Theor Appl Climatol (2015) 122:531–541
DOI 10.1007/s00704-014-1309-6

ORIGINAL PAPER

Urban field classification by “local climate zones” in a medium-sized Central European city: the case of Olomouc (Czech Republic)

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Received: 21 November 2013 / Accepted: 29 October 2014 / Published online: 13 November 2014

Abstract The stations of the Metropolitan Station Network in Olomouc (Czech Republic) were assigned to local climatic zones, and the temperature characteristics of the stations were compared. The classification of local climatic zones represents an up-to-date concept for the unification of the characterization of the neighborhoods of climate research sites. This study is one of the first to provide a classification of existing stations within local climate zones. Using a combination of GIS-based analyses and field research, the values of geometric and surface cover properties were calculated, and the stations were subsequently classified into the local climate zones. It turned out that the classification of local climatic zones can be efficiently used for representative documentation of the neighborhood of the climate stations. To achieve a full standardization of the description of the neighborhood of a station, the classification procedures, including the methods used for the processing of spatial data and methods used for the indication of specific local characteristics, must be also standardized. Although the main patterns of temperature differences between the stations with a compact rise, those with an open rise and the stations with no rise or sparsely built areas were evident; the air temperature also showed considerable differences within particular zones. These differences were largely caused by various geometric layout of development and by unstandardized placement of the stations. For the direct comparison of temperatures between zones, particularly those stations which have been placed in such a way that they are as representative as possible for the zone in question should be used in further research.

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1 Introduction

With the development of computing capabilities, new perspectives have opened up for the measurement, analysis, and modeling of the regime of meteorological variables that are critical for the study of urban climate (Grimmond 2006). In spite of this technical progress, the expected shift in the knowledge acquired in the study of urban climate onto a wider level of application has occurred slowly.

Dozens of papers relating to cities’ climates have recently been published in Central Europe. Only a small number of these papers describe the specific local features of the urban climate in a way that brings accepted knowledge into this field of study (e.g., Unger et al. 2001; Kłysik and Fortuniak 1999; Offerle et al. 2005, 2006; Fortuniak et al. 2006; Bokwa 2011). Roth (2000) reports that many studies on urban climate lack information about its background. Stewart and Oke (2009a) reported that up to a third of the papers dealing with urban heat island (UHI) provides no quantitative or qualitative description of the measurement sites defining the magnitude of a UHI. Subsequently, Stewart (2011) concluded that up to three quarters of UHI studies fail in the documentation and the presentation of proper metadata.

It is understandable, therefore, that some members of the urban climate research community have called for the unification of the methodology of the study of urban climate and a consequent improvement of its applicability in practice (Scherer et al. 1999; Arnfield 2003; Oke 2006a; Stewart 2007, 2011). In order to standardize the character of urban locations, a number of classification schemes have been proposed (Muller et al. 2013). One of the new schemes aiming at the standardization of the characteristics of the urban morphology of urban sites is the concept of local climate zones (LCZ), which has been suggested by Stewart and Oke (2012). The applications of the LCZ classifications published to date (Stewart and Oke 2009b; Bechtel 2012; Stewart et al. 2013; Fenner et al. 2014 and Lelovics et al. 2014) suggest that this concept could significantly contribute to the unification of metadata reporting in urban climate research.

An LCZ is defined as a universal classification that may be applied across the landscape in all the regions of the world. From a methodological point of view, the new classification of LCZ—see Stewart and Oke (2012) is built on the same principles as the older simplified classification of urban climate zones (UCZ) by Oke (2004). While in Oke's former (2004) classification of the UCZ, the structural and land cover properties include the roughness of the terrain, aspect ratio, and impervious surface fraction; the new LCZ classification contains seven parameters covering geometric and surface cover properties and three parameters covering thermal, radiative, and metabolic properties. Thus, each of the defined LCZs is characterized by intervals of typical values of 10 measurable physical properties.

In our paper, we have applied the LCZ classification to the meteorological sites of the Metropolitan Station System in Olomouc (MESSO), Czech Republic. The study has two main objectives: (a) to use the values of geometric and surface cover properties to classify the MESSO stations into relevant LCZs and thereby test the versatility and practicality of the LCZ classification; (b) to compare the selected temperature characteristics of the MESSO sites with their LCZ classes to better understand the heat island of the city of Olomouc.

2 Data and methods

2.1 Temperature measurement and network specification

Olomouc is a medium-sized Central European city (100,000 inhabitants), which has undergone several significant phases of spatial, cultural, and socioeconomic development during its history (Ptáček et al. 2007). Besides the predominantly midrise historical buildings with courtyards and narrow streets in the city center, which is surrounded by city parks, Olomouc has a lot of brownfields, midrise and high-rise blocks of flats, low-rise residential areas, industrial areas, and large low-rise business centers and suburbs, which were formerly separate villages and are now integrated into the city.

Olomouc is located in a valley oriented in a NW-SE direction at an average altitude of 220 m. The elevation differences of the area are low as a result of the flatland to upland character of the relief. The difference between the highest- and the lowest-lying MESSO stations used in this study was only 47 m. In the northeast beyond the compact rise, the relief passes along a fault slope and changes into an upland character and rises by about 200 m, which results in a change in the mesoclimate (the stations in this part of the city and its surroundings were not included in the study). The city is almost entirely surrounded by agricultural areas, with mostly low plants. In some places, the large fields give way to smaller gardens and orchards. On the northwestern outskirts of the city, i.e., in the direction of the prevailing air flow, there is a southern end of a belt of floodplain forests along the Morava River and its cutoffs, with numerous wetlands and water surfaces. In the city itself, there are no large areas of water or rivers exceeding 40 m in width.

