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ORIGINAL PAPER

Evaluation of outdoor human thermal sensation of local climate zones based on long-term database

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Abstract This study gives a comprehensive picture on the diurnal and seasonal general outdoor human thermal sensation levels in different urban quarters based on long-term (almost 3 years) data series from urban and rural areas of Szeged, Hungary. It is supplemented with a case study dealing with an extreme heat wave period which is more and more frequent in the last decades in the study area. The intra-urban comparison is based on a thermal aspect classification of the surface, namely, the local climate zone (LCZ) system, on an urban meteorological station network and on the utilization of the physiologically equivalent temperature (PET) comfort index with categories calibrated to the local population. The selected stations represent sunlit areas well inside the LCZ areas. The results show that the seasonal and annual average magnitudes of the thermal load exerted by LCZs in the afternoon and evening follow their LCZ numbers. It is perfectly in line with the LCZ concept originally concentrating only on air temperature (T_{air}) differences between the zones. Our results justified the subdivision of urban areas into LCZs and give significant support to the application possibilities of the LCZ concept as a broader term covering different thermal phenomena.

Keywords Local-scale (urban) thermal sensation · Calibrated PET scale · Local climate zones · Representative stations · Heat wave · Szeged, Hungary

Introduction

Background

Urbanized areas have distinct climate features compared to the natural or agricultural surroundings, which can be summed as urban climate (Oke 1987). This climate varies from city to city depending on the natural (topography, climate, actual weather, etc.) and artificial factors (city size, urban structure, fabrics and activities, etc.). Furthermore, the climate modification effects can be different within the city too (intra-urban differences). The urban heat island in the near-surface air (and the urban thermal pattern on the surface) is the best-known and most studied phenomenon of the urban climate.

The recently introduced local climate zone (LCZ) concept (Stewart and Oke 2012) provides a new approach and a new framework for the analysis of thermal conditions in the settlements (originally T_{air} conditions; see the "The concept of LCZs" section). The recent comparative analyses of the thermal reactions of neighborhoods with different built-up characteristics confirmed the legitimacy and usefulness of the LCZ system (e.g., Stewart et al. 2014; Unger et al. 2014; Leconte et al. 2015; Skarbit et al. 2017). Lately, the comparison was extended to the surface temperature too (e.g., Skarbit et al. 2015; Geletič et al. 2016), and an attempt was made to run an urban energy balance model using LCZ data (Alexander et al. 2015).

A new application of LCZs and thus an interesting new research field is the local-scale (intra-urban or inter-zone) human comfort comparison. The monitoring of outdoor human thermal comfort conditions by LCZs provides important data for urban planners and decision-makers in order to create lively urban areas for its residents in the future (Milošević et al. 2015).

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The outdoor human thermal sensation is a complex effect of air temperature, air humidity, radiation, and wind conditions. That is why the examination of temperature differences is not sufficient to demonstrate the thermal sensation of people within the settlement. In order to characterize its intra-urban differences, the utilization of one of the rational indices, the physiologically equivalent temperature (PET) index seems to be an appropriate solution as it contains the combined effect of all the climatic variables on human thermal sensation. PET is defined as "the temperature (in °C) of a standardized fictitious environment (where the mean radiation temperature is the air temperature, vapor pressure is 12 hPa, and wind speed is 0.1 ms^{-1}), in which the body, in order to maintain its energy balance, gives the same physiological responses as in complex real-world conditions" (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999). Thus, PET values demonstrate thermal comfort conditions and provide a proper measure for the analysis of the daily and seasonal climatic behavior of urban spaces in different built-up texture.

Studies of the abovementioned new research line are still scarce and they are very much in their early stages. Actually, the first step was made by Kovács and Németh (2012) and they found that the annual and seasonal average PET values were higher in the central area (LCZ 2) than the suburban area (LCZs 6) in Budapest, Hungary, based on a 30-year dataset. Puliafito et al. (2013) used data from 15 mobile measurement runs studying the local influence of green areas in nine LCZs on thermal comfort during daylight and at night in Mendoza, Argentina. Müller et al. (2014) in Oberhausen, Germany, performed measurements in eight LCZs to demonstrate the influence of evaporation surfaces and other factors on thermal comfort based on a 1-year dataset, using numbers of climatic event days. The further analyses are limited on only a few days with clear sky (Villadiego and Velay-Dabat 2014), or on the warmest and coldest days of a year (Milošević et al. 2015), as well as on a 4-day heat wave period (Milošević et al. 2016). Of these, only two represent a semi-climatological evaluation (longer datasets), but one of them is limited to only two stations (Kovács and Németh 2012); the other's study period is a bit short in this respect (Müller et al. 2014).

We think that further development of this type of climatological studies is definitely justified. Our innovation is that we utilize long (several years) datasets from different parts of the city. The seasonal peculiarities of the urban areas belonging to different LCZs and their deviations from each other can be detected only on this basis.

Objectives

Considering the foregoing, in this study, we intend to give a comprehensive picture on the general outdoor human thermal sensation levels appreciable in different urban quarters based on a long (almost 3 years) data series from the urban and rural areas of Szeged, Hungary.

