

Temperature differences among local climate zones established by mobile measurements in two central European cities

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ABSTRACT: Air temperature in urban areas is strongly influenced by the properties of surface cover, material and structure, and by human activity. Stewart & Oke (2012) quantified these properties and used them to introduce the definition of local climate zones (LCZs). LCZs should express characteristic temperature regimes of local-scale areas, and are supposed to be generic; however, their link to characteristic temperatures needs to be established based on field measurements. We investigated the link between LCZs and temperature in the central European cities of Brno and Olomouc, which differ in topography, relief, urban morphology and city size. We delineated LCZs, applying a clearly defined algorithm that uses data on the physical properties of the environment. In the next step, we performed night-time mobile air temperature measurements, and examined the differences between and within the LCZs. The results show that during calm and clear weather, the order of LCZ temperature was $LCZ\ 2 > 5 > 8 > 6 > 9 > A \approx D$ in Brno and $LCZ\ 2 > 5 > 8 \approx 6 \approx 9 > B > D$ in Olomouc. Temperature differences between LCZs, as well as their significance, were more pronounced in the larger of the 2 cities (Brno). Similarly, intra-class temperature variability was generally higher in the larger city, which has a more complex topography. Overall, this study supports the general LCZ temperature patterns and thus the validity of the concept of LCZs.

KEY WORDS: Local climate zone (LCZ) · Mobile measurement · Air temperature · Analysis of variance · Urban climate

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1. INTRODUCTION

Urban climate, particularly the phenomenon of the urban heat island (UHI) and its formation and structure, has been the subject of research for decades (Oke 1982, Arnfield 2003, Souch & Grimmond 2006, Mills 2014). Considering recent global climate change and ongoing urbanization, as well as burgeoning computing capabilities and progress in geographic information system (GIS) science, investigations into the temperature fields of urban areas still face new challenges. These include the need for standardized methods, applicability of the research to practice and the use of numerical modelling (Mills

2014, Stewart 2011); not surprisingly, these challenges are interconnected (e.g. modelling and validation should be based on high-quality field data and be widely intelligible to experts from other fields).

One of the responses of the urban research community to these challenges has been to work within the concept of local climate zones (LCZs) (Stewart & Oke 2012). LCZs consist of areas of uniform surface cover structure, material and human activity; they may cover areas ranging from hundreds of metres to several kilometres on the horizontal scale. The classification of LCZs was designed to be generic and intelligible to a wider community (local policy-makers, urban specialists, architects, ecologists and

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others), and thus general enough to cover both urban and rural areas around the world within a reasonable number of classes, yet sufficiently specific to allow objective delimitation and comparison (Stewart & Oke 2015). LCZs are currently employed in most major UHI studies (Skarbit et al. 2017) and their application in studies of phenology, urban ecology and epidemiology is also emerging (Bechtel et al. 2017). Nevertheless, LCZs are defined using structural characteristics (impervious surface fraction, pervious surface fraction, roughness, etc.) and not based on climate data measured in those climate zones. Thus, it is important to substantiate this definition and validate the concept with climate data measured in cities of different size, structure and climate background (Stewart & Oke 2012).

The findings of recent studies largely demonstrate temperature differences between LCZs (Table 1), supporting the validity of the concept. However, differences in the methods used and in the presented indicators, together with either missing or not well-documented statistical evaluation of temperature differences between LCZs, has often made any deeper comparison of LCZ temperature variability between cities impossible. The aim of the present study was to investigate and compare the link between LCZs and night-time air temperature in the central European cities of Brno and Olomouc (Czech Republic) based on the same method of LCZ delineation, using the same method of mobile measurements of air temperature and performing statistical evaluation of temperature differences between LCZs. The result of this study should contribute to the knowledge of general LCZ temperature patterns, particularly those in cities located in temperate climate zones. This study extends our team's recent efforts to develop a GIS-based classification of LCZs (Geletič & Lehnert 2016) and analyze land–surface temperature differences in LCZs (Geletič et al. 2016a).

2. MATERIALS AND METHODS

Brno and Olomouc are typical mid-sized central European cities with a varied mix of land-use and building patterns reflecting their historical periods of development (distinct historical centres, parks, residential buildings, industrial zones, housing estates, modern shopping centres and stores, satellite developments and cultivated allotments). Research into various aspects of urban climate has been carried out in the 2 cities (Dobrovolný & Krahula 2015, Lehnert et al. 2015).

The city of Brno, the second largest city in the Czech Republic, is situated in the southeastern part of the country (Fig. 1, Table 2). It lies in a basin position and its terrain is complex. Altitudes range from 190 m in the south to 479 m in the north. Generally, the higher elevations are covered with forest, lying largely in the western and northern parts of the study area. Lower and flatter terrain, typical of the southern and eastern parts, is largely covered with fields and orchards. The mean annual temperature is 9.4°C and the mean annual precipitation is 505 mm (1961–2000 reference period). The prevailing north-westerly wind direction is strongly influenced by the relief, especially in the northern part of the city. Higher wind speeds are generally observed on the southern outskirts of Brno. The highest temperatures in the early night hours are typical for the city centre and for certain neighbourhoods located west or east of the compact city (housing estates). Lower temperatures in the early night hours are characteristic for the northern part of the city, which may correspond with the katabatic flow from elevated forested areas (Dobrovolný et al. 2012).

The city of Olomouc is situated 64 km northeast of Brno (Fig. 1). It is smaller than Brno (Table 2). Much of Olomouc lies in a wide, flat river valley with elevations between 205 and 260 m. Typical land use in the surroundings of Olomouc consists of intensive crop production (low plants). The mean annual temperature in Olomouc is 8.7°C and the mean annual precipitation is 582 mm (1961–2000 reference period). In the prevailing northwesterly wind direction, a large floodplain forest is located, which cools down the neighbouring part of the city. In the early evening hours, cooler air originating in the wetlands also tends to stagnate in the waterlogged fields north of the city. No substantial effect of local circulation systems on the urban climate has been detected (Vysoudil et al. 2012).