The Olomouc climate has a typical Central European character. The average annual temperature is 8.9 °C. The annual air temperature variation in the Olomouc region shows 1 maximum and 1 minimum. The warmest month is July (19.1 °C) and the coldest is January (−2.2 °C). The average annual rainfall is 546.7 mm, and it is characterized by a summer maximum (76.8 mm in July) and winter minimum (22.4 mm in February). The average occurrence of permanent snow cover in Olomouc is 42 days a year (the abovementioned data relate to the period 1961–2010 and were obtained from the measurements of the station of the Czech Hydrometeorological Institute in Olomouc-Holice).

MESSO included up to 24 sites. The network design was approximately radial in order to capture various locations in Olomouc and its surroundings. Aiming to follow the guidance of Oke (2006b) for urban observations and the criteria of Stewart (2011) for representative UHI observation, 14 stations of MESSO were found to be sufficient for this study (Fig. 1).

The MESSO network consisted of two types of stations: the BOT_PdF, DOMI, HOLI, and LETO stations were fully automated, and, besides the air temperatures, they also registered other meteorological characteristics—humidity, precipitation, global radiation, wind speed and direction, ground temperature, soil temperature, and soil moisture (Fig. 2b). The reading intervals at these stations were 10 min, and the data were automatically sent to the server via GSM once a day. The stored data were checked every day. Physical checks on these stations were carried out at monthly intervals, or, in the event of a technical failure, as soon as possible.

The CHVA, CMSE, EINS, HODO, HORL, KOJE, KREL, PRAZ, REPC and VVMU stations only measured air temperature and humidity (Fig. 2a). Data were recorded in the internal memory at 30-min intervals and had to be downloaded in situ every month.

The temperature sensors at all the stations were placed in radiation shields at a height of 1.5 m above the ground and were only naturally ventilated. Note that the absence of active (artificial) ventilation must be taken into account throughout the results, especially those where the daytime temperatures were analyzed. More information on the individual stations is provided in Table 1.

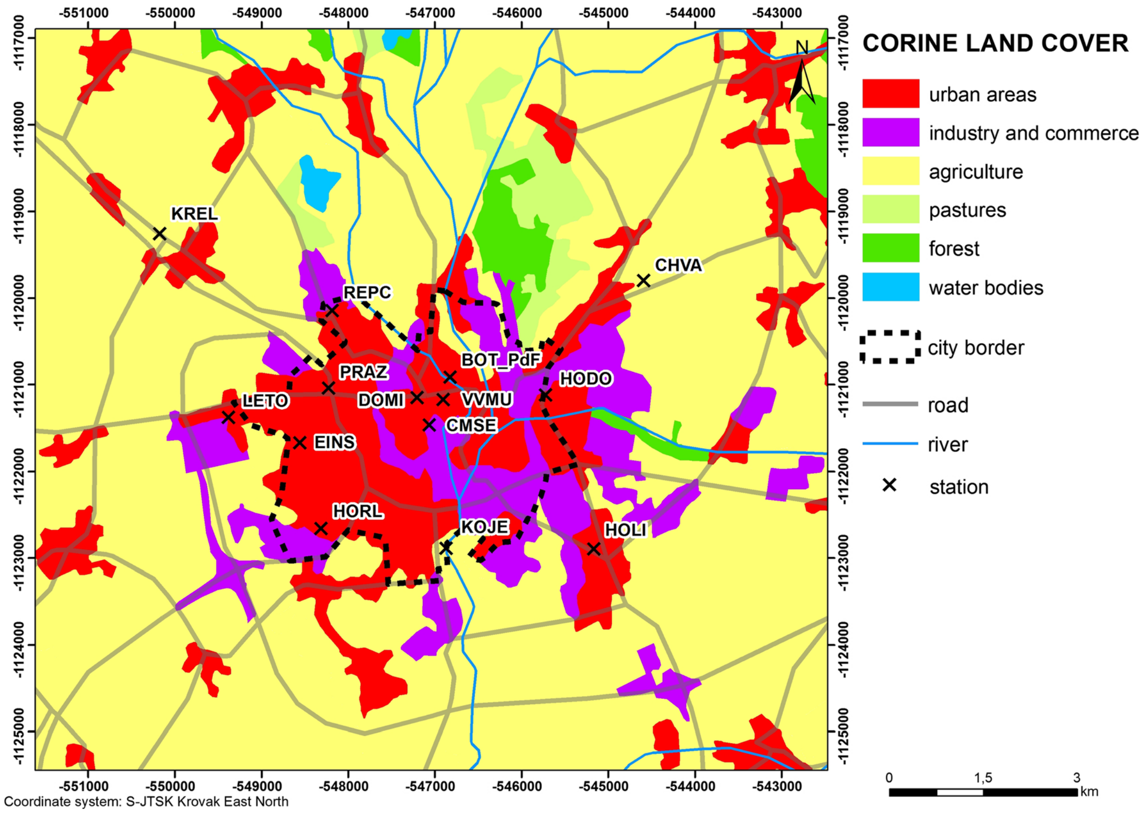

Fig. 1 Map of selected Metropolitan Station System in Olomouc stations; basis data: CORINE Land Cover 2006 Czech Republic Database (© AOPK, Nature Conservation Agency of the Czech Republic) and WMS-ZM10 (© ČÚZK, Czech Office for Surveying, Mapping and Cadaster)

2.2 Temperature data treatment

To illustrate the spatial variability of the air temperature, we have chosen the years 2010 and 2011, when the highest number of MESSO stations was in operation. We selected only days with radiation weather regime that followed another day with radiation weather regime (i.e., the second day in a series of 2 days with radiation weather regime), and with snow cover not appearing on either of these 2 days. The days with a radiation weather regime were those with a wind velocity below 2 m s^{-1} and when cloudiness was less than two-tenths of the sky cover. These criteria were chosen so that the local