The general aim of this study is the intra-urban diurnal and seasonal investigation of the PET index related to sunlit urban spaces in different LCZs occurring in and around Szeged, based on data series of measurement sites representative to these zones. In addition, we examine the situation in one of the several-day-long heat wave periods, which are more and more frequent in the last decades in the Szeged region (OMSZ 2015). In details, our objectives are as follows:

(1) Determination of the mean annual and seasonal thermal sensation by LCZs in the early afternoon and evening.
(2) Evaluation of the thermal sensation variations of LCZs in the seasons relevant to staying outdoors (spring, summer, autumn) and their comparison in the transition seasons (spring, autumn).
(3) Comparison of the thermal sensation of LCZs during a very stressful heat wave period.

Study area, LCZs

Szeged is located in the south-eastern part of Hungary (46°N, 20°E) at 79 m above sea level on a flat terrain with a population of 162,000 within an urbanized area of about 40 km^2. It is in Köppen's climatic region Cfb (warm temperate climate, no dry season, warm summer) (Kottek et al. 2006) with an annual mean temperature of 10.9 °C, sunshine duration of 2049 h, and an annual amount of precipitation of 514 mm (1981–2010, OMSZ 2015). Szeged is characterized by a densely built midrise core, with openly spaced blocks of flats in the east-northern part of the city, as well as family homes and warehouses on the outskirts. The rural surroundings are mostly croplands (wheat, maze) with few scattered trees (Skarbit et al. 2017).

The concept of LCZs

The main purpose of the LCZ system is the characterization of the local environment around an air temperature measurement site in terms of its ability to influence the local thermal climate. Therefore, the number of types is not too large and their separation is based on objective, measurable parameters. LCZs are defined as "regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale" (Stewart and Oke 2012).

The LCZ types can be distinguished by typical value ranges of measurable physical surface properties (geometry, cover, and thermal). As a result, the LCZ system consists of ten "built" and seven "land cover" types, and their names reflect the main characteristics of these types (Stewart and

Oke 2012). In the context of the LCZ classification system, the urban heat island intensity is not an “urban-rural” temperature difference (ΔT_{u-r}), but a temperature difference between pairs of LCZ types ($\Delta T_{\mathrm{LCZ}\ X\text{–}Y}$), that is an inter-zone temperature difference (Stewart and Oke 2012). Consequently, the usage of the system allows the objective comparison of the thermal reactions in different areas within a city and between cities (intra-urban and inter-urban comparisons).

LCZ types and their representative stations in Szeged

In order to delineate the LCZ types occurring in the study area, a recently developed automated method was used (Lelovics et al. 2014). We concentrated only on the most typical built types without applying further sub-classification. This gave us sufficiently large LCZ areas to work within, and an easily interpretable map. Figure 1 shows the obtained pattern of seven built and two land cover LCZ types in and around Szeged. Compact buildings (LCZs 2 and 3) and open-set/low-rise buildings (LCZs 6, 8, and 9) exist mainly in central and outlying areas, respectively. Compact midrise buildings (LCZ 5) exist in both the inner and ex-central parts of the city. On the periphery are large areas of sparse settlement (LCZ 9), where the landscape changes from urban to rural uses (LCZ D) (Skarbit et al. 2017). The mentioned method was applied also in Novi Sad (Serbia) having similar geographical characteristics to Szeged (Savić et al. 2013).

Within the framework of an EU project (URBAN-PATH Project 2017), an urban meteorological network with 24 stations was set up in Szeged. One of them (station D; see Fig. 1) is the station of the Hungarian Meteorological Service (HMS). Two stations represent the rural area and 22 stations the different built-up areas (different LCZs) of the city (for more details, see Unger et al. 2015).

In this study, we selected six stations which represent the built and land cover LCZs occurring in Szeged. Two exceptions are (i) LCZ 8 where the stations have large data gaps (therefore, their datasets cannot be used for a longer-term climatological evaluation and comparison) and (ii) LCZ G which means small water surfaces without measurement sites. Thus, the data of the selected stations representing LCZs 2 (compact midrise), 3 (compact low rise), 5 (open midrise), 6 (open low rise), 9 (sparsely built), and D (low plants) are used for the present investigation (Fig. 1).

Data and methods

Data

We calculated 10-min averages of parameters necessary for PET calculation considering the longest period available (32 months, from 1 June 2014 to 31 January 2017). This period contains three summers, three autumns (2014, 2015, 2016), two springs (2015, 2016), and two winters (2014/2015, 2015/2016). Air temperature (*T*) and relative humidity (RH) data were obtained from all the selected measurement sites, while global radiation (*G*) and wind speed (*u*) data are from