2.1. Local climate zones

A GIS-based approach was applied to delimit LCZs (Geletič & Lehnert 2016), based on the measurable physical properties of the environment and a clearly defined decision-making algorithm. This algorithm includes basic physical parameters defined by Stewart & Oke (2012): building surface fraction (BSF), pervious surface fraction (PSF), impervious surface fraction (ISF) and height of roughness elements (HRE). These were supplemented by number of buildings (NoB). For the classification process, the study area

Table 1. Nocturnal air-temperature measurements in terms of local climate zones (LCZs) under calm, clear-sky weather conditions. *Including all nights in the period regardless of weather conditions; **values corrected for altitude; ***annual average, order differing with season

City Reviewed sample	Method	LCZ order by temperature	Source
Berlin (Germany) 5 stations, summer period 2001–2010 (night temperature)	Fixed	5 > 6 > A > B*	Fenner et al. (2014)
Brno (Czech Republic) 5 stations, 3 nights in July–September 2011 (night temperature)	Fixed	2 > 5 ≈ D ≈ B	Geletič et al. (2016b)
Brno (Czech Republic) 4 nights in July–September 2011 (0–5 h after sunset)	Mobile	2 > 5 > 8 > 6 > 9 > A ≈ D	Present study
Cluj-Napoca (Romania) 8 fixed points, 3 nights, 13–14 May, 22–23 July and 24–25 October 2015 (23:00–02:00 h)	Fixed	1 ≈ 2 ≈ 3 ≈ B > 8G > 9**	Herbel et al. (2016)
Dublin (Ireland) 6 stations, 3 nights, 30 August–1 September 2010 (01:00–02:00 h)	Fixed	2 > 3 > 6 ≈ 5 > D	Alexander & Mills (2014)
Dublin (Ireland) 3 nights of 30 August–1 September 2010 (01:00–02:00 h)	Mobile	2 > 3 > 8 > 6 ≈ 5 > D	Alexander & Mills (2014)
Glasgow (UK) 4 stations, 1 night, 11 April 2010 (night temperature)	Fixed	9 > D	Emmanuel & Krüger (2012)
Hradec Králové (Czech Republic) 7 stations, 1 night, 28 July 2013 (night temperature)	Fixed	2 > 3 > B > 9 > 8 > A	Stredová et al. (2015)
Kochi (India) 12 nights in January 2011–March 2013 (19:30–22:30 and 04:00–06:00 h)	Mobile	2 > 3 > 6 > 9	Thomas et al. (2014)
Nagano (Japan) 32 nights in 2001–2002 (22:00–02:00 h)	Mobile	2 > 3 > 6 > 2	Stewart et al. (2014)
Nancy (France) Up to 20 traverses with various routes in July–September 2012 and 2013 (00:00–02:30 h)	Mobile	2 > 5 > 8 > 6/9 > D	Leconte et al. (2015)
Novi Sad (Serbia) 32 stations, 5 nights in July 2014 (night temperatures)	Fixed	2 > 5 > 8 > 3 ≈ 6 > 9 > A > D	Lelovics et al. (2016)
Oberhausen (Germany) 8 stations, August 2010–July 2011 (number of tropical nights, warm nights and BBQ days)	Fixed	2 > 8 > 5 > 6 > 9 > A ≈ D	Müller et al. (2014)
Olomouc (Czech Republic) 14 stations, 15 nights in 2010–2011 (8 h after sunset)	Fixed	2 > 5 > 4 > 6 ≈ 9 > D	Lehnert et al. (2015)
Olomouc (Czech Republic) 5 nights in July–September 2016 (2–5 h after sunset)	Mobile	2 > 5 > 8 ≈ 6 ≈ 9 > B > D	Present study
Szeged (Hungary) 4 nights in 2002–2003 (reference time 4 h after sunset)	Mobile	2 > 3 > 8 > 5 > 6 > 9 > D	Lelovics et al. (2014)
Szeged (Hungary) 27 stations, 5 nights in July 2014 (night temperatures)	Fixed	2 ≈ 3 > 8 > 5 > 6 > 9 > D	Lelovics et al. (2016)
Szeged (Hungary) 24 stations, June 2014–May 2015 (mean maximal nocturnal temperature differences)	Fixed	3 > 2 > 5 > 8 > 6 > 9***	Gál et al. (2016)
Uppsala (Sweden) 31 nights in 1948–1949 (sunset–sunrise)	Mobile	2 > 5 > 9 > D	Stewart et al. (2014)
Uppsala (Sweden) 9 stations, 3 nights, 21–23 September 1976 (night temperatures)	Fixed	2 > 5 > 6 ≈ 9 > D	Stewart & Oke (2010)
Vancouver (Canada) 4 nights in March 2008 and 2010 (3–5 h after sunset)	Mobile	1 > 4 > 8 > 6 > B > A > D	Stewart et al. (2014)

