Spatial Variability of Soil Temperature in an Urban Area: A Case Study for a Medium-sized European City

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Abstract

Even though soil temperature in urban environment influences a range of processes, it has been studied rather sparsely in comparison with surface temperature or air temperature. Our research extends the soil temperature observation in Olomouc (Czechia) and uses semi-stationary measurement to describe detailed spatial variability of soil temperature in the area of a medium-sized Central European city. Differences in soil temperature 20 cm below grass-covered surface may exceed 3°C due to soil type, shadow cast by buildings and grass characteristics, which means that the representativeness of the data on soil temperature from a meteorological station within a city may be limited. Further research and a conceptual approach towards the study of soil temperature in urban landscape is needed.

Keywords: soil temperature; urban climate; Olomouc

Introduction

Soil temperature influences a range of significant processes in the landscape; however, it remains studied rather infrequently. Data on temperature and thermal regimes of soils are essential for many scientific as well as technical contexts and applications, from pedology and ecology to agronomy and construction (e.g. Šulgin, 1972; Bedrna et al., 1989; Jenny, 1994; Probert, 2000; Gens, 2010; Duray et al. 2015). In recent years, the study of thermal regimes of soils and soil temperature has also gained attention in the research of urban and suburban climate (urban climate science); due to climate change a progressive field requiring (fine-scale) climatic models that demand accurate input data on the characteristics and physical properties of land surface and its adequate parametrisation (Masson et al., 2020).

In the studies of urban climate, emphasis is given to the characteristics of anthropogenic surfaces and their accurate parametrisation (Mohajerani et al., 2017). Soils represent a considerable part of active surface in urban areas (Kopp & Raška, 2017); however, their characteristics are strongly generalized (Sievers et al., 1983; Bokwa et al., 2019; Feranec et al., 2019; Resler et al., 2020) considering the range of factors influencing temperature and thermal regimes of soils (Lehnert, 2014) and the general variability of soils in urban areas (Milošević et al. 2014; Sobocká et al., 2020). This leads to significant inaccuracies in the presumed radiative balance of active surface, and to differences between simulated and observed/real heat fluxes (Christen and Vogt, 2004).

Unlike many studies on surface temperature (in Central Europe e.g. Schwarz et al., 2012; Dobrovolný, 2013; Gemés et al., 2016; Geletič et al., 2019; Fricke et al., 2020), only a limited number of empirical studies have been carried out with focus on soil tempera-
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The research was carried out in the city of Olomouc in the eastern part of the Czech Republic (Figure 1). Olomouc is a mid-sized city (100 thousand inhabitants, area of 103 km²) located mostly in the flat floodplain of the Morava river, with mean elevation of 245 m a.s.l. Haplic and gleyic Fluvisols prevail, complemented in the urban landscape of Olomouc by larger areas of urban Anthrosols. Olomouc has a moderate climate (Cfb temperate oceanic climate according to Köppen classification) with average annual temperature of 8.9°C and annual sum of precipitation 547 mm (Vysoudil et. al., 2012). A long-term research of urban climate is underway in Olomouc and the urban heat island (UHI) effect of more than 2.0°C has been detected (Lehnert et al., 2013a). The city structure is typical of a wide range of the types of urban development, from the preserved historical centre with compact streets to quarters of detached houses with gardens, mid-rise blocks of flats, recently built shopping zones and suburban settlements. In the surroundings of the city, agricultural landscape prevails.

Methods

Study area

The research was carried out in the city of Olomouc in two days of August 2010 to detect larger spatial variability of soil temperature within a city. In our previous study (Lehnert, 2013b) we analysed stationary (station) measurements in Olomouc and its surroundings but we did not detect any clear influence of the city on soil temperature but we showed that spatial variability of soil temperature in urban and sub-urban landscape could be studied in further detail by means of field measurements (Lehnert et al., 2015). Considering the growing interest in the topic of temperature and thermal regimes of soils in urban environment, we aim in this case study to assess spatial variability of average daily soil temperature in the city of Olomouc, Czechia using two days of detailed field measurements of soil temperature.