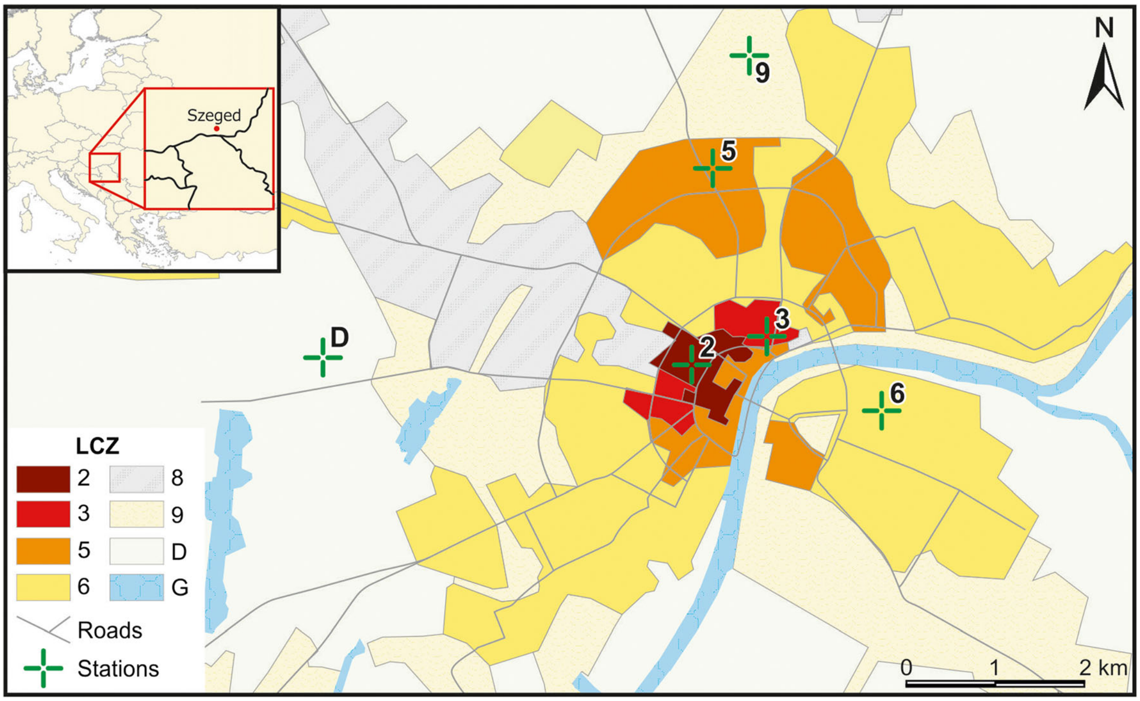

Fig. 1 Location of Szeged as well as its LCZ map and the sites of the selected stations

the rural HMS station (D) situated in an open area (see the "PET calculation, calibrated PET categories" section).

PET calculation, calibrated PET categories

The calculation of 10-min PET values was carried out with the RayMan software (Matzarakis et al. 2007, 2010), developed according to Guideline 3787 of the German Engineering Society (VDI 1998). It calculates radiative fluxes in simple and complex environments on the basis of various parameters, such as air temperature, air humidity, degree of cloud cover, time of day and year, and the albedo of the surrounding surfaces, elevation, and location.

If the aim is to determine the thermal comfort conditions not at the micro-scale but the local scale (as LCZs), the G and u data directly measured on site are not appropriate as they are highly affected by the micro-scale surroundings. In order to avoid this, to use data independent from the effects of the surrounding micro-environments, the undisturbed global radiation measured at station D representing no-shade conditions was taken. In the case of u, calculations were based on the values measured at station D and on roughness parameters (roughness length, displacement height) of the urban stations' surroundings using logarithmic profile and the empirical reduction constants related to the given site (for more details, see Unger et al. 2015). Thus, the G and the calculated u values were considered to be representative values at the local scale with no shade, i.e., representative for the LCZs. It is clear that the calculated PET values do not represent the shaded areas within LCZs, but in this study, we concentrate on the local-scale differences instead of micro-scale variance.

In contrast to the abovementioned two parameters, the spatial distributions of T and RH are more homogeneous as they vary at local rather than micro-scale. That is why we can use the data directly from the selected stations.

Ranges of the general thermal sensation categories of PET concerning the Western-Central-European population (Table 1) are originally based on the work of Matzarakis and Mayer (1996). Since the original thermal sensation scale was created for the temperate climate, it is not entirely appropriate as an indicator to other climates. Nonetheless, this scale is widely used in the literature to characterize the thermal comfort conditions in Europe (e.g., Gulyás et al. 2006; Knez and Thorsson 2006; Andrade and Alcoforado 2008; Müller et al. 2014; Milošević et al. 2016) and outside Europe too (e.g., Toy and Yilmaz 2010; Puliafito et al. 2013; Provencal et al. 2016). As the climates can be rather various spatially and temporally, the ranges of categories for a population acclimatized to the climate characteristics of a smaller region could be different from the general categories mentioned above. To calibrate the ranges (even seasonally) for a relatively homogeneous geographical area or for a place (for example, a holiday resort), a very comprehensive objective and subjective data collection is needed (Kántor et al. 2012). There are only a few examples of attempts to carry out this type of calibrated (localized) thermal sensation characterization (e.g., Lin and Matzarakis 2008; Mahmoud 2011; Cohen et al. 2013; Lai et al. 2014; Kovács et al. 2016; Krüger et al. 2017). Based on the results of a thorough multi-annual survey accomplished in Szeged recently (Kántor et al. 2016), we have up-to-date seasonal information about the thermal sensation features of the local (Hungarian) inhabitants (Table 1).

Selected periods and the evaluation steps

As we investigate the outdoor thermal sensation, we mainly focus on the periods of the year when the weather in the area is suitable for outdoor (leisure) activities. Taking into account the climatic conditions, in the case of Szeged, these are the transitional seasons (spring, autumn) and the summer (OMSZ 2015).

Considering the 24-h period, we evaluate the conditions in essentially two phases. One of them is the *early afternoon* between 13 and 14 LST (average of six 10-min values) when the largest heat load is expected during the day. With that, we get information about the maximum heat load and thermal stress of different LCZs in different periods of the year. The other phase is the *evening* (after the working hours and/or after the possibly stressful daylight hours) for 2 h from sunset (average of 12 10-min values). It helps to outline the areas within the city where favorable thermal conditions exist for outdoor leisure activities (street restaurant, cafe, open air theater, etc.).

In order to get a general picture, firstly, we calculate the mean seasonal PET values in the early afternoon and in the evening by LCZs. For completeness, we present also the yearly and winter means (see the "Mean annual and seasonal thermal sensation by LCZs" section).