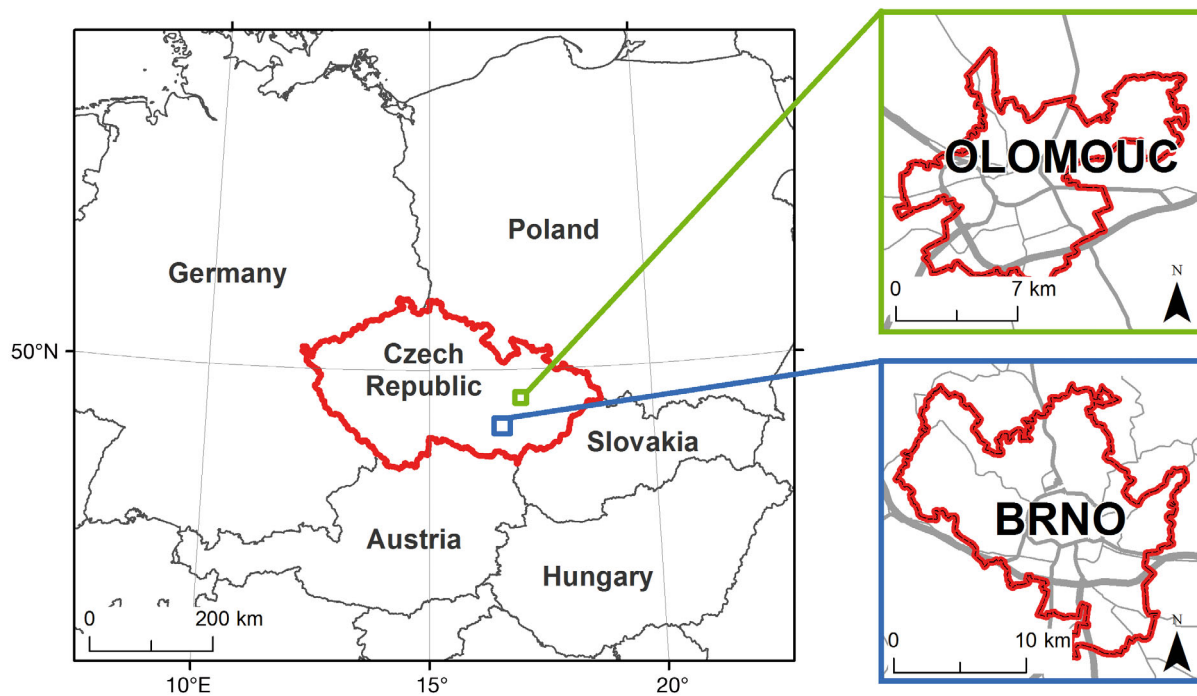


Fig. 1. Location of Brno and Olomouc in central Europe, and demarcation of the study areas with cadastral borders of compact urban development

Table 2. Study areas: basic data

Location	Cadastral area (km ²)	Number of inhabitants	Mean elevation (m)	Latitude (city centre)	Longitude (city centre)
Brno and surroundings	230.22	37028	259	49° 12' N	16° 37' E
Olomouc and surroundings	103.36	100154	219	49° 35' N	17° 15' E

was divided into a regular grid of 100×100 m cells, and each cell was assigned to an LCZ based on the values of the defined physical parameters (see Geleti & Lehnert 2016 for details). In the following step, the LCZ areas were delineated using a majority filter to smooth the results of classification.

2.2. Mobile measurements

Mobile air-temperature measurements in Brno were carried out on 4 selected days in July–September 2011. Each campaign lasted about 3.5 h and was around 90 km in length, with an elevation difference of >200 m. Measurements in Olomouc were carried out in July–September 2016, with each of the 4 campaigns lasting over an hour for a distance of approximately 30 km with an elevation difference <50 m (Table 3, Fig. 2). All meas-

urements were taken in radiation-dominated weather characterized by minimum cloud cover and weak advection. Measurements took place after sunset in all cases. In temperate climates, this time of day is typified by a slowing of the drop in temperature (Geiger et al. 2009), while a

simultaneous period of highest UHI intensity begins at this time (the end of phase 1 sensu Leconte et al. 2017).

The same type of special resistance thermometer was used in both cities, featuring a NiCr-Ni sensor with a rapid response time (0.8 s for up to 90% of temperature change). The sensor was mounted on the top-left side of an automobile, 1.8 m above ground level. Air temperature was recorded every 5 s at a mean vehicle velocity of $30\text{--}40$ km h⁻¹. To minimize the influence of traffic (heat release) on the data, measurements at traffic lights where the car had to stop were excluded. Further correction took into account natural temperature changes taking place at the time of measurement. This correction, based on temperature measurement in urban networks, does not account for the differences in elevation, as there was no significant relationship between elevation and temperature drop during the measure-

Table 3. Basics of individual mobile measurements in Brno and Olomouc. T : temperature; SD: standard deviation; CV: coefficient of variation

City	ID (yyyymmdd)	Time (h)	Cloud cover (tenths)	Wind speed (m s ⁻¹)	Wind direc- tion	T_{avg} (°C)	T_{min} (°C)	T_{max} (°C)	T_{range} (°C)	SD (°C)	CV (%)
Brno	20110708	21:00–23:50	1	2.5	ENE	22.0	16.3	26.0	10.6	1.6	7.2
	20110803	20:20–23:40	1	2.9	NE	21.1	15.8	24.0	8.2	1.4	6.8
	20110913	20:10–23:00	2	1.4	SW	21.2	15.6	24.5	8.9	1.6	7.7
	20110927	20:00–23:20	1	1.3	NNW	17.3	12.6	20.0	7.4	1.5	8.6
Olomouc	20160710	21:50–22:50	3	1.2	ENE	20.7	17.4	22.6	5.2	1.1	5.3
	20160808	21:20–22:20	0	0.9	ENE	21.0	18.2	23.0	4.8	1.1	5.2
	20160828	20:40–21:40	0	1.7	SE	22.6	19.7	24.2	4.5	0.9	4.0
	20160925	19:50–20:50	3	1.1	NNE	13.5	10.5	15.5	5.0	1.2	8.9

ment campaigns. Finally, temperatures were expressed as differences from the mean measurement temperature. This enabled easy comparison of results across both days (campaigns) and cities.

2.3. Analyses of air temperature in local climate zones

The mobile measurement routes were overlaid on an LCZ map and each temperature measurement was assigned to an appropriate LCZ class. Typical LCZ classes with a sufficiently large representative sample were then selected for the 2 cities, and their air temperature variability was further analysed: LCZ

2 (compact mid-rise), 5 (open mid-rise), 6 (open low-rise), 8 (large low-rise), 9 (sparsely built-up), A (dense trees) and D (low plants) for Brno and LCZ 2, 5, 6, 8, 9, B (scattered trees) and D for Olomouc. It was assumed in the analysis that temperature differences between LCZs were not random, and individual LCZ class would demonstrate certain features of a typical air temperature regime distinguishable from other zones.