Field measurement

The field measurement was designed with the aim to cover locations that would represent the variability of urban environment and types of housing development (Figure 1). Potential research locations were identified using the leading factor (compact development, flat terrain, grass surface) and subsequently a defined set of research locations was established by means of expert selection. Each research point was placed inside the area of the research location far enough from its fringe, it was covered with vegetation representative for the whole location and preliminary measurements were carried out before the main measurement campaign to ensure that soil moisture and soil temperature data measured at that point were characteristic for the whole research location.

Measurements were carried out using digital penetration thermometers Hanna HI 145 (Figure 2) with an accuracy of 0.3°C in the used temperature range. The thermometers were chosen considering their fast sampling response, acceptable accuracy tested through comparison with meteorological station measurement, and financial accessibility (Lehnert 2013a). Thermometer inertia was taken into account, soil temperature record was taken only after stabilisation of the value measured on the probe (usually 2–5 minutes after insertion into soil). In order to obtain representative data records, soil temperature was measured at each research point at least twice and always using at least two thermometers, following the recommendation of Buchan (2001).

The case study measurement campaign was carried out in the city of Olomouc in two days of spring, 5 and 7 May 2015, at 25 research points (Table 1). The weather during the experiment days is described in Table 2 and synoptic situation in Europe is illustrated by charts in Appendix A, showing a transition of a cold front across Central Europe on 6 May, 2020. The measurement was carried out in the times used for the determination of average soil temperature 07, 14 and 21 Central European Time ±30 minutes necessary for all the measurement teams to cover all locations of measurement. Eventual inaccuracy of measurement due to this temporal span does not exceed 0.1°C at the 98% probability level, as demonstrated before by stationary soil temperature measurement in Olomouc (Lehnert, 2013a)
Table 1. Characteristics of the research points of the field experiment*

| Point | Elevation (m a.s.l.) | Soil type (FAO WRB) | LCZ | Grass height (cm) | Soil moisture (% vol.) |
|-------|---------------------|---------------------|-----|-------------------|-----------------------|
|       |                     |                     |     | 5 May 2015  | 7 May 2015 |
| BE1   | 217                 | FL ha               | 89  | 6-10              | 16                     |
| BE2   | 217                 | FL ha               | 8D  | 6-10              | 13                     |
| BE3   | 216                 | FL ha               | 9   | 11-15             | 15                     |
| BE4   | 216                 | FL ha               | 9   | 1-5               | 7                      |
| BE5   | 216                 | FL ha               | 11-15| 11-15             | 18                     |
| EN1   | 212                 | AT                  | 59  | 6-10              | 13                     |
| EN2   | 212                 | FL ha               | 59  | 1-5               | 12                     |
| EN3   | 213                 | FL ha               | 5   | 1-5               | 15                     |
| EN4   | 214                 | FL ha               | 5   | 11-15             | 17                     |
| EN5   | 214                 | AT                  | 5   | 16-20             | 13                     |
| NU1   | 233                 | AT                  | 8   | 11-15             | 14                     |
| NU2   | 238                 | CH ar               | 89  | 6-10              | 24                     |
| NU3   | 250                 | CH ar               | 59  | 1-5               | 20                     |
| NU4   | 236                 | AT                  | 5   | 11-15             | 20                     |
| NU5   | 237                 | CH ar               | 5   | 11-15             | 13                     |
| ST1   | 215                 | AT                  | 5   | 11-15             | 14                     |
| ST2   | 214                 | AT                  | 9   | 6-10              | 19                     |
| ST3   | 214                 | FL ha               | DB  | 6-10              | 10                     |
| ST4   | 214                 | FL ha               | 85  | 11-15             | 14                     |
| ST5   | 214                 | FL ha               | 59  | 1-5               | 12                     |
| UD1   | 222                 | CM lv               | 5B  | 6-10              | 15                     |
| UD2   | 212                 | AT                  | 5   | 1-5               | 24                     |
| UD3   | 213                 | FL ha               | 5   | 6-10              | 12                     |
| UD4   | 214                 | FL ha               | 5   | 6-10              | 13                     |
| UD5   | 213                 | FL ha               | D   | 6-10              | 19                     |

* Base map sources: COSMC 2020, Natural Earth 2020

Notes:
1) FAO WRB – World Reference Base for Soil Resources by the Food and Agriculture Organization of the United Nations: FL ha – Fluvisol haplic, AT – Anthrosol, CH ar – Chernozem arenic, CM lv – Cambisol luvis
2) LCZ – Local Climate Zones (see Stewart & Oke, 2012 for further details)
3) Vegetation cover of soil (vertical view) 76–100% in all cases except UD4, where it was 50–75%.

