* values, ranging from moderate to extreme category (Fig. 7f) at unshaded locations of the square. Our observations indicate that even small shading devices (such as a couple of low-hanging sun sails or a single tree with sparse canopy) were able to reduce heat stress levels by at least one category on a sunny summer day. Artificial shading devices were found to be less effective than natural ones: the low-hanging sun sails reduced *PET* to 29–36 °C, while the small honey locust tree reduced *PET* values to 25–34 °C (Fig. 7f). This difference is in line with the findings of Shashua-Bar et al. (2011), who also reported that a fabric shading mesh is less effective than trees in reducing heat stress. The above difference can be explained by the greater transmissivity value of sun sails, which let through greater amount of short-wave radiation than the tree canopy (Fig. 7g). This means both a direct energy gain for the human body in the short-wave radiation domain and the heating up of the ground, which results in greater amount of emitted long-wave radiation (Fig. 7m). Compared with sun sails, even a tree with sparse canopy has more layers, which are able to reduce incoming short-wave radiation more effectively, and thus prevent the heating up of the ground surface below. It is worth mentioning that Middel et al. (2016), who studied the impact of shading on subjective thermal comfort in Arizona, did not found significant differences when comparing the impact of different types of shading. Their analyses suggest that shading from natural (tree canopy) and artificial (photovoltaic canopy) objects have the same effect on the thermal perception in each season. However, based on field measurements similar to those adopted in this study (utilizing six-directional radiation measurement technique in another Central-European town, Freiburg) Lee et al. (2013) found that the maximum relative reduction of T_{mr} and *PET* owing to tree canopies was somewhat greater compared to shading due to buildings.

In our study sun sails installed at higher elevation to shade an entire urban canyon (Irgalmasok Str.) were found to be more effective in reducing heat stress levels than in the case where they were installed right above the head of people (Széchenyi Sq.). During the second measurement at Irgalmasok Str. on August 14th, *PET* remained above 35 °C for more than four hours (Fig. 8f) at the sunlit locations in the nearly N-S oriented street canyon. Under these circumstances, the high-mounted sun sails, which formed a continuous shield over the investigated street section (P2), mitigated the initial, strong heat stress level by two to three categories. Nevertheless, it should be noted that the efficiency of these shading devices may depend greatly on their layout, and we hypothesize that if sun sails were to be mounted more loosely, the intermittent penetration of solar radiation would result in higher T_{mrt}, and consequently in higher *PET* values. Admittedly, in locations where available space is limited, simple sun-shelters can be more practical for protecting pedestrians from strong solar radiation, and therefore improving thermal comfort.

The third measurement at Sétatér Sq. on September 3rd investigated the heat stress reducing capacities of large and mature trees with dense canopies. Our investigation on a partly cloudy day found that horse chestnut trees were able to reduce *PET* values by up to 10 °C during the sunny hours and mitigate heat stress level by two categories (Fig. 9f). From a human-biometeorological point of view, the vegetated promenade at the site provided more comfortable thermal environment for visitors, suggesting that urban greenery is the most effective measure to mitigate micro-scale heat stress when it is a viable alternative.

Table 4 summarizes the findings of other Central-European studies on the human-biometeorological benefits (T_a, T_{mrt} and *PET* reduction) of urban trees (street trees or park trees) based on the same radiation-measurement procedure adopted by this study. While employing the same measurement technique, one must be careful when comparing the outcomes of different studies, as differences in instrumentation and experiment design may themselves also be the source of differences. In our case, the differences in the utilized Kipp & Zonen sensors (CNR 1 and CNR 4) and in the different length of the rotatable arms (Fig. 5) may have effected the sensitivity and the field of view of the sensors. According to a long-term survey at an open point, the mentioned differences can result in 4–6 °C higher T_{mrt} values from April to September for the mobile station with CNR 4. Due to the particular measurement design during the field surveys on the Széchenyi Sq. and Sétatér Sq., (CNR 4 in the shade, CNR 1 in the sun), our results likely underestimate the evolved human-biometeorological differences in contrast with the surveys in the Irgalmasok Str. (CNR 1 in the shade, CNR 4 in the sun).

At downtown narrow streets where tree-planting is difficult due to spatial limitations, and where strong direct radiation during high sun elevations significantly deteriorates thermal conditions during summertime, installation of sun sails is a viable solution. However, in open public places, such as squares, tree-planting should be prioritized, as they not only deliver human-biometeorological benefits, but also provide a range of other environmental and social advantages.

Table 4
Studies investigating the human-biometeorological effect of urban trees in Central-Europe.