Fig. 2 Stations: **a** EINS and **b** LETO

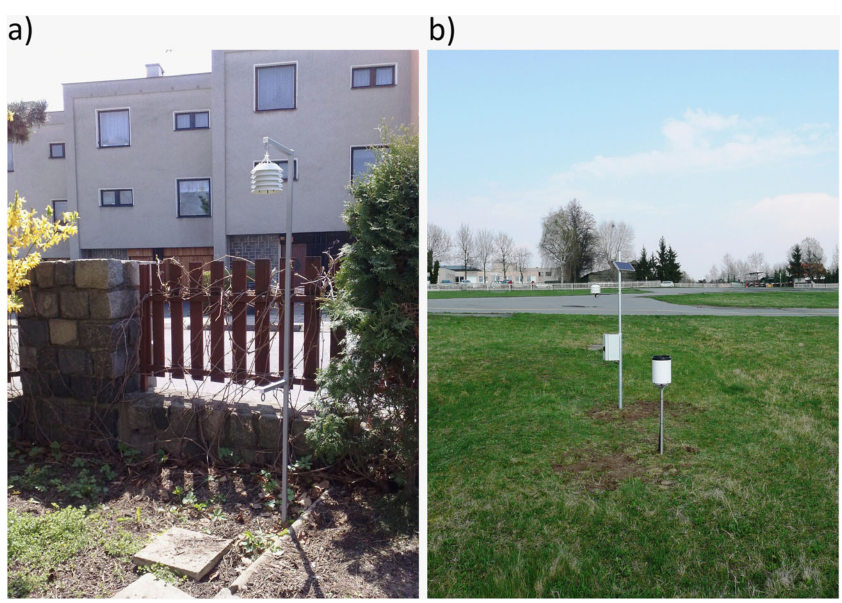

Table 1 Metadata of selected Metropolitan Station System in Olomouc stations

Station	Start-up date	Status	Sensor type	Sensor accuracy (°C)	Active surface in immediate surroundings (20 m)	Altitude (above sea level) (m)	Latitude	Longitude
BOT_PdF	8 April 2010	Working	SHT75K (Sensirion)	±0.3	Grass, buildings, trees	211	49° 36.016′ N	17° 15.457′ E
CHVA	24 March 2009	Working	MicroLog EC750 (Fourier)	±0.2	Grass, trees, buildings	216	49° 37.010′ N	17° 17.882′ E
CMSE	27 April 2007	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, pavement, buildings, bushes	237	49° 35.591′ N	17° 15.243′ E
DOMI	8 April 2010	Working	SHT75K (Sensirion)	±0.3	Grass, trees, pavement, buildings	220	49° 35.810′ N	17° 15.044′ E
EINS	1 February 2010	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, trees, asphalt, pavement, buildings	243	49° 35.326′ N	17° 13.558′ E
HODO	1 January 2009	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, asphalt, buildings	214	49° 35.994′ N	17° 16.738′ E
HOLI	8 May 2009	Working	SHT75K (Sensirion)	±0.3	Grass, asphalt, buildings	217	49° 34.664′ N	17° 17.578′ E
HORL	1 February 2010	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, trees, gravel, asphalt, buildings	233	49° 34.606′ N	17° 13.949′ E
KOJE	30 May 2007	Working	MicroLog EC750 (Fourier)	±0.2	Grass, trees, asphalt, buildings, pavement	210	49° 34.545′ N	17° 15.625′ E
KREL	1 December 2007	Working	MicroLog EC750 (Fourier)	±0.2	Grass, trees	250	49° 37.010′ N	17° 11.239′ E
LETO	27 March 2007	Working	SHT75K (Sensirion)	±0.3	Grass, asphalt, buildings	257	49° 35.482′ N	17° 12.582′ E
PRAZ	1 February 2010	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, pavement, buildings, trees	227	49° 35.817′ N	17° 13.863′ E
REPC	1 May 2009	Working	MicroLog EC750 (Fourier)	±0.2	Grass, pavement, buildings, trees	219	49° 33.608′ N	17° 14.487′ E
VVMU	30 April 2009	Stopped (1 January 2012)	MicroLog EC750 (Fourier)	±0.2	Grass, trees, gravel, asphalt, buildings, pavement	225	49° 35.816′ N	17° 15.394′ E

climate was reflected. In 2010, we had 10 days (July 9–12, August 11, August 21–22, September 22, and October 11–12), and in 2011, we had 5 days that met the above conditions (March 30, May 7, September 27, October 1, and October 17).

For the days selected by the above method, two thermal characteristics were chosen—the temperature 8 h after sunset and the maximum daily temperature. The average temperature variability between the stations in a period of a negative energy balance was at its greatest just 8 h after sunset. Therefore, this characteristic well expresses the intensity of the UHI, which is best expressed in the night hours (Arnfield 2003). As a second characteristic temperature, we chose the maximum daily temperature, which does not describe the intensity of the UHI at a particular moment, but corresponds well with the maximum warming-through of the surface and the temperature stress.

2.3 Treatment of data on structural and land cover properties

We established values for six geometric and surface cover properties (henceforth referred to as "parameters"): sky view factor (SVF), aspect ratio (AR), building surface fraction (BSF), impervious surface fraction (ISF), pervious surface fraction (PSF), and height of roughness elements (HRE).

SVF was established directly in the place of the station using fish-eye photo-based calculation. AR was established for the immediate surroundings of the station (using 3D layers of the development for the built type subset of classes and field investigation for the land cover type subset of classes). The other parameters (ISF, PSF, BSF, and HRE) were calculated for the 200-m circle radius.