Table 1 Ranges of original thermal sensation categories (PET, °C) for the whole year (Matzarakis and Mayer 1996*) and ranges of calibrated ones to Hungarians for different seasons (Kántor et al. 2016**)

	Thermal sensation (PET, °C)						
	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Year*	4–8	8–13	13–18	18–23	23–29	29–35	35–41
Spring**	−0.8–3.5	3.5–8.4	8.4–14.0	14.0–20.8	20.8–30.7	30.7–	
Summer**		−13.1	13.1–17.3	17.3–22.4	22.4–28.9	28.9–41.4	41.4–
Autumn**	−2.6	2.6–7.9	7.9–13.9	13.9–21.4	21.4–32.6	32.6–	

Secondly, we evaluate the temporal variations of the 10-day mean PETs seasonally by LCZs, concentrating only on the warmer periods (see the "Thermal sensation variations of LCZs in the warmer seasons" section). The usage of the 10-day periods (decas) is a common method in studies of recreational climatology and in outdoor human comfort investigations when finer resolution than 1 month is needed to determine the favorable periods from different aspects of the recreational or leisure activities (e.g., Lin and Matzarakis 2008; Zaninović and Matzarakis 2009; Toy and Yilmaz 2010; Kovács et al. 2016).

Finally, we investigate a heat wave period when a *level 3 heat alert was issued in Hungary* (daily average temperatures exceed 27 °C during at least three consecutive days (Páldy and Bobvos 2010)) and compare the temporal variations of the hourly PETs by LCZs during this period (see the "Thermal sensation variations of LCZs during a heat wave period" section).

Results and discussion

Mean annual and seasonal thermal sensation by LCZs

Considering the annual and seasonal means of PET, the highest values appear in LCZs 2 and 3 while the lowest ones in LCZ D in both investigated periods of the day. The PET values decrease from the densely built-up compact zones to the more open and vegetated zones independently from the time of the day and year (Table 2). From the heat stress mitigation aspect, the most favorable built-up types are LCZs 6 and 9. The largest differences occur in summer when $\Delta PET_{LCZ\ 2\text{–}D}$ = 3.6 °C in the afternoon and $\Delta PET_{LCZ\ 2\text{–}D}$ = 3.5 °C in the evening. For the other seasons, the differences are smaller after sunset than during the day. The smallest difference in the afternoon can be found in autumn ($\Delta PET_{LCZ\ 2\text{–}D}$ = 2.4 °C), and in the evening, it is in winter ($\Delta PET_{LCZ\ 2\text{–}D}$ = 2.1 °C).

Table 2 Annual and seasonal means of PET (°C) of the selected representative stations in the early afternoon (13.00–14.00 LST) and in the evening (from sunset until 2 h after it) (Szeged, June 2014–January 2017)

Period of the day	Period of the year	Station/LCZ					
		2	3	5	6	9	D
Early afternoon	Spring	19.3	18.9	18.5	18.3	17.6	16.0
	Summer	35.0	34.6	34.2	34.1	32.8	31.4
	Autumn	20.3	20.2	20.2	19.7	18.9	17. 9
	Winter	3.5	3.6	3.4	3.3	1.9	0.7
	Year	19.0	18.8	18.6	18.3	17.3	16.2
Evening	Spring	8.6	8.5	8.0	7.4	7.1	6.0
	Summer	18.7	18.9	18.0	17.5	16.5	15.2
	Autumn	9.8	9.8	9.4	8.6	8.4	7.6
	Winter	−2.0	−2.1	−2.3	−2.7	−2.8	−4.1
	Year	8.3	8.3	7.8	7.2	6.8	5.8

According to the frequencies of the thermal sensation categories of the LCZs, it can be established in general that in the evening, the "colder" categories (cold, cool, s. cool) are more frequent in the case of less built LCZs (LCZ 2 < … < LCZ D) and vice versa, and the "warmer" categories (s. warm, warm, hot) are more frequent in the more built zones (LCZ 2 > … > LCZ D) (Table 3). Although, this does not mean large thermal load as these frequency numbers are not high. The largest occurrence of the "neutral" sensation (requiring the smallest thermal response of the body) is in the compact zones; in summer, it is over 40%, which means several evening to enjoy the leisure time outdoors in the central part of the city where otherwise the appropriate facilities (cafes, restaurants, open air stages, etc.) are also available.

In contrary, in the afternoon, there are more neutral and less "warm" periods in the less built zones (except autumn). That is, in the daytime, the most pleasant zones are the less built ones (LCZs 6, 9, and D), but in the evening, the situation will turn; namely, the inner urban parts (LCZs 2 and 3) are more pleasant to spend the leisure time outdoors.

Thermal sensation variations of LCZs in the warmer seasons

With a quick glance at Figs. 2, 3, and 4, it can be stated that the PET curves form two groups according their variations: the curves of LCZ 2, 3, 5, and 6, having substantial impervious fraction, change rather together (hereinafter built LCZs), while LCZ 9 and D, having mainly impervious cover, are clearly separated from them with their lower values (hereinafter "vegetated" LCZs).

The mean thermal conditions in the transitional seasons (decas 7–15 and 25–33) in and around the city are illustrated in Figs. 2 and 3. Spring is characterized by gradually improving and autumn by gradually worsening conditions in both investigated times of the day, and the sequence of LCZs is what is expected (except during the decas 29–31 in the afternoon).