Figure 1. Study area and soil temperature measurement sites in Olomouc

Figure 2. Semi-stationary soil temperature measurement in Olomouc and surroundings

Source: Lehnert, 2013a
Results

On the reference meteorological station Olomouc-Holice of the Czech Hydrometeorological Institute, average daily soil temperature in 20 cm depth was 14.2°C on 5 May, 2015 and 14.7°C on 7 May, 2015 (Table 3). Based on soil temperature measurements at various depths, a trend typical for the season of increasing soil temperature occurred at depths of 20, 50 and 100 cm, while short-term weather patterns influenced the near-surface layers of the soil. Vertical profile of soil temperature during the measurement campaign can be derived from the reference station Olomouc-Holice. Horizontal spatial variability of soil temperature, however, can only be obtained through detailed field measurement.

On the first day of the experiment (5 May 2015), values of average daily soil temperature in 20-cm depth at the research locations in the city showed a −1.8°C to +1.4°C deviation from the average daily temperature of 14.2°C at the reference station Olomouc-Holice, so the overall soil temperature range in average daily soil temperature was 3.2°C at the study locations within the city. Figure 3 shows that the lowest average daily soil temperature (in 20-cm depth) was detected at research point UD5 followed by NU4 and NU5, while the highest average daily soil temperature was detected at research point EN1 followed by EN5 and EN2. Values higher than the temperature at the reference station were observed namely within the research sector EN. The average daily soil temperature in 20-cm depth, calculated as the average of all research points, was 14.4°C, a good fit with the average daily soil temperature at the reference station Olomouc-Holice (14.2°C).

Results from the second day of the field experiment (7 May 2015) indicate rise by 0.3°C in average daily soil temperature in comparison with the records from the first day of the experiment (on the reference station Olomouc-Holice, the rise was by 0.5°C). In detail, soil temperature was higher on 20 from the 25 research points on the second day (Figure 3), while the overall spatial variability in average daily soil temperature within the city was smaller on the second day. On 7 May 2015, average daily soil temperature at the research points deviated −1.7°C to +1.1°C from the average daily soil temperature at the reference station Olomouc-Holice (14.7°C), thus the overall temperature range was 2.8°C. The lowest average daily soil temperature was detected at research points NU4 (13.0°C) and NU5 (13.3°C), the highest at the research point EN2 (15.8°C). The average daily soil temperature derived from the whole set of research points within the city was 14.7°C, equal to the value at the

| Table 2. Weather conditions on 5–7 May 2015 at the meteorological station Olomouc-Holice |
|-----------------------------------------------|---|---|---|
| Air temperature (°C) | 5 May 2015 | 6 May 2015 | 7 May 2015 |
| max. | 23.8 | 19.0 | 20.1 |
| avg. | 19.1 | 15.1 | 13.8 |
| min. | 12.5 | 14.0 | 9.6 |
| Relative humidity (%) | 5 May 2015 | 6 May 2015 | 7 May 2015 |
| avg. | 74 | 88 | 59 |
| Precipitation (mm) | 5 May 2015 | 6 May 2015 | 7 May 2015 |
| Wind speed (m/s) | 2.3 | 1.3 | 3.3 |
| Sunshine duration (hrs) | 3.2 | 0.0 | 10.7 |

Source: Czech Hydrometeorological Institute.

| Table 3. Soil temperature [°C] at the reference station Olomouc-Holice on 5–7 May, 2015 |
|-----------------------------------------------|---|---|---|
| Tdepth(cm) | 5 May 2015 | 6 May 2015 | 7 May 2015 |
| T05 | 15.9 | 16.0 | 15.5 |
| T10 | 15.5 | 15.9 | 15.3 |
| T20 | 14.2 | 15.1 | 14.7 |
| T50 | 12.3 | 13.1 | 13.3 |
| T100 | 10.8 | 11.0 | 11.2 |

Source: Czech Hydrometeorological Institute.
reference station and thus again confirming a good fit in the selection of the reference station as well as the relevance of the field experiment.