A thermal source area with a circle radius of about 200 m was adopted on the basis of the results of the analysis of the factors influencing the temperature field in Olomouc and its surroundings, where buffer zones around the stations with a radius of 100, 200, 400, and 800 m were tested using the land use regression method. The land use regression method is described, for example, by Ryan and LeMasters (2007). For more than 20 parameters, the air temperature correlated best with the land use. Overall, the highest values of R^2 were found just for the 200-m buffer zone (0.85) except that a slightly smaller value of R^2 (0.83) was observed for the 100-m buffer zone. Similar radius of circle of influence may be found in the studies of urban climate by Houet and Pigeon (2011) or Merbitz et al. (2012).

BSF, ISF, and PSF were determined on the basis of the simple calculation of the ratio of the individual surfaces of a freely accessible satellite image. To determine the HRE, the 3D layer of the development was used for LCZ 1–10, and the average height of the vegetation found in the field investigation was used for LCZ A-G.

2.4 Matching sites to LCZ zones

In accordance with the guidelines of Stewart and Oke (2012), the MESSO stations were classified within the LCZ. The actual procedure of the classification process has not been clearly established yet. Two approaches are distinguishable in the current literature—expert knowledge classification (e.g., Stewart et al. 2013; Fenner et al. 2014) and automated classification (e.g., Lelovics et al. 2014; Bechtel and Daneke 2012). We decided to use an approach which is not completely automated but where the process of the assignment of the station into the LCZ has an objective framework (Table 2).

As a first step, we decided whether a station is classified within the built type or land cover type subset of classes. We used the BSF, ISF, and PSF parameters. For each of these parameters, we calculated the difference from the nearest outer limit of the interval of typical values of the parameter, as suggested for individual zones by Stewart and Oke (2012). If the values fell inside the suggested interval, the difference was calculated as zero. The station was then classified into the subset of classes in which that class was found for which the sum of the absolute values of the differences found was the smallest.

In the second step, we classified the stations in the respective LCZs. For stations classified in the built type subset of classes, the method of calculation was the same as in the first step, with the only difference being that the HRE parameter was added to the calculation. The values of absolute differences for HRE were multiplied by three, because BSF, ISF, and PSF are not independent of each other. For stations classified in the land cover type classes of subset, a station was included in the respective zone following the value of HRE, as well as visual assessment of vegetation in the height category (e.g., low plants vs. bushes and shrubs).

In the third step, the classification of stations within LCZs was reviewed in terms of the actual visual appearance of the area. This step should ideally serve only to supplement a subclass to a parent class where necessary (e.g., specific properties of land cover and geometric layout of development around the station or the occurrence of areas with properties characteristic of another LCZ). In one case, however, because of the inhomogeneity of the buildings in the neighborhood of the stations and the averaging of the values of the calculated parameters, we decided to change the parent class (Table 3). The class we selected as the new parent class was, in accordance with the first and second steps, the second closest class which corresponded well with the real visual appearance of the area around the station (see Section 4).

In the fourth step, we used the AR and SVF parameters calculated for the immediate surroundings of the station to check the representativeness of the location of the station for a particular parent class. The limits of the representativeness of a station within a parent class were selected as follows: for

Table 2 Methods of classification of the Metropolitan Station System in the Olomouc stations within local climate zones

Step	Sample	Decision	Method	Parameter
1	All sites	Subset of classes	Sum of absolute differences of parameters from the nearest outer limit of intervals of typical values	BSF, ISF, PSF
2a	Built types	LCZ	Sum of absolute differences of parameters from the nearest outer limit of intervals of typical values	BSF, ISF, PSF, HRE
2b	Land cover types	LCZ	HRE value in relation to interval of typical values, description of vegetation	HRE
3	All sites	Subclass/reclassification	Evaluation of land cover properties and geometric layout of development in the immediate surroundings of a station	–
4	All sites	Site representativeness	Values of AR and SVF in relation to the suggested intervals	SVF, AR

SVF: within an interval of typical values=high representativeness, extending the interval by ±(≤10)=limited representativeness and extending the interval by ±(>10)=low representativeness; for AS: within an interval of typical values=high representativeness, extending the interval by ±(≤0.2)=limited representativeness and extending the interval by ±(>0.2)=low representativeness.

3 Results

3.1 Site classification

The concept of the classification of LCZ urban sites according to Stewart and Oke (2012) was applied to the MESSO stations. The typical features of the urban development of Olomouc and the original MESSO design, i.e., a network with an approximately radial placement of stations, prevented the unambiguous classification of some stations within the LCZ classes. In many cases, it was difficult to apply a suitable classification as the homogeneity of the buildings, and the land cover was usually maintained only in small polygons. Historical center is immediately bordered by parks, and housing estates adjoin original low rural buildings or even spread into agricultural areas (Fig. 3). Therefore, it was often necessary to use the subclasses (Table 3).

The DOMI station, whose BSF, ISF, PSV, and HRE parameters best corresponded to LCZ 2, was defined as 2_{Boc}, where oc (open courtyard) indicates its location in an open courtyard and B indicates scattered trees in the courtyard. The CMSE station, according to the BSF, ISF, PSF, and HRE

Table 3 Values of geometric and surface cover properties, results of classification of Metropolitan Station System in Olomouc stations within local climate zones, and representativeness of stations within a parent class