In the spring afternoon, the PET varies between "slightly cool" and "slightly warm" (9.7–27.7 °C) for the built LCZs, but for the vegetated LCZs, it is one category lower ("cool") in the early spring (Fig. 2a). The really pleasant part of the season (neutral and "s. warm") starts at decas 9–10 (end of March to early April) and lasts until the end of May, providing appropriate thermal conditions for different outdoor activities

Table 3 Frequencies (%) of the thermal sensation categories of the LCZs occurring in different seasons and times of the day (Szeged, June 2014–February 2017)

Season	Period	Category	*LCZ*					
			2	3	5	6	9	D
Spring	Early afternoon	Cold	1.0	1.4	1.5	1.3	2.4	4.3
		Cool	6.9	7.8	8.2	9.4	12.2	13.9
		s. cool	23.1	24.3	26.0	25.3	25.2	26.8
		Neutral	23.3	22.9	21.1	22.3	23.3	26.4
		s. warm	34.3	33.5	33.9	32.3	29.4	23.5
		Warm	11.4	10.1	9.3	9.4	7.5	5.1
	Evening	Cold	21.9	22.1	24.6	28.4	30.7	36.8
		Cool	27.6	27.4	27.3	25.9	25.2	26.8
		s. cool	29.7	29.8	30.3	30.4	30.6	27.8
		Neutral	18.9	18.9	16.8	14.7	13.2	8.5
		s. warm	1.9	1.8	1.0	0.6	0.3	0.1
Summer	Early afternoon	Cool	0	0	0	0	0	0.1
		s. cool	0.9	0.8	0	0.8	1.6	2.4
		Neutral	3.9	3.8	4.8	5.3	7.4	10.6
		s. warm	14.5	16.0	17.0	16.1	18.1	20.7
		Warm	60.9	61.6	60.7	61.4	58.6	55.7
		Hot	19.8	17.8	17.5	16.4	14.3	10.5
	Evening	Cool	9.9	9.2	13.0	15.1	21.8	30.3
		s. cool	26.7	26.1	29.6	32.2	35.6	38.1
		Neutral	40.4	41.1	39.2	38.7	32.5	27.5
		s. warm	21.7	22.3	17.5	13.6	9.9	4.1
		Warm	1.3	1.3	0.7	0.4	0.2	0
Autumn	Early afternoon	Cold	5.1	4.7	5.4	5.5	7.1	7.8
		Cool	9.0	7.8	7.6	7.8	10.3	12.4
		s. cool	21.9	22.6	22.0	22.8	22.4	23.2
		Neutral	27.9	29.3	29.2	29.0	29.1	26.9
		s. warm	26.3	26.3	26.6	25.9	22.7	21.7
		Warm	9.8	9.3	9.2	9.0	8.4	8.0
	Evening	Cold	17.8	18.5	20.4	23.2	24.6	27.5
		Cool	28.3	28.7	28.7	28.4	28.8	31.1
		s. cool	31.7	30.8	30.4	29.9	28.4	26.3
		Neutral	18.2	18.4	17.8	16.4	16.5	14.0
		s. warm	4.0	3.6	2.7	2.1	1.7	1.1

and sunbathing. This is a "charging period" for the people after the long and relatively dark winter weeks.

However, after the warm summer days, autumn begins with higher thermal conditions; the first PET values being in the warm category are much higher than the last ones in spring (by 6.7–7.1 °C approaching 35 and 7.6–7.9 °C in built and vegetated LCZs, respectively) (Fig. 2b). It has to be noted that the favorable categories (from "s. cool" to s. warm) are a bit wider in this season with a few tenths of degree and the warm category starts almost 2 °C higher (see Table 2). The latter indicates that people are better acclimated to the warmer conditions after the summer months. The pleasant part of the season (neutral and s. warm) lasts until decas 29–30 and 30 for the vegetated and built LCZs, respectively (mid-October to end of October). At the end of season, LCZ D is already in the cool category (<7.9 °C).

In the evening, the shape of PET variations is very similar to the afternoon ones for both transitional seasons, just down the values of two categories (about 12–18 °C) (Figs. 2 and 3). In spring, the favorable conditions for staying outdoors in the evening appear already at deca 10 (mid-March) in the built zones but in the vegetated ones only 3 weeks later and remain in the s. cool category until the end of season (Fig. 3a). The autumn also begins with higher thermal conditions; namely, the first PET