One-way ANOVA was employed to analyse inter-class LCZ temperature differences. First, normality distribution was tested by means of a normal q–q plot. When the ANOVA F -test indicated statistically significant ($p < 0.001$) differences in mean air temperatures for LCZs, the Tukey HSD test ($p > 0.05$)

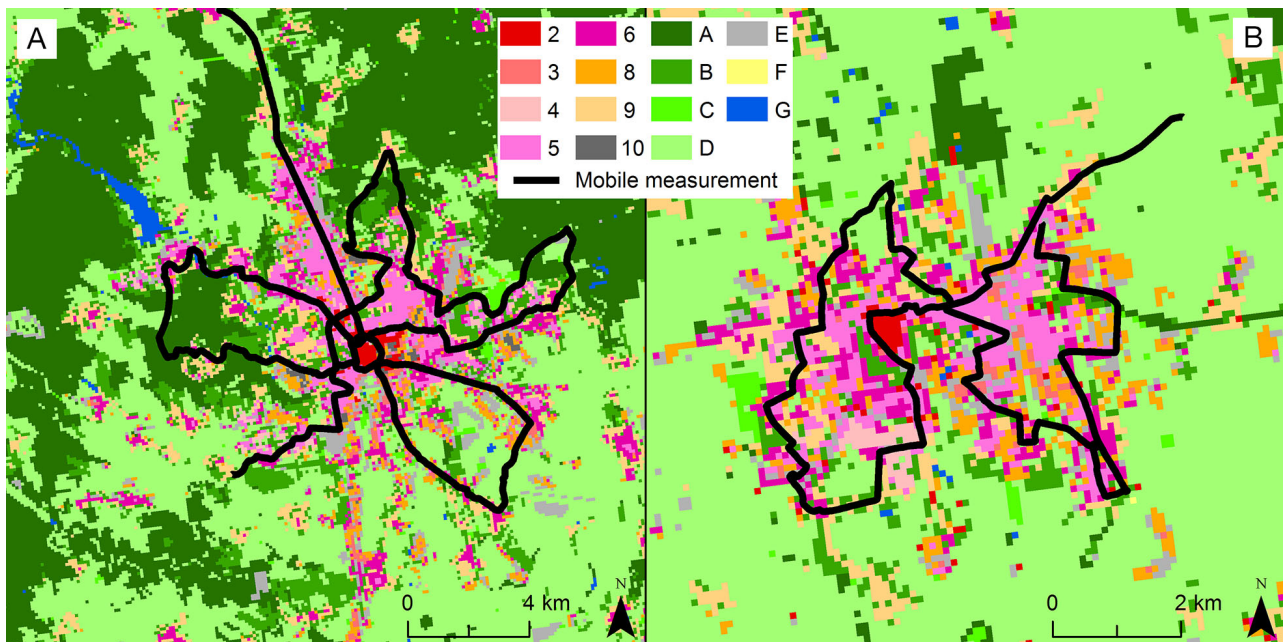


Fig. 2. Local climate zones (see key for colour) and mobile measurement routes (black line) performed in (A) Brno and (B) Olomouc

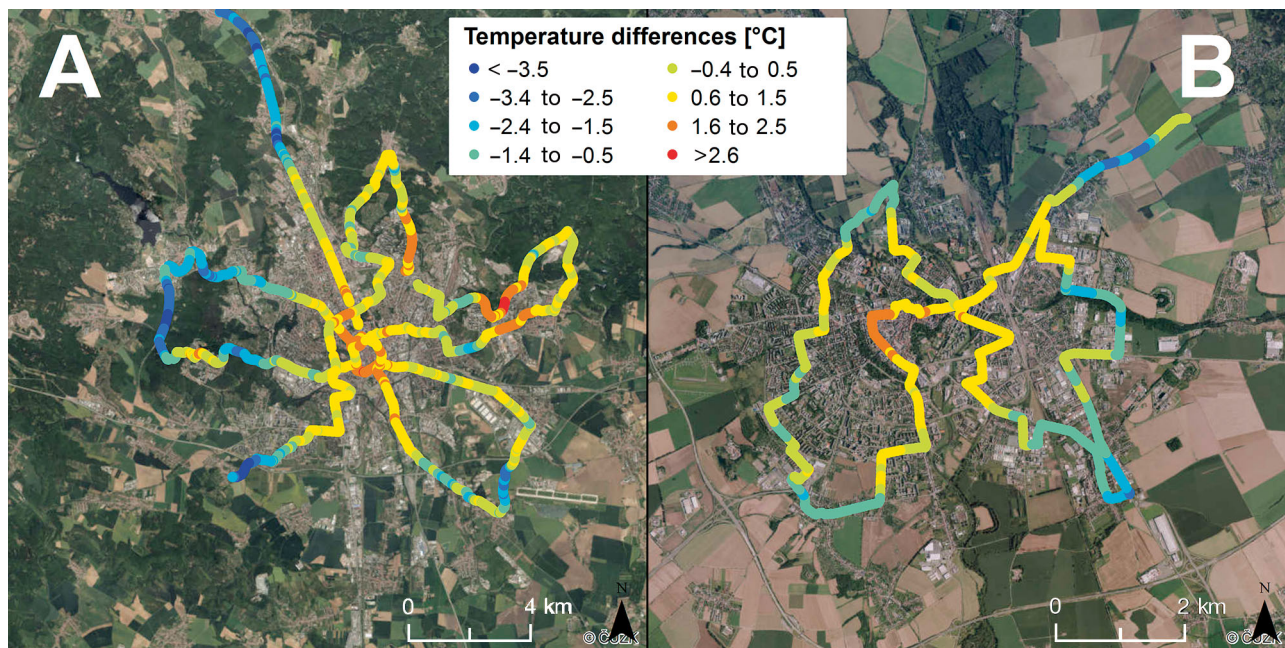


Fig. 3. Temperature differences based on mobile measurements: (A) Brno, 3 August 2011 and (B) Olomouc, 8 August 2016

was employed to control for the effect of multiple comparisons (Livezey 1995), and to reveal which LCZs differed significantly in their mean air temperatures. The analysis was performed for all 8 mobile measurements separately (2 study areas with 4 mobile measurement campaigns each).

