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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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ture in urban environment. Harman (2003) presented a theory presuming lower average temperature of the soil surface in built-up areas compared to areas outside of housing development. On the contrary, Lokoshchenko and Korneva (2015) used long-term measurements in Moscow (Russia) to calculate that the mean difference in soil temperature between central areas of the city and rural surroundings equals to 0.6–0.8°C and the mean difference between urban periphery and rural surroundings equals to 0.4–0.6°C. The differences were most pronounced in the winter season and less pronounced in the summer. Similarly, Tang et al. (2011) observed soil temperature 1.2°C higher in urban area compared with its rural surroundings, using stationary measurement of temperature in homogenised soil placed into plastic tubes in Nanjing (China). Tang et al. (2011) also used semi-stationary measurements (600 research points 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.

Methods

Study area

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 km^2) 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., 2018). 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.

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).

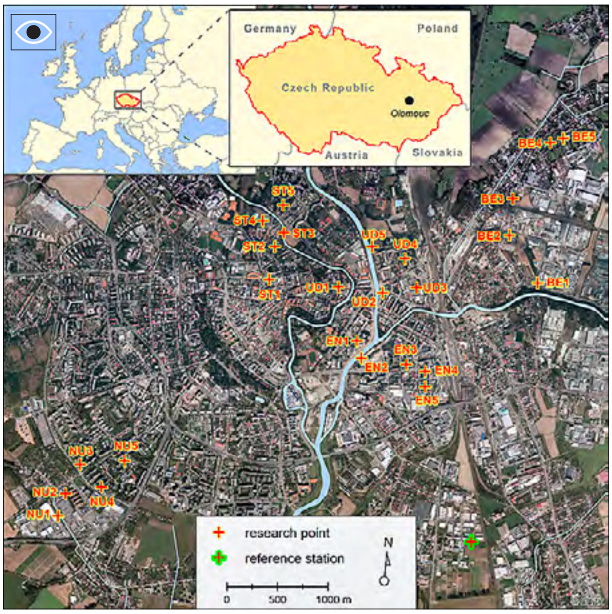

Figure 2. Semi-stationary soil temperature measurement in Olomouc and surroundings
Source: Lehnert, 2013a

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

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	14
BE2	217	FL ha	8D	6-10	13	18
BE3	216	FL ha	9	11-15	15	16
BE4	216	FL ha	9	1-5	7	14
BE5	216	FL ha	9	11-15	18	21
EN1	212	AT	59	6-10	13	15
EN2	212	FL ha	59	1-5	12	20
EN3	213	FL ha	5	1-5	15	16
EN4	214	FL ha	5	11-15	17	16
EN5	214	AT	5	16-20	13	20
NU1	233	AT	8	11-15	14	18
NU2	238	CH ar	89	6-10	24	20
NU3	250	CH ar	59	1-5	20	18
NU4	236	AT	5	11-15	20	19
NU5	237	CH ar	5	11-15	13	16
ST1	215	AT	5	11-15	14	11
ST2	214	AT	9	6-10	19	16
ST3	214	FL ha	DB	6-10	10	15
ST4	214	FL ha	85	11-15	14	20
ST5	214	FL ha	59	1-5	12	28
UD1	222	CM lv	5B	6-10	15	25
UD2	212	AT	5	1-5	24	18
UD3	213	FL ha	5	6-10	12	23
UD4	214	FL ha	5	6-10	13	18
UD5	213	FL ha	D	6-10	19	22

** 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 luvic
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%.

Table 2. Weather conditions on 5–7 May 2015 at the meteorological station Olomouc-Holice

		5 May 2015	6 May 2015	7 May 2015
Air temperature (°C)	max.	23.8	19.0	20.1
	avg.	19.1	15.1	13.8
	min.	12.5	14.0	9.6
Relative humidity (%)	avg.	74	88	59
Precipitation (mm)		11.7	1.4	0.0
Wind speed (m^{s-1})		2.3	1.3	3.3
Sunshine duration (hrs)		3.2	0.0	10.7

Source: Czech Hydrometeorological Institute.

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 3. Soil temperature [°C] at the reference station Olomouc-Holice on 5–7 May, 2015

$T_{depth(cm)}$	5 May 2015	6 May 2015	7 May 2015
T_{05}	15.9	16.0	15.5
T_{10}	15.5	15.9	15.3
T_{20}	14.2	15.1	14.7
T_{50}	12.3	13.1	13.3
T_{100}	10.8	11.0	11.2

Source: Czech Hydrometeorological Institute.