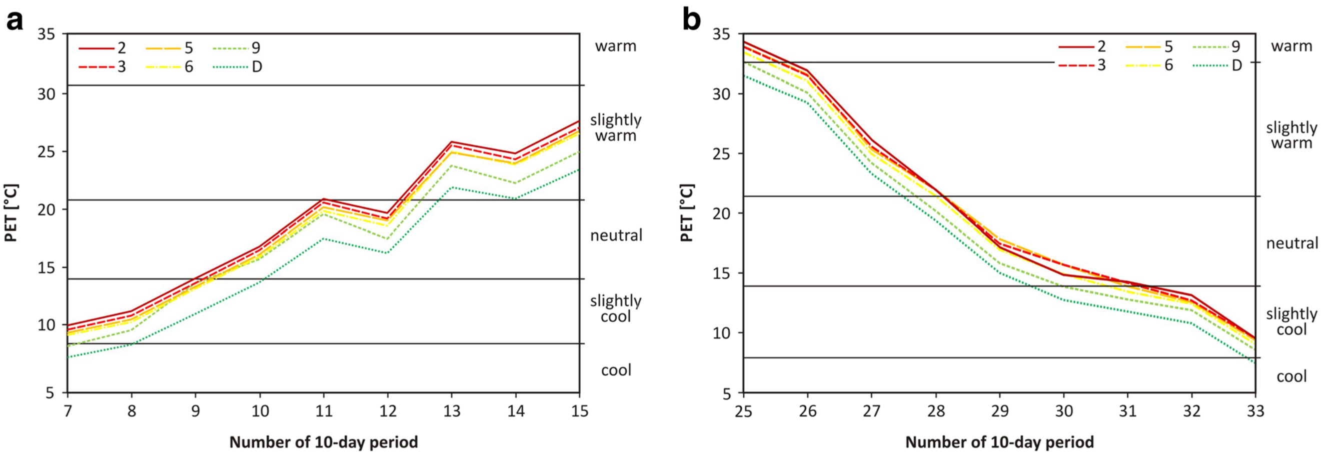

Fig. 2 Temporal variation of 10-day PET averages of the selected representative stations with calibrated seasonal PET categories on the right vertical axis (early afternoon, spring (**a**) and autumn (**b**), Szeged)

values (neutral category) are higher than the last ones in spring (4.9–5.1 and 4.7–4.8 °C in built and vegetated LCZs, respectively) (Fig. 3b). After end of September (deca 28) and early October (deca 29), the thermal conditions are no longer favorable for outdoor activities in the vegetated and built zones, respectively. Based on these results, generally, we can state that the time period with favorable outdoor thermal comfort conditions is longer in the built zones compared to the vegetated ones.

In summer afternoon (decas 16–24), the four built zones vary almost together with a maximum difference of 1 °C between them and their sequence follows their LCZ numbers (Fig. 4a). The vegetated zones break away from them, LCZ 9 at about 2 °C and LCZ D at a further 1 °C. The largest PET differences can be found between LCZ 2 and D (e.g., $\Delta PET_{LCZ\ 2\text{–}D}$~3.7 and ~4.6 °C at decas 18 and 20, respectively). The common feature is that all the 10-day averages are in the warm thermal sensation category except for LCZ D (slightly warm) at week 18 (mid-June) when an overall decline occurs in line with the long-term observations of Hungary's climate. At that time, usually moist air masses come to the area from the Atlantic Ocean resulting in heavy rainfalls associated with overcast sky and cooling. At decas 21–23 (end of July to August), the PET values (>37 °C) slightly approach the "hot" category in the most built-up zones (LCZs 2, 3, 5). The largest mean values occur at the end of July in each zone ($PET_{LCZ\ 2} > 38$ °C, $PET_{LCZ\ D} > 34$ °C), which mean a rather large heat load on humans. Thereafter, a setback is discernible, accelerating at the end of August.

In the evening, the increases or decreases in the summer PET variation are similar to the afternoon case but the values are two categories lower (neutral and slightly cool) (Fig. 4b). The differences in cooling started during this period result in differences between the densely built and more vegetated zones similar to those in the afternoon (e.g., $\Delta PET_{LCZ\ 3\text{–}D}$~4.8 and ~3.8 °C at decas 19 and 21, respectively). At that time, only the values in LCZs 2 and 3 vary together with slightly larger PETs in LCZ 3 in the neutral zone except in

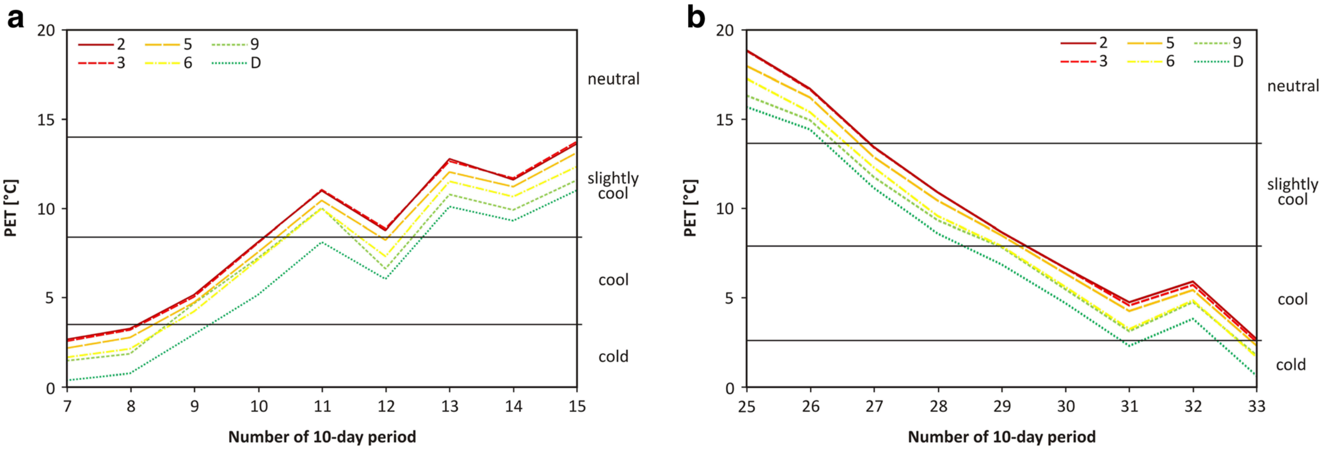

Fig. 3 Temporal variation of 10-day PET averages of the selected representative stations with calibrated seasonal PET categories on the vertical axis (evening, spring (**a**) and autumn (**b**), Szeged)