Station	Sky view factor (%)	Aspect ratio	Building surface fraction (%)	Impervious surface fraction (%)	Pervious surface fraction (%)	Height of roughness elements (m)	LCZ after step 2	LCZ	Representativeness for parent class (sky view factor)	Representativeness for parent class (aspect ratio)
BOT_PdF	84	0.1	10.5	14.9	74.6	17.0	9	9_5	High	High
CHVA	78	0.2	5.8	5.0	89.2	9.0	B	B_{Dw}	High	Limited
CMSE	25	2.5	45.0	28.1	27.0	23.5	2	2_{cc}	Limited	Low
DOMI	70	0.8	42.6	34.2	23.2	24.3	2	2_{Boc}	Limited	High
EINS	50	0.5	21.5	25.1	53.4	10.0	6	6	Limited	High
HODO	48	0.8	27.0	34.6	38.3	15.6	5	5	Limited	Limited
HOLI	84	0.6	34.0	30.1	35.9	11.1	5	5_6	Limited	High
HORL	49	1.1	14.9	32.5	52.6	28.6	4	4	Limited	High
KOJE	70	0.6	7.0	22.9	70.1	13.0	9	9_5	Limited	Low
KREL	74	0.2	4.0	4.2	91.8	8.0	B	B_D	High	Limited
LETO	100	0.1	7.1	20.6	72.4	16.8	9	9_5	High	High
PRAZ	72	0.5	27.1	32.2	40.8	14.7	5	5	High	High
REPC	80	0.7	26.0	36.4	37.6	11.0	5	6_5	High	High
VVMU	37	1.7	38.0	28.8	33.3	27.2	4	4_2	Low	Low

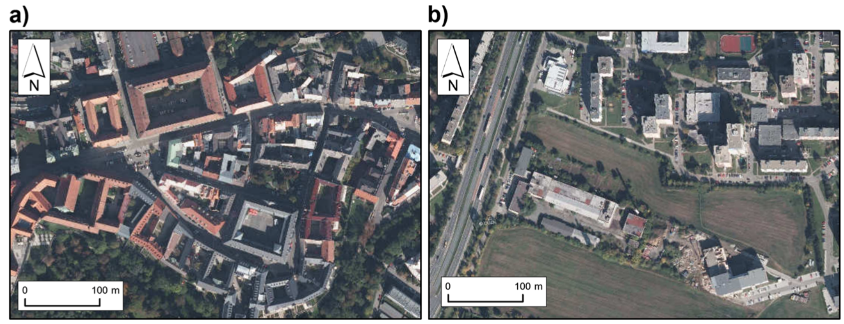

Fig. 3 The character of development in Olomouc: **a** historical center and **b** outskirts. Source: WMS-ORTOFOTO (© ČÚZK, Czech Office for Surveying, Mapping and Cadaster)

values, corresponded well with LCZ 2. However, its location in a closed courtyard (cc) must be indicated, as suggested by low SVF values or high AR values. The VVMU station was classified as LCZ4_2, because the development in some patches in its neighborhood corresponds better to LCZ 2. Its representativeness for the parent class LCZ 4 is therefore low. The values of the parameters of the HOLI station correspond perfectly to LCZ 5, but in its immediate neighborhood, some areas with development typical for LCZ 6 can be found, and the station was therefore classified as LCZ 5_6. The BOT_PdF, LETO, and KOJE stations were identified as LCZ 9_5 stations. The BSF, ISF, PSF, SVF, and AR values of the BOT_PdF and LETO stations correspond to LCZ 9, but the buildings around them were considerably higher than those typical for LCZ 9. The KOJE station is located in such a way that even the AR and SVF values indicate the presence of higher buildings. The development around these stations reflects the unfinished urbanization of the outskirts of the city in the period of central planning (associated with socialist era in former Czechoslovakia). The KREL and CHVA stations were marked as B_D because their immediate surroundings were typically occupied by orchards but in the circle of influence low plants fields prevailed. More precisely, the CHVA station was classified as B_{Dw}, where w indicated waterlogged soil.

In the case of the REPC station, we reconsidered the classification of the station in the suggested parent class in the third step on the basis of the real visual appearance of the area. The reason for the change was the influence on the classification process of a distorted value of HRE, which was increased as a result of the occurrence of a multi-storey building that disrupted the homogeneity of the surrounding development. In accordance with the prevailing development in the source area, the station was classified as LCZ 6_5, where subclass 5 indicated the occurrence of a higher building.

After the classification of all the stations in the zone or subzones, the geometric and surface cover properties' values correspond fairly well to those proposed for the particular zones by Stewart and Oke (2012); (Fig. 4). Nevertheless, some variations may be found that are caused by specific local features. The causes of the higher HRE values at some stations have been described above. It also happened that even where the remaining geometric and surface cover properties corresponded well with the typical values for the LCZ in question, the PSF values were sometimes slightly higher than it is typical for a particular zone (the CMSE, DOMI, HORL, and PRAZ stations). This is caused by the amount of greenery (public spaces, courtyards, and gardens) that is maintained in the compact urban rise of Olomouc. In some cases, the values of the SVF and AR parameters were also moving beyond the suggested intervals. They are immediately related to the actual location of a station, and therefore, they were taken into account in considering the representativeness of a station within a relevant parent class. If the values of the parameters were moving beyond the typical intervals of these parameters for a particular zone, the station was classified as limitedly or insufficiently representative of the particular parent class (Table 3). For the interpretation of temperature measurements at these stations, the indicated subclass must always be taken into account.

Although the specified geometric and surface cover properties' values for the MESSO stations corresponded well with the LCZ that was assigned, the character of the development around the stations classified within the same LCZ was not even approximately the same in all cases. As Olomouc is characterized by a wide variety of compact morphologies and the MESSO stations were located in different parts of the city, areas with different geometric layouts and urban greenery differentiating in its distribution and rise may be found within the same LCZ. This internal inhomogeneity was particularly evident within LCZ 2, LCZ 4, and LCZ 5.

3.2 Temperature variation

The temperatures 8 h after sunset and the maximum daily temperatures had very similar relationships between the stations that were monitored on particular days with radiation weather regime (Fig. 5). It is therefore surprising that the temperature values do not show a clearer correlation with respect to the classification of the stations within individual LCZs. However, when the temperatures are examined in more detail in the context of the location of the stations, the causes of such results can be found.