3. RESULTS

In Brno, the highest air temperatures after sunset occurred in the city centre (LCZs 2 and 5; see Fig. 3). Higher air temperatures were also located south of the city centre, where the historical residential area gradually transitions to old industrial building zones (largely transformed into warehouses or shopping centres; LCZ 8). In the cases of 3 August 2011 and 27 September 2011, another significant area of high temperature was identified in the mixed residential area east of the city centre. The lowest air temperatures occurred in areas located in the forested areas of the northwestern and northeastern outskirts of Brno (LCZ A). Lower air temperatures were also measured at the southern edge of the city (LCZ D); however, those minima were conditioned by terrain (Dobrovolný & Krahula 2015).

In Olomouc, the general distribution of the relatively higher air temperatures after sunset was similar to that found in Brno (Fig. 3). The maxima occurred largely in the densely built-up areas, espe-

cially in the historical city centre (LCZs 2 and 5). Higher air temperatures were also observed in industrial and commercial areas (LCZ 8; with the exception of the campaign of 25 September 2016). Measurement points near the city parks (LCZ B) that surround the historical centre were substantially cooler than those in the dense development nearby. Lower air temperatures were located on the outskirts of the city (LCZ D) in areas with cultivated fields (Fig. 3). In several cases, lower temperatures were also observed in the adjacent built-up areas.

Comparing the results of the temperature measurements in the 2 cities, the temperature range and variability among the measurement campaigns were higher in Brno than in Olomouc (Table 3). This finding may be related to Brno's larger built-up area and more complex topography. Absolute temperature differences between individual LCZs were also larger in Brno (Table 4, Fig. 4). More precisely, the temperature differences between the LCZ with the highest temperature (LCZ 2) and the LCZs with the lowest temperatures (LCZs A and D) were in the range of 1.1–3.4°C for Brno and 1.1–1.8°C for Olomouc.

The ranking of LCZs based on the mean temperatures of all measurements within the LCZs were similar in the 2 cities and all measurement campaigns (Fig. 4). Mean temperatures of LCZ 2 were the highest in both cities within all analysed mobile measurement campaigns. Mean temperatures of LCZ 5 were usually the second highest. LCZ A was the zone with

the lowest mean temperatures in Brno (with the exception of 3 August 2011, when LCZ D had the lowest mean temperature). In Olomouc, the lowest mean temperatures occurred in LCZ D.

The results of a one-way ANOVA F -test ($p < 0.001$) showed that there were significant differences among the means of LCZ air temperatures. Moreover, these results stand for both study areas and for all 8 mobile measurements analysed. Subsequently, Tukey HSD tests revealed which pairs of LCZ differentiate significantly in terms of mean air temperatures (Fig. 5). An interpretation of all tests for both cities and analysis of their measurements is provided in a simple binary format in Fig. 5. Blue points express when the result of the test indicated no significant difference in mean air temperatures between the 2 given zones ($p > 0.05$)—a ‘negative’ result in the analysis (a ‘miss’), i.e. no difference in mean air temperatures for a given pair of LCZs. Empty cells in the table show significant differences ($p < 0.05$) in average air temperatures—a ‘positive’ result in this analysis (a ‘hit’).

Specifically, for both study areas, LCZ pairs with statistically significant differences in mean LCZ air temperatures (‘hits’) prevail, while pairs with no air temperature differences (‘misses’) are less frequent and such LCZ pairs differ in individual mobile measurements. The relative number of ‘hits’ is considerably higher for Brno (83.3%) compared to Olomouc (59.5%). More specifically, in Brno, the differences in mean temperature between LCZ 2 and all other LCZs were significant in all measurement campaigns, while mean temperature differences between LCZs 5, 6, 8 and 9 were significant only in certain cases, and mean temperature differences between LCZ A and LCZ D were not statistically significant at all (Fig. 5). The temperature differences in Olomouc were generally lower. Despite this, in most cases there were statistically significant differences between LCZ 2 and the other LCZs, apart from LCZ 5. In contrast, mean temperature differences between LCZs 6, 8, 9 and B were not statistically significant in most cases (Fig. 5).

The box-plots shown in Fig. 4 indicate that intra-class LCZ temperature variability was frequently higher than differences in mean temperatures between LCZs. In general, higher interquartile ranges were found in Brno (a larger city with a more complex topography) than in Olomouc. Nevertheless, in

Table 4. Differences between mean temperatures of local climate zones (LCZs) and mean temperature of measurement campaigns (all LCZs)

Brno	LCZ						
	2	5	6	8	9	A	D
8 July 2011	2.1	1.0	−0.2	0.6	−0.8	−1.3	−1.3
3 August 2011	1.4	0.5	−0.3	0.7	−0.5	−0.7	−0.9
13 September 2011	2.1	0.8	0.2	0.1	−0.9	−1.1	−1.2
27 September 2011	1.4	0.5	0.0	0.4	−0.2	−0.9	−0.6
Olomouc	LCZ						
	2	5	6	8	9	B	D
10 July 2016	0.6	0.6	−0.4	−0.1	0.1	−0.4	−0.5
8 August 2016	0.8	0.6	−0.3	0.0	−0.1	−0.3	−0.8
28 August 2016	0.5	0.5	−0.2	−0.2	−0.3	−0.3	−0.6
25 September 2016	0.9	0.7	−0.1	0.0	−0.3	−0.8	−0.9

the case of LCZ A, a lower interquartile range was observed in Brno. In Olomouc, the temperature variability of LCZ 2 was higher, due to sharp boundaries between LCZ 2 (historical centre) and LCZ B (city parks). The temperature variability of LCZ 5 was relatively low in both cities in comparison with the other LCZs, even though LCZ 5 arose out of 2 different morphological processes of development in central European cities—functionalist inter-block developments with extensive green courtyards, and housing estates with greenery established according to the socialist concepts of urbanism (Geletič & Lehnert 2016). In contrast, temperature variability in LCZs 8 and 9, located predominantly on the outskirts (Fig. 2), was relatively high in both cities. In Brno, but not in Olomouc, a substantial temperature variability was also found in LCZ D, which may be attributed to Brno’s more complex terrain.