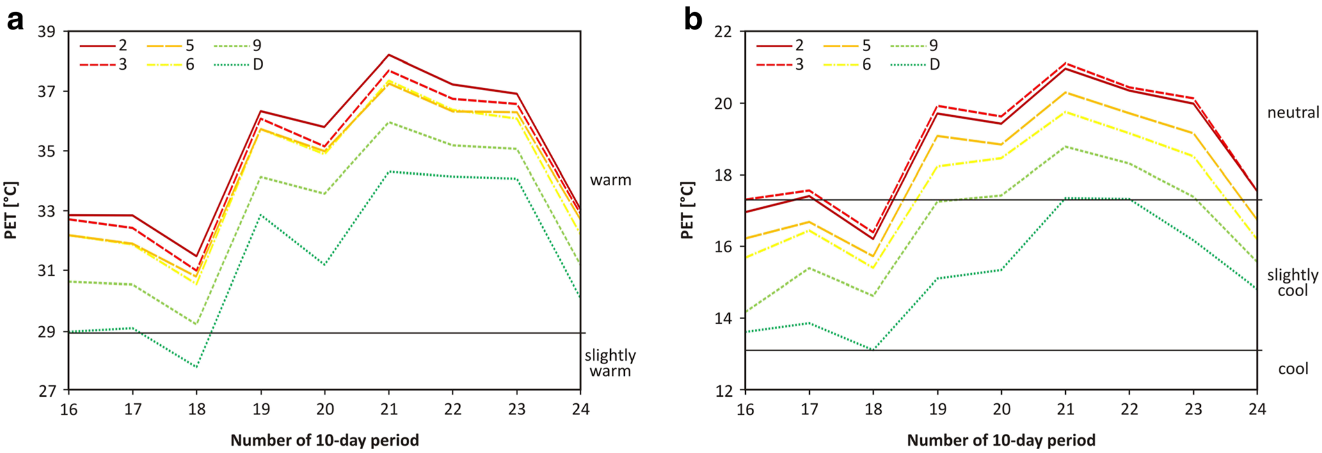

Fig. 4 Temporal variation of 10-day PET averages of the selected representative stations with calibrated seasonal PET categories on the vertical axis (early afternoon (**a**), evening (**b**), summer, Szeged)

week 18, while the other built zones follow them with differences of 0.5–1 °C between them. The PETs of LCZ D are in the slightly cool category during the whole season. As a consequence, in the evening, the built LCZs are generally suitable for outdoor leisure activities in almost the entire summer period.

Thermal sensation variations of LCZs during a heat wave period

During the selected heat wave period, the daily average temperatures exceed 27 °C on all 4 days with maximum temperatures of 35.7–37.2 °C and minimums of 16.9–19.5 °C (Fig. 5). The insolation was undisturbed during the daylight hours (regular bell-shaped *G* variation, cloudless sky) with maximum values over 800 $\mathrm{Wm^{-2}}$. The air movement, by and large, was moderate (0–4.8 $\mathrm{ms^{-1}}$) with smaller values at the nocturnal hours except the last night when the advection intensified slightly. All these data were measured in the rural surroundings of Szeged (at the HMS station representing LCZ D).

The daily variations of PET were similar on the investigated 4 days (Fig. 6). The values in the mid-day hours (from 9–10 to 17–18 LST) are in the hot category with only a few °C intra-urban differences (the largest one is $\Delta\mathrm{PET}_{\mathrm{LCZ}\ 2\text{–}\mathrm{D}}$ = 2.6 °C), indicating a very serious heat load in the daylight hours in every part of the city. The largest values are in LCZ 2 (>45 °C), and they approach 50 °C on 15 August. Near the sunset (18.50 LST) in a short time, the values drop back two categories to the slightly warm category in all LCZs and begin to separate because of the different cooling rates of the zones. During the night, the $\Delta\mathrm{PET}_{\mathrm{LCZ}\ 2\text{–}\mathrm{D}}$ is sometimes larger than 6 °C. In the nocturnal hours, the LCZs 2, 3, and 5 are in the neutral, while LCZs 9 and D are in the slightly cool categories except the night of the 15th when the abovementioned intensified advection mixed the air

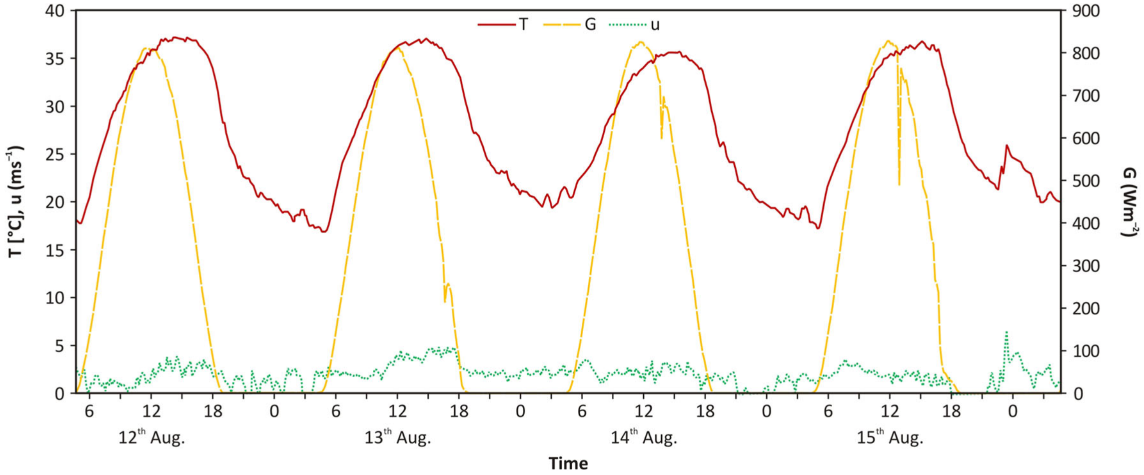

Fig. 5 Temporal variation of *T*, *G*, and *u* at the HMS station representing LCZ D during a heat wave period (12–16 August 2015, Szeged)