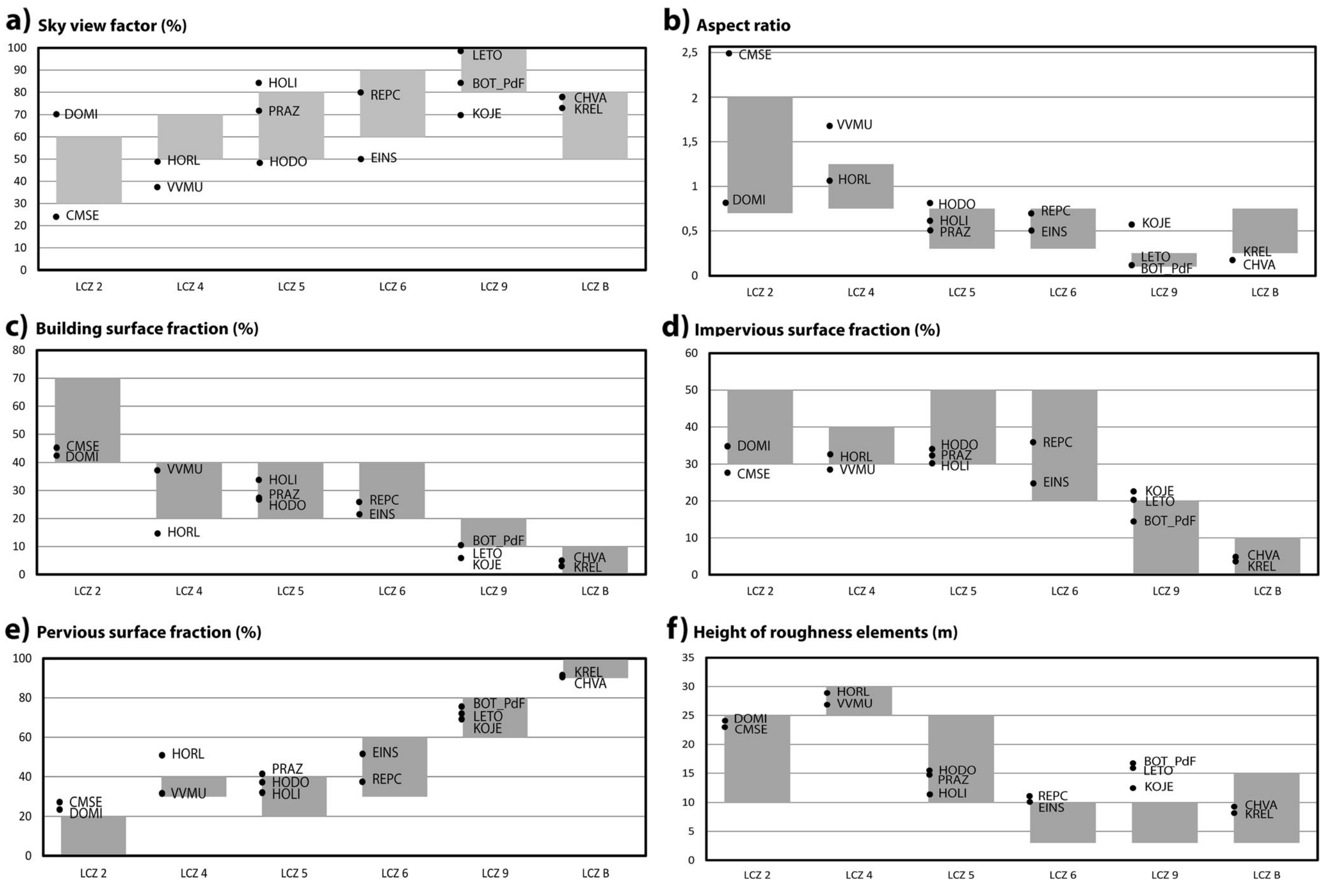

Fig. 4 Values of geometric and surface cover properties at Metropolitan Station System in Olomouc stations classified within local climate zones in comparison with typical values by Stewart and Oke (2012): **a** sky view factor, **b** aspect ratio, **c** building surface fraction, **d** impervious surface fraction, **e** pervious surface fraction, and **f** height of roughness elements; the interval highlighted in gray indicates the default values; if the zones are divided, the interval for the parent class is indicated

In Fig. 5a, which shows the temperature 8 h after sunset, it is clear that higher temperatures were regularly found late at night at the CMSE (LCZ 2_{cc}) and VVMU (LCZ 4_2) stations with a compact rise. In a majority of cases, and without any visible relationship to the density of development, the stations HOLI (LCZ 5_6), EINS (LCZ 6), and LETO (LCZ 9_5) located near large asphalt surfaces also averaged higher temperatures. Where the development surrounding the stations was more open and with larger areas of vegetation, the temperatures were lower, including the stations DOMI (LCZ 2_{Boc}), HORL (LCZ 4), REPC (6_5), and BOT_PdF (9_5). The lowest temperature was reported by the CHVA station (LCZ B_{Dw}). When the temperatures at all the stations are compared, it is clear, however, that the UHI is incoherent and its intensity varies. Therefore, the temperature values at some stations require specific explanation.

The high night temperatures at the LETO (LCZ 9_5) station were probably caused by its location in the slightly elevated area of the local airfield, where the presence of concrete and asphalt surfaces substantially influenced the surrounding temperatures on some days. The EINS (LCZ 6) station was located in a development which corresponded well to the characteristics of LCZ 6. However, the built-up area of row houses separated from the asphalt road only by a small garden, in which the station was located, kept the temperatures in the street higher (there are larger gardens located behind the houses). On the contrary, in the case of the REPC (LCZ 6_5) station, where the measured temperatures were mostly lower, the station was located in a larger garden behind a house. The differences between the night temperatures at the two stations located in scattered trees CHVA (LCZ B_{Dw}) and KREL (LCZ B_D) were also considerable; the cause of this has been examined and may relate to a specific temperature-humidity regime in the ground layer of the atmosphere affected by the increased level of the soil moisture and waterlogged areas around the CHVA station.