4. DISCUSSION

When the LCZ scheme was introduced by Stewart & Oke (2012), it was suggested that temperature differences between classes exhibiting significant differences in geometry and land cover could often exceed 5.0°C , whereas contrasts between classes with lesser physical differences might be $<2.0^{\circ}\text{C}$ under favourable conditions. Therefore, the present study focused its analyses on the nocturnal period characterized by calm and clear-sky weather conditions, when the effect of local climate is particularly marked. The results indicate that the temperature contrast between LCZs in the larger city of Brno could be as high as 3.4°C , while in Olomouc the contrast between LCZs did not exceed 1.8°C . Further, the other studies included in Table 1 reported tem-

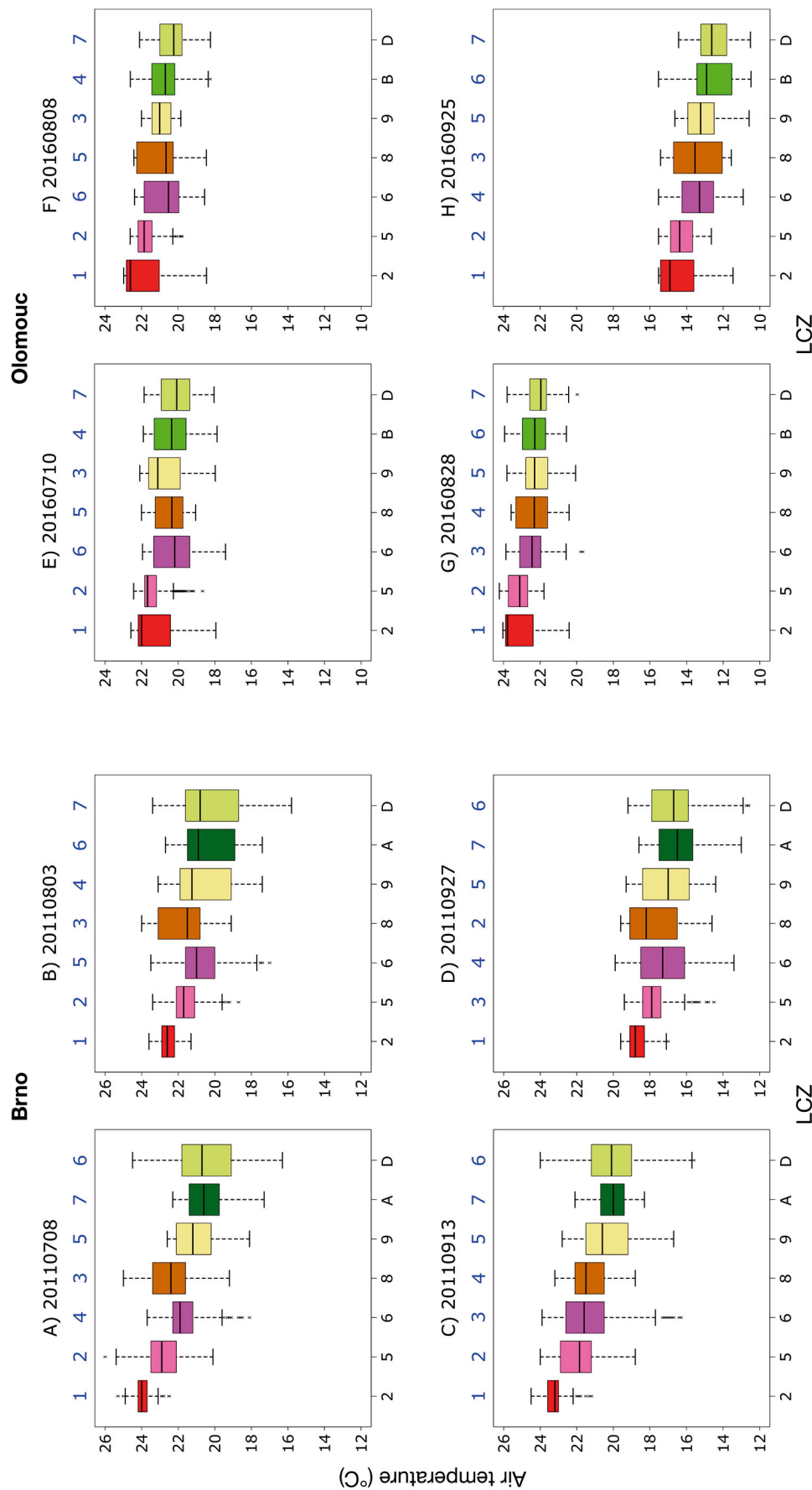


Fig. 4. Typical air temperatures of individual local climate zones (LCZs) calculated from mobile measurements in (A–D) Brno and (E–H) Olomouc. See Table 3 for measurement ID. Horizontal line within the box: median; lower part of box: first quartile; upper part: third quartile; whiskers: lowest and highest values still within 1.5 IQR (interquartile range = third quartile – first quartile). Black crosses: outliers. Top row with blue numbers: order of LCZs by average air temperature