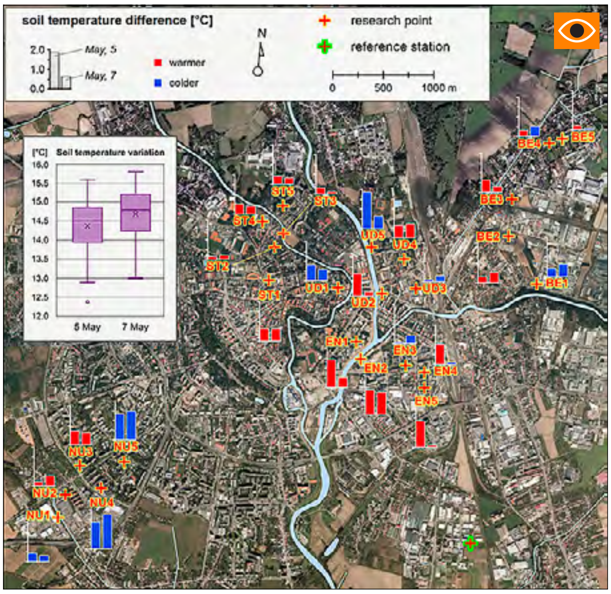

Figure 3. Soil temperature in 20-cm depth at research points of the field experiment in Olomouc, 5 and 7 May 2015
Base map source: COSMC 2020

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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References

Bedrna, Z., Fulajtár, E., Zrubec, F., & Juráni, B. (1989). *Pôdne režimy*. Veda, Bratislava.

Bokwa, A., Geletič, J., Lehnert, M., Žuvela-Aloise, M., Hollósi, B., Gál, T., Skarbit, N., Dobrovolný, P., Hajto, M.J., Kielar, R. & Walawender, J. P. (2019). Heat load assessment in Central European cities using an urban climate model and observational monitoring data. *Energy and Buildings*, 201, 53-69.

Buchan, G. D. (2001): Soil temperature regime. In: Smith, K. A., Mullins, C. E. [eds.]: *Soil and Environmental analysis: Physical methods* (pp. 539-594). New York, Marcel Dekker.

Čeplová, N., Kalusová, V., & Lososová, Z. (2017). Effects of settlement size, urban heat island and habitat type on urban plant biodiversity. *Landscape and Urban Planning*, 159, 15-22.

Chmelová, R., & Šarapatka, B. (2002). Soil erosion by water: Contemporary research methods and their use. *Geographica*, 37, 23-30.

Christen, A., & Vogt, R. (2004). Energy and radiation balance of a central European city. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 24(11), 1395-1421.

COSMC – Czech Office for Surveying, Mapping and Cadastre (2020): Esri ArcGIS Server View Service - Orthophoto CR. Publicly available at: https://ags.cuzk.cz/ArcGIS/rest/services/ortofoto/MapServer

Dobrovolný, P. (2013). The surface urban heat island in the city of Brno (Czech Republic) derived from land surface temperatures and selected reasons for its spatial variability. *Theoretical and Applied Climatology,* 112(1-2), 89-98.

Dolschak, K., Gartner, K., & Berger, T. W. (2015). A new approach to predict soil temperature under vegetated surfaces. *Modeling Earth Systems and Environment,* 1(4), 32.

Duray, B., Nagy, I., Andres, L., & Milošević, D. (2015). Soil pollution in the Hungarian-Romanian border region (Valley of Körös-Cris rivers). *Carpathian Journal of Earth and Environmental Sciences,* 10(3), 207–216.

Feldhake, C. M., & Boyer, D. G. (1986). Effect of soil temperature on evapotranspiration by C3 and C4 grasses. *Agricultural and Forest Meteorology*, 37(4), 309-318.

Feranec, J., Kopecká, M., Szatmari, D., Holec, J., Šťastný, P., Pazúr, R., & Bobáľová, H. (2019). A review of studies involving the effect of land cover and land use on the urban heat island phenomenon, assessed by means of the MUKLIMO model. *Geografie*, 124, 83-101.

Fricke, C., Pongrácz, R., Gál, T., Savić, S., & Unger, J. (2020). Using local climate zones to compare remotely sensed surface temperatures in temperate cities and hot desert cities. *Moravian Geographical Reports*, 28(1), 48-60.

Geletič, J., Lehnert, M., Savić, S., & Milošević, D. (2019). Inter-/intra-zonal seasonal variability of the surface urban heat island based on local climate zones in three central European cities. *Building and Environment*, 156, 21-32.

Geletič, J., & Vysoudil, M. (2012): Analysis of surface temperatures in urban and suburban landscapes from satellite thermal images: A case study of olomouc and its environs, Czech Republic [Analýza povrchové teploty v městské a příměstské krajině na základě analýzy satelitních termálních snímků, Olomouc a okolí (Česká Republika)]. *Moravian Geographical Reports*, 20 (1), pp. 2-15.

Gémes, O., Tobak, Z., & Van Leeuwen, B. (2016). Satellite based analysis of surface urban heat island intensity. *Journal of Environmental Geography,* 9(1-2), 23-30.

Gens, A. (2010). Soil–environment interactions in geotechnical engineering. *Géotechnique*, 60(1), 3-74.

Harman, I. N. (2003): *The energy balance of urban areas*. Dissertation. Reading: University of Reading.

Jenny, H. (1994): *Factors of soil formation: a system of quantitative pedology.* New York: Dover Publications, Inc.

Kang, S