The other characteristic that was presented was the maximum temperature (Fig. 5b). High maximum temperatures were usually found at the stations DOMI (LCZ $2B_{oc}$), HORL (LCZ 4), PRAZ (LCZ 5), and BOT_PdF (LCZ 9_5), which were located in or close to open spaces in the city.

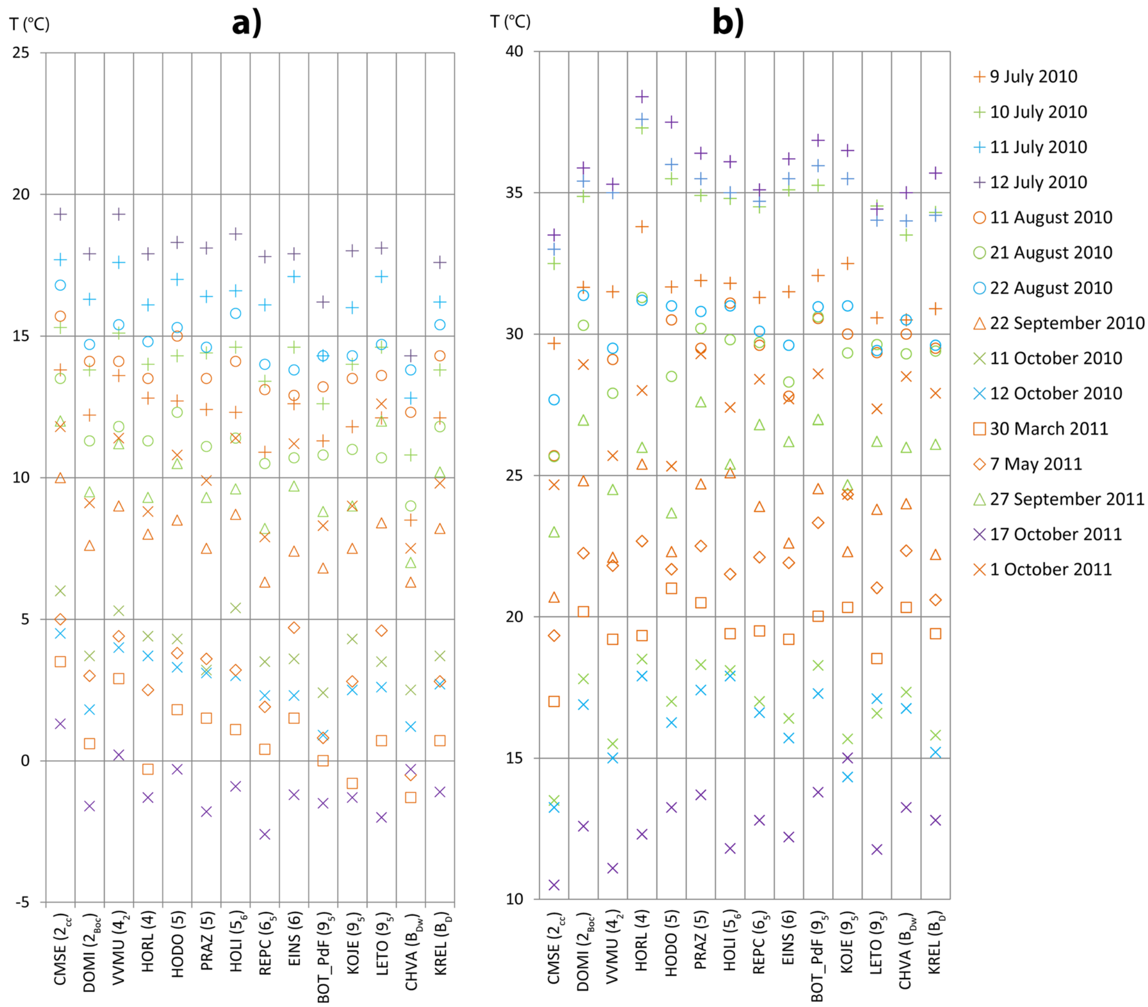

Fig. 5 Selected temperature characteristics of Metropolitan Station System in Olomouc stations classified in the LCZ: **a** temperatures 8 h after sunset and **b** maximum daily temperatures

However, considerably lower maximum temperatures were not found in most cases, even for the CHVA (LCZ B_{Dw}) and KREL (LCZ B_D) stations located outside the city. The lowest maximum temperatures were therefore regularly measured at the CMSE (LCZ 2_{cc}) and often also at the VVMU (LCZ 4_2) station, with dense development, narrow streets, and tiny courtyards in the historic center of the city, which were in the shade for most of the day.

In comparison with the maximum temperatures at other stations, the maximum temperature at the KOJE (LCZ 9_5) station showed very specific values. While on 12 October 2010, 27 September 2011, and 1 October 2011, the maximum temperature at the KOJE station were ranked among the lowest; on 9 July 2010, 10 July 2010, 7 May 2011, and 17 October 2011, the maximum temperatures at this station ranked among the highest of all. The cause of this anomaly probably lies in the influence of a 30-m-wide river that flows past about 60 m from the station.

4 Discussion

The values of the geometric and surface cover properties of BSF, ISF, and PSF are relatively easy to identify with sufficient accuracy and indicate very well which the LCZ zone station belongs to. SVF can also be defined very easily, while the determination of HRE and AR values can be more difficult. When 3D layers are used, their values can be calculated relatively easily, but it is necessary to overcome some methodical problems in their calculation. For example, it appeared that the simple method of assessing HRE using the average height of a building weighted by the area of the bottom of the building, which was used by us and by Lelovics et al. (2014), can devalue the results of the classification. Similarly, the method used to calculate AR in a location outside the street canyon must be specified more precisely.