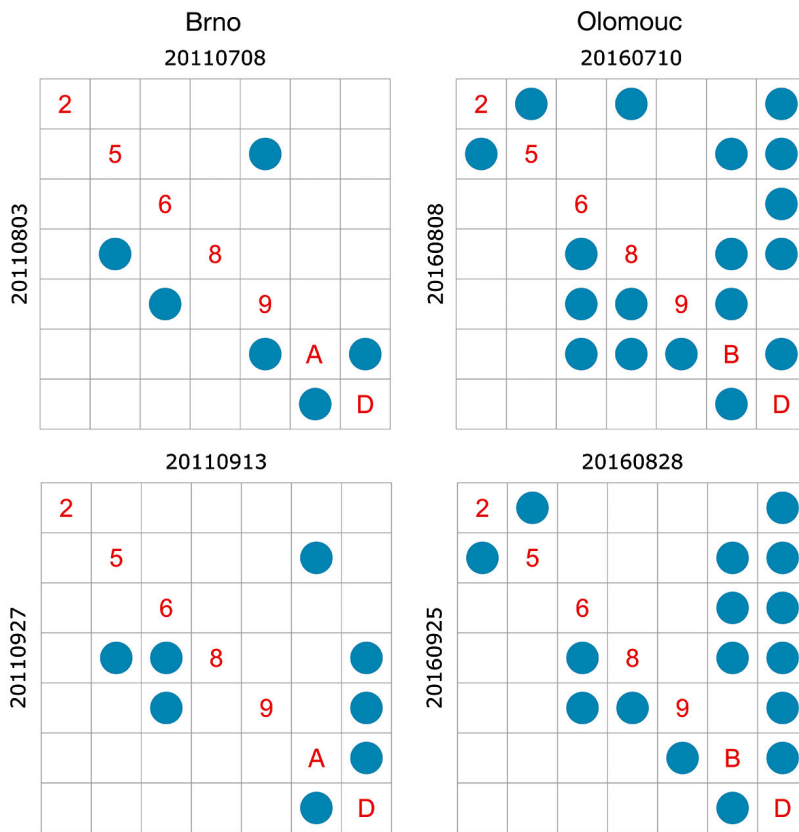


Fig. 5. Results of Tukey's HSD test for all combinations of local climate zone (LCZ) classes (red numbers and letters) and for all measurement campaigns in (A) Brno and (B) Olomouc. See Table 3 for measurement ID. Blue points: pairs of LCZs for which mean temperatures are not significantly different ($p > 0.05$); empty cells: LCZ pairs for which mean temperatures are significantly different

perature differences between LCZs that are largely in agreement with those presented by Stewart & Oke (2012). Nevertheless, from a methodological point of view, it is difficult to compare LCZ temperature contrasts across all of the studies, as different sample sizes (numbers of measurements), methods (e.g. fixed or mobile) or indicators (e.g. time after sunset, average night temperatures, etc.) have been variously employed. Ordering LCZs by temperature was therefore considered more valuable (Table 1).

According to our literature review (Table 1), the LCZ with the highest nocturnal temperature was generally LCZ 1 or 2. However, LCZ 1 was not evaluated in the present study. Even though the temperatures of LCZ 1 (compact high-rise) and LCZ 2 (compact mid-rise) have been studied in only one case (Herbel et al. 2016), temperatures in LCZ 1 may be assumed to be higher (because of building height) based on an earlier hypothesis (Oke 1981). This also

applies for lower nocturnal air temperatures in LCZ 3 (compact low-rise) than in LCZ 2 (compact mid-rise) in most of the cities reviewed (Table 1). The nocturnal temperatures of LCZ 2 were the highest in both Brno and Olomouc in all mobile measurement campaigns in the present study. Our results also demonstrated that temperature differences between LCZ 2 and other LCZs are statistically significant in most cases. In agreement with the assumption of Stewart & Oke (2012), nocturnal temperature measurements classified as LCZ 5 were, on average, lower than temperatures measured within LCZ 2 in both cities (Brno and Olomouc). Nevertheless, the temperature differences between LCZ 2 and LCZ 5 were only statistically significant in Brno. Similarly, in most cities in the literature reviewed, the nocturnal temperatures in LCZ 2 were higher than those in LCZ 5 (Table 1).

The results of this study show that LCZ A was usually the coolest LCZ in Brno. This may be due to its higher elevation; however, no clear relationship between temperature and elevation was found during the measurement campaigns. In Olomouc, LCZ D was the coolest, which agrees with the findings in most cities reviewed

(Table 1). However, although LCZ D was found to be the coolest during calm, clear-sky weather nights in most cities, it must be noted that LCZs E and F were not monitored in the present study, nor in most of the studies reviewed (Table 1). A further problem may be related to the fact that cultivated fields covered with low plants and classified as LCZ D (low plants) might actually belong to LCZ F (bare soil and sand) before the vegetative season and after harvest (Gélet & Lehnert 2016). On that account, a limitation of the present study and of most similar studies is that they do not consider seasonal variation of land-cover types within LCZs. The results of Gál et al. (2016) indicate that temperature contrast and the order of LCZs by temperature may vary with the seasons, even in the built-up subset of LCZ classes.

The results of the present study and Lelovics et al. (2016) indicate that temperature differences between LCZs are higher in large cities. This could be ex-