A comparison of soil temperature at the individual research points and at the reference station Olomouc-Holice reveals that there are characteristic differences at most locations for both days; therefore, the detected differences are not random and indicate that there is a pattern of spatial differences in soil temperature across the city (of Olomouc). The results also demonstrate a considerable variability in soil temperature at the scale of individual city quarters (research sectors), which means that it is rather difficult to identify areas with higher/lower soil temperature on the basis of the methodology used in the experiment (see Discussion). Nevertheless, the results from 7 May 2015, when cloudiness was lower and sun irradiation was more intense, reveal higher soil temperature in the sector of Envelopa (EN1–EN5) with low-rise buildings and subterranean anthropogenic sources of heat.

**Discussion and conclusion**

The field experiment was incited by previous studies analysing temperature characteristics in the urban environment of Olomouc (Geletič & Vysoudil, 2012; Lehnert et al., 2018; Lehnert et al., 2020) and pedological research in the area (e.g. Chmelová & Šarapatka, 2002). Spatial variability of soil temperature within the city was illustrated on the example of two days with different weather conditions and using semi-stationary field measurement. This study explicitly expresses the differences in average daily soil temperature across the city in comparison with the background reference station. The range of soil temperature differences may exceed 3.0°C on a sunny day. The average of soil temperature from all research points is in good fit with the value at the reference station, a confirmation of the relevance of the field experiment and of the adequate location of the meteorological station Olomouc-Holice for soil temperature measurement. The results of the experiment also confirm the assumption that it is not possible to find any simple relation between soil temperature and city parts, urban building types etc., which is similar to the complexity of differences in soil temperature between urban and suburban landscape (Lehnert et al., 2015).

Detected spatial variability in soil temperature in urban environment may result in various practical applications – it may influence the composition/diversity of low vegetation in individual parts of the city (Čeplová et al., 2017), it may influence evaporation (Feldhake & Boyer, 1986), technical parameters of buildings and underground utilities (Low et al., 2013), or in the context of thermal characteristics of soils and of active surface it may be included into and influence the accuracy of (fine-scale) meteorological models (Maronga et al., 2020). The detected spatial variability of soil temperature also points to the issue of representativeness of stationary meteorological measurements not only in the urban environment. The vast majority of stations that observe soil temperature are located on the basis of requirements for meteorological observation (air temperature, precipitation, wind direction and velocity etc.) or based on research parameters for urban climate studies (Vysoudil et al., 2012). When selecting locations for soil temperature measurements, research of the field of soil temperature in the area should be performed and physical characteristics of soils should be determined prior to selecting the definitive location, one that would properly represent the characteristic soil temperature pattern and regime in the area (Shein et al., 2009). Otherwise, local differences in soil temperature may completely override the regional differences, failing the representativeness of the results for a wider area (Lehnert, 2013b).

Spatiotemporal variability of soil temperature cannot be determined neither on the basis of spatiotemporal variability of air temperature (Zheng et al. 1993; Kang et al., 2000; Dolschak et al., 2015) nor on the basis of surface temperature, therefore further research and a methodological and conceptual approach to the study of temperature and thermal regimes of soils (not only for fine-scale climatological modelling) is essential.
This approach must respect the specifics of urban landscape and a substantial variability of soils in urban areas, where pedogenesis and the resulting spatial variability of soils is largely interconnected with human activity.

For further analyses of temperature and thermal regimes of soils in urban environment in the context of their applicability, the concept of pedo-urban complexes or urban pedotope (Sobocká, 2010; Sobocká et al., 2020) seems applicable and it may be to a large extent compatible with the concept of local climate zones (Stewart & Oke, 2012), a concept well established in the study of urban climate.

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Appendix A

Synoptic charts for Europe, 5–7 May, 2020 (Source: UK Met Office in https://www.wetterzentrale.de/reanalysis.php)

5 May, 2020 (00 UTC)