	Investigation day	**Background weather**		**Study area**	**Investigated type of shading (shaded site)**	**In comparison to an other survey point (sunny site)**	**Human-biometeorological impact**			**Time frame**	**Reference**
		T_a *max* [°C]	*G max* [W/m^2]				ΔT_a [°C]	ΔT_{mrt} [°C]	ΔPET [°C]		
Freiburg, Germany	**2008-07-24**	ca. 26.0	N.A.	**Vauban dist., Freiburg** (WNW-ESE oriented street canyon)	**Tree shade** SSW-facing sidewalk	**sunny** point a sidewalk facing to SSW	-0.8	-30.4	-12.4	10:00-16:00	Holst & Mayer (2010) Lee at al. (2013)
	summer days in 2007, 2008 and 2009	N.A.	N.A.	**different sites, Freiburg** (street canyons with different orientation)	**Tree shade** larger canopy coverage	**sunny** point lower canopy coverage	-1 to 3	-31 to -6	-17.5 to 1	10:00-16:00	Holst & Mayer (2011) *(data were extracted from Table 4 and Fig. 9)*
				Wiehre I	veg_{90-270}: 85%	veg_{90-270}: 75%	-0.5	-20.0	-8.0		
				Wiehre II	veg_{90-270}: 61%	veg_{90-270}: 34%	3.0	-9.0	-2.5		
				Herdern	veg_{90-270}: 85%	veg_{90-270}: 75%	0.0	-6.0	1.0		
				Herdern	veg_{90-270}: 85%	veg_{90-270}: 10%	-0.5	-25.0	-6.5		
				Rheinstrasse	veg_{90-270}: 70%	veg_{90-270}: 5%	1.0	-20.0	-4.5		
				Rheinstrasse	veg_{90-270}: 72%	veg_{90-270}: 29%	-0.5	-8.5	-3.5		
				Albertstrasse	veg_{90-270}: 75%	veg_{90-270}: 33%	1.0	-14.0	-5.0		
				Albertstrasse	veg_{90-270}: 75%	veg_{90-270}: 17%	1.5	-27.0	-9.0		
				Rheinstrasse (green space)	veg_{90-270}: 82%	veg_{90-270}: 23%	1.5	-24.0	-3.0		
				Rheinstrasse (green space)	veg_{90-270}: 87%	veg_{90-270}: 23%	0.5	-18.0	-6.0		
				Hebelstrasse	veg_{90-270}: 78%	veg_{90-270}: 6%	-1.0	-31.0	-17.5		
Szeged, Hungary	**2015-05-08**	23.9	ca. 900	**Dugonics Sq., Szeged** (middle-sized urban square)	**Tree shade** a large shade tree with great and sparse canopy	**sunny** point in the middle of the square	-0.2	-19.8	-9.2	10:00-18:00	Kántor et al. (2016) *(differences were calculated for the purpose of this comparison from the original database)*
	2015-05-13	27.3					-0.4	-22.3	-10.2		
	2015-05-20	29.4					-0.4	-22.7	-9.4		
	2015-06-08	29.4					-0.5	-22.0	-10.1		
	2015-06-15	29.8					-0.7	-23.3	-10.2		
	2016-08-08	26.9	848	**Bartók Sq., Szeged** (middle-sized urban square)	**Tree shade** cluster of shade trees in the middle of the square	**shaded** point (sidewalk) facing to NNE (all day shaded by **building**)	0.7	3.8	2.3	10:00-18:00	Takács et al. (2017) *(differences were calculated for the purpose of this comparison from the original database)*
						sunny point (sidewalk) facing to ESE (afternoon shaded by building)	-0.5	-13.7	-8.6		
						sunny point (sidewalk) facing to SSW (early morning shaded by building)	-1.6	-30.8	-17.1		
						shaded point (sidewalk) facing to WNW (shaded by **building and street trees**)	-0.8	-3.9	-0.3		
Pécs, Hungary	**2016-08-09**	26.8	1115	**Széchenyi Sq.** (middle-sized open urban square)	Free standing **small tree** with small leaves and sparse canopy	**sunny** point in the middle of the square	-1.0	-18.2	-9.0	9:00-16:00	this study
	2016-09-03	28.2	963	**Sétatér Sq.** (E-W oriented promenade)	**Tree shade** group of mature trees with large leaves and dense canopy	**sunny** point in the middle of the promenade (morning and afternoon shaded by nearby trees)	-0.7	-12.6	-5.7	9:00-17:00	
							-1.0	-21.4	-10.1	10:22-12:37	

See Ref. Takács et al. (2017).

5. Conclusions and outlook

This paper presents an empirical human-biometeorological study from the Hungarian city of Pécs. Extensive human-biometeorological measurements utilizing the accurate six-directional radiation measurement technique were conducted within three different urban settings, and the effectiveness of different means of shading in mitigating local heat stress was compared. The following conclusions are drawn from the study:

- Heat stress during summertime is largely determined by the radiation conditions which, on the one hand, is governed by sky conditions and, on the other hand, is influenced by the immediate environment—i.e., by the presence of overhead shading solutions and by the thermal characteristics of adjacent surfaces. Both sun sails and trees can improve greatly the thermal comfort conditions depending on their dimensional characteristics, the urban settings in which they are adopted, as well as the background weather.
- At large open squares, trees—especially mature ones with dense and extensive canopy—provide more extensive shading and can reduce heat stress more effectively than artificial devices. Although artificial sun sails block direct solar radiation they are not as effective as trees.
- Warmed up artificial materials (such as pavements or building facades) are effective sources of long-wave radiation in sunlit locations. Therefore, they both extend the period and increase the level of radiation that people are exposed to in their vicinity. Consequently, high-mounted and large sun sails are more effective in heat stress reduction than low-hanging sun sails locate just above the head of pedestrians. Similarly, mature trees with large and dense canopy are more beneficial than small trees with sparse canopy.

Our study demonstrates that detailed field measurements can enhance our understanding of microclimatic conditions at a fine-scale, which, in turn, can be used by landscape designers and architects for climate-responsive urban design. Recent planning directives of the European Commission (EC) gave priority to nature-based solutions (NBS) and hence to re-naturing cities (EC European Commission, 2015). NBS is a recently introduced concept in environmental research and management that promotes nature as a means to address the challenges brought about by climate change. Within the scope of the international Nature4Cities project fostering the use of NBS within urban areas, an inter- and cross-disciplinary research is conducted to assess the performance of archetypal nature-based solutions (different types of green walls, green roofs, urban trees, parks etc.) for addressing various urban challenges such as mitigating heat in urban areas. In European cities, especially in those with dense historic urban cores, carefully planned and properly maintained shade trees constitute the most effective NBS for mitigating extreme thermal conditions, while also offering several co-benefits.

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