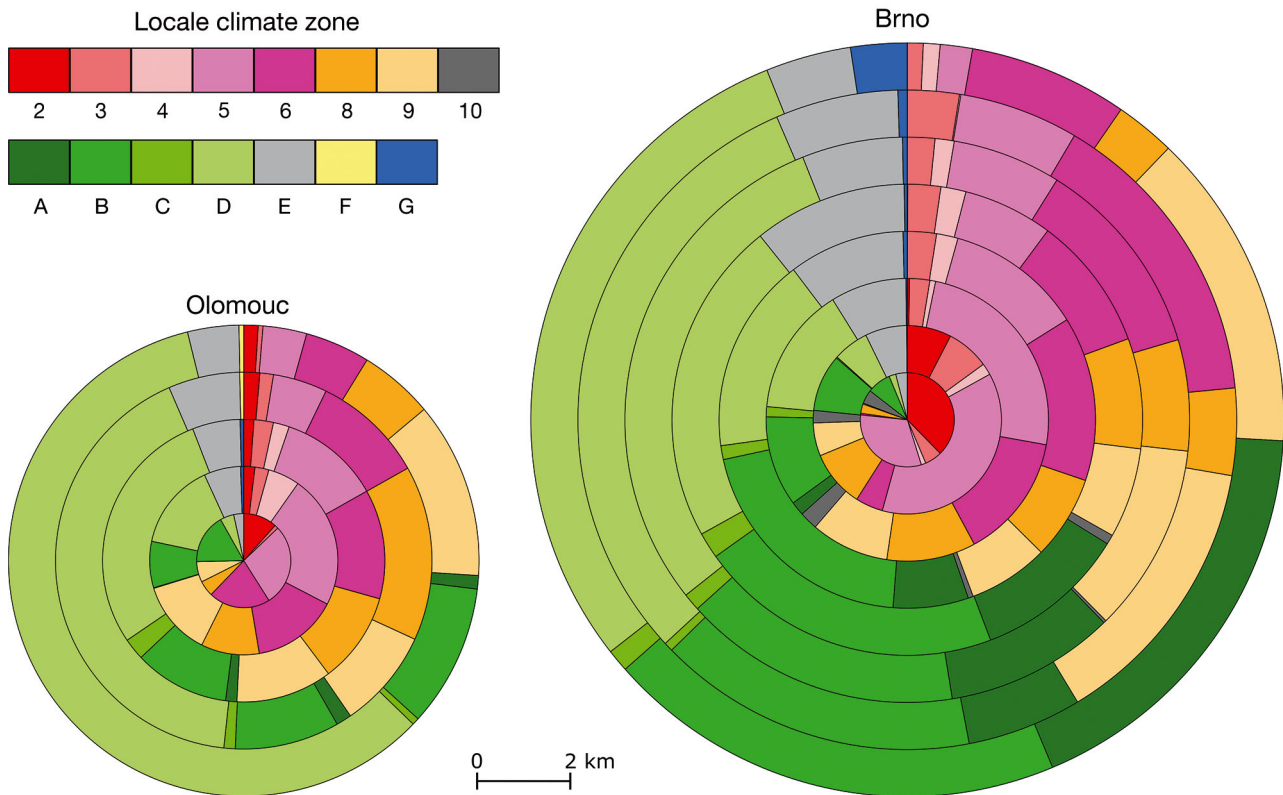


Fig. 6. Proportion of local climate zone areas in the compact urban development of Olomouc and Brno according to distance from the city centre (each ring represents a concentric zone 1 km wide)

plained by an increase in UHI intensity with the size of a given city (Arnfield 2003). More specifically, considering that LCZs are, by the very nature of urban morphology, usually confined to characteristic parts of the city (e.g. LCZ 2 to the city centre and LCZ 9 to the outskirts; see Fig. 6), the temperature differences between zones might be expected to rise with increasing size of the city (and UHI). This bias could lead to systematic errors when evaluating the influence of LCZs (effects of physical properties of the environment on a local scale) on air temperature. Similarly, another type of bias might be expected when particular terrain features (e.g. housing development in sunlit south slopes) or altitude (e.g. forest in higher areas) are more characteristic of certain types of LCZ (or types of land cover in general). Nevertheless, there was no significant relationship between temperature and altitude during the measurement campaigns.

Another limitation of this type of study is that it depends on the degree to which temperatures are representative along the measurement routes in individual LCZs. Despite the fact that mobile measurements provide a spatially more representative sam-

ple than fixed measurements, mobile measurements are restricted to zones accessible by car, which may also cause systematic error (e.g. preference for paved roads).

Although significant inter-class temperature differences emerged between pairs of LCZs in more than half of the cases in this study, intra-class variability of temperatures within individual LCZs was not negligible. One must therefore be aware that, by definition, the concept of LCZs covers only land-use-related factors (land cover, urban morphology, human activity), whereas other factors influencing temperature in urban areas (such as elevation, altitude, terrain morphology, general climatic conditions, etc.) are not included (Stewart & Oke 2012). Several studies have also pointed out that the temperature measured within a given LCZ may be significantly influenced by its internal structure (e.g. pattern of housing), position within (or beyond) the city (Fenner et al. 2014, Lehnert et al. 2015, Leconte et al. 2015), microclimatic effects (Tsin et al. 2016, Skarbit et al. 2017) or pattern of circulation systems (Tsin et al. 2016, Skarbit et al. 2017). Further, Leconte et al. (2015) and Thomas et al. (2014) also pointed out

that advection from neighbouring zones has been shown to make a substantial difference to the air temperature of road sections classified as a particular LCZ. This effect is influenced by wind speed and direction and temperature contrast between neighbouring zones. Considering that wind speed was rather low during the radiation-dominated weather presented in the present study, we suggest that this variation could also be considered as part of the inherent temperature variability of a given LCZ; however, this effect should be specifically analysed in any follow-up studies.

A certain degree of error in interpreting temperature variability may arise from the characteristic spatial distribution of a particular LCZ (e.g. low interquartile ranges for LCZ 2, which typically consists of one or several compact areas in the city centre, contrasting with high interquartile ranges for LCZ 9, which is typically made up of smaller areas on the outskirts; see Figs. 2 & 4). Lastly, a certain part of the intra-zonal temperature variability might stem from an inevitable degree of scientific uncertainty in delineation of geographical areas (here LCZs). As in many cases of delineating geographical areas, the true boundary between individual LCZs is often less exact than the sharp line on the map, and often resembles a rather fuzzy border, a buffer of mutually permeating types.

5. CONCLUSIONS

The air temperatures characteristic of most LCZs during calm, clear-weather nights in 2 central European cities which differ in size, topography and regional climate patterns were confirmed using coherent research methods in both cities. The order of LCZs by temperature was LCZ 2 > 5 > 8 > 6 > 9 > A ≈ D in Brno and LCZ 2 > 5 > 8 ≈ 6 ≈ 9 > B > D in Olomouc. These are very similar to those found in other cities worldwide. Moreover, our statistical analyses showed that temperature differences between LCZs were not random. The example of Brno and Olomouc demonstrated that temperature differences between LCZ 2 and other LCZs were statistically significant, while temperature differences between pairs of LCZs 5, 6, 8 and 9 were significant only in certain cases, temperature differences between LCZs A/B and D were not significant at all. Temperature differences between LCZs were higher in the larger city of Brno than in the smaller city of Olomouc, which was explained by bias introduced by an increase in UHI intensity with size of the city. Similarly, intra-class

temperature variability increased with city size and with topographic complexity. Considering the regularity in the order of LCZs by temperature and the statistical significance of temperature differences between LCZs with dissimilar physical properties, it may be concluded that the concept of the LCZs is a good representation of inherent local climate control factors. Intra-class LCZ temperature variability is, however, frequently higher than differences of mean temperatures between pairs of LCZs, and thus should be further tested in subsequent research (especially in the context of specific microclimatic effects and influence of neighbouring zones).

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