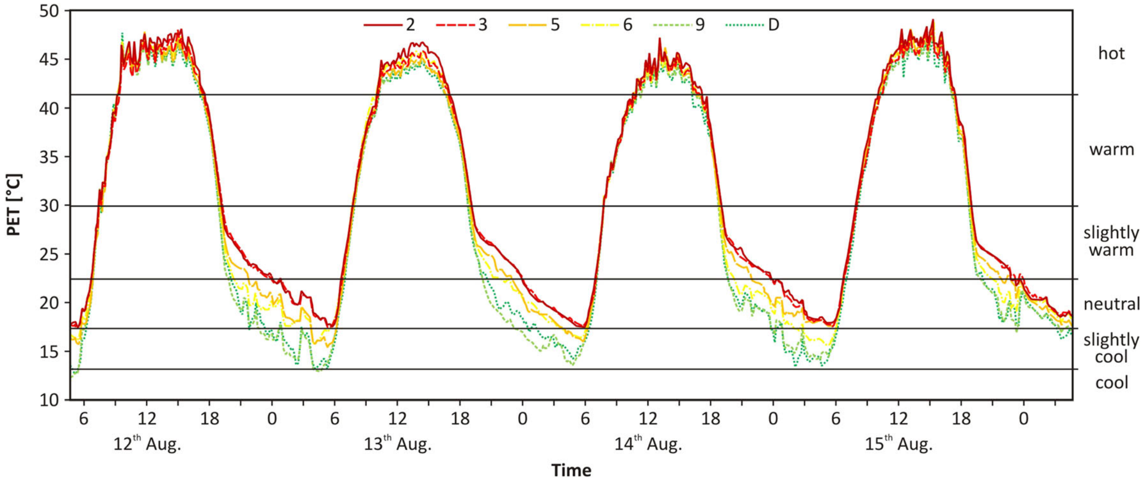

Fig. 6 Temporal variation of PET at the selected representative stations with calibrated summer PET categories during a heat wave period (12–16 August 2015, Szeged)

between the zones reducing the cooling in the more vegetated zones.

During this period, the daily range of PET was very large; its day-night variations exceeded 30 °C in the four built zones (LCZ 2—31.2 °C, LCZ 3—30.6 °C, LCZ 5—31.1 °C, LCZ 6—33.2 °C). Moreover, in the greener zones, it approached 35 °C (LCZ 9—33.9 °C, LCZ D—33.7 °C) spanning five thermal sensation categories.

According to Fig. 6, a 24-h day in this period can be divided clearly in two parts: when there is a thermal load and when there is not. This means that the city's entire population was exposed for 6–8 h to very stressful thermal conditions (hot) and additionally for about 5 h to conditions somewhat less stressful (warm). The real relief could only be expected after 19–20.00 LST (s. warm and neutral) and it took until 8.00 LST. In the LCZs 9 and D, one could even experience a little cold as the thermal sensation dropped to slightly cool for a few hours.

Summing up, there are no special, distinguishable thermal sensations in the different zones during the daylight hours. Contrary to this, the thermal sensations at night could clearly be separated by LCZs.

Conclusions

Our results provided insight into the outdoor thermal conditions in various urban and rural environments using the LCZ concept. The long-term (almost 3 years) data originated from an urban meteorological station network established in 2014.

Investigating and comparing the levels of outdoor human thermal sensations based on seasonal and annual LCZ averages and their temporal variations in different parts of the day, the following general findings emerged about the LCZ sequence according to the magnitudes of the thermal load exerted by them in Szeged:

LCZ 2−LCZ 3−LCZ 5−LCZ 6−LCZ 9−LCZ D

This sequence follows the LCZ numbers and it is perfectly in line with the LCZ concept originally concentrating only on air temperature differences between the zones. This LCZ sequence of thermal load means that in the daytime, the most pleasant zones are the less built ones, but in the evening, the situation will turn; namely, the inner urban parts are more pleasant to spend the leisure time outdoors.

Our results justified the subdivision of urban areas into LCZs and give significant support to the application possibilities of the LCZ concept as a broader term covering different thermal phenomena (e.g., outdoor human thermal sensation, as in our study).

It should be noted that the meteorological data used in this research relate to urban open spaces and represent the built and vegetated environments' effect generally. Therefore, the results presented here relate to a given zone type generally; that is, they can only apply to exposed open areas well inside the LCZs and are not applicable to a specific complex urban micro-environment (as no urban effects of the radiation exchange between a pedestrian and its environment were determined in this study).

Based on the previous findings, the LCZ system is an appropriate classification for interpreting *general* (*local-scale*) human thermal comfort but it has limitations regarding the *micro-scale* thermal comfort investigations.

These type of long-term studies based on LCZ division could locate the thermally stressful areas within the cities providing valuable information for urban planners and decision-makers for evolving strategies against the adverse effects of urban climate and climate change.

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