Stations can easily be classified within a particular LCZ using only BSF, ISF, PSF, and HRE, whereas AR and SVF can be considered as convenient tools for the verification of representativeness of the location of a station with respect to the associated parent class. This can be considered a great contribution of the LCZ classification in comparison with the earlier UCZ classification. However, especially if the stations are classified within LCZ ex-post, as in our case, it seems appropriate also to estimate the surroundings of a station visually. In addition, to be able to use the automatic classification, some new input parameters should be involved and their typical values for particular zones defined in the first instance. Only then will it be possible to use quantitative methods to differentiate between stations (locations) included in the land cover type subset of classes. For example, Bechtel (2012) used albedo, the composition of the vegetation and a normalized difference vegetation index.

When classified within particular LCZs, most of the parameters of geometric and surface cover properties found for the MESSO stations corresponded to the values suggested by Stewart and Oke (2012). However, the geometric layout around the stations classified within the same LCZ was dissimilar (especially in the case of LCZ 2, LCZ 4, and LCZ 5). A similar problem in the classification of LCZs has already been solved by Bechtel and Daneke (2012) or Bechtel (2012) in the case of Hamburg (Germany); they split the central part of the city into "urbcores" (perimeter block buildings of uniform height with courtyards in the center) and "urbdens" (regular patterns aligned in rows). Even this solution, however, is incomplete. On the basis of the results of Bechtel (2012) and our results, it is clear that when LCZ classes are applied in individual cities, one must adapt the classes to the peculiarities of the city or region. In the case of many European cities, this means a compact midrise class with variously sized courtyards (Fig. 3a).

The courtyards are also problematic from a methodological point of view when selecting a location for a station. Oke (2006b) considers courtyards to be a typical example of a microclimate, which, as a result of the closed nature of the courtyards, does not allow such a place to be used as a representative location for the local climate. The local climate is highly relevant to the LCZ. The question is how to resolve the location of the stations in the area where courtyards with a similar geometric layout represent the same proportion of the surface cover as the street or even a larger one. In our case, we take into account the location of stations in a courtyard within the subclasses using the abbreviations cc (closed courtyard) and oc (open courtyard), which express the specific geometric layout of the development. In any case, the location of a station in a courtyard should reflect the ratio of ISF and PSF and the geometric layout typical of the development surrounding the courtyards (as in the case of the CMSE station). Because the courtyards often represent the only choice for a secure placement of a station, we must pay greater attention to looking for a representative location of the stations within the courtyards.

The fact that the temperature 8 h after sunset and the maximum temperature in our case clearly did not correspond to the classification of stations within particular LCZs, as, for example, in the case of Stewart et al. (2013), might be caused by three main reasons. The first is the aforementioned heterogeneity of the development around the stations classified within particular zones. Second, the location of the MESSO stations was not originally selected so as to make each station a good representative of a particular LCZ. Third, the sensors were not actively ventilated and therefore errors induced by radiation might occur, especially for the maximum temperatures in stations with a high SVF. Nakamura and Mahrt (2005), Huwald et al. (2009), and some others found that temperatures measured using non-actively ventilated radiation shields might be higher by a few tenths of a degree over a lawn as a result of radiative forcing on the sensor-shield system induced predominantly by reflected shortwave radiation. A similar degree of variability in the maximum and minimum daily temperatures within a UCZ was, however, also recorded by Houet and Pigeon (2011).

Nevertheless, the results pertaining to the spatial variability in the air temperature that were obtained are generally similar to the results of other authors who compared air temperatures between zones. For example, in accordance with the findings of Stewart et al. (2013) in Uppsala (Sweden), we found that the maximum temperatures of LCZ B or D may be higher than the maximum temperatures of LCZ 5 and LCZ 6, and also that, during the night hours, the warmest stations are mostly located in a compact rise (LCZ 2). The lower maximum temperature in the historic center of the city (LCZ 2) in comparison with the surrounding rise of the LCZ 5 type corresponded with the findings of Houet and Pigeon (2011), who, through the example of Toulouse (France), were the first to point out the lower maximum temperatures of the historic centers (UCZ 2 within the older UCZ classification, which they used) in comparison with the surrounding development (UCZ 3). In accordance with our results, higher night temperatures in LCZ 2 than in those in LCZ 5 were also described by Lelovics et al. (2014) in Szeged (Hungary). This variability in the air temperatures within a city indicates a necessity to overcome the existing urban–rural dichotomy, and the LCZ classification thus appears to be an essential tool for the new concept of UHI studies.

5 Conclusion

The LCZ classification can be used easily and properly as a basic source of information about the nature of the area around station. However, in order to have a full standardization of the description of the neighborhood of a station, we must also standardize the classification procedures, including the methods used for the processing of spatial data. The classification of subclasses should also be defined in detail so that the LCZ classification takes into account any specific local features without losing its general applicability and practical usability. Within subclasses, the classification of LCZ should also distinguish the geometric layout of the area.

Although the air temperatures varied greatly within a particular zone as a result of the nature of the development around the stations and insufficient standardization of the location of the stations in relation to a respective LCZ, it was clear that during the night hours, the air temperatures at stations located in the compact rise (LCZ 2) were higher than in the open rise (LCZ 4, 5, and 6), sparsely built areas (LCZ 9) and on the outskirts of the city (LCZ B). On the other hand, the maximum daily temperatures were lowest in the compact rise (LCZ 2) and higher in the open rise (LCZ 4, 5, and 6) and on the outskirts of the city (LCZ B). However, if the classification is to be used for comparing the temperatures between particular LCZs, it is necessary to follow more detailed recommendations regarding the location of the stations that are to represent a particular LCZ.

Acknowledgments This research project was funded by the Czech Grant Agency, Project No. 205/09/1297: "Multilevel analysis of the urban and suburban climate taking medium-sized towns as an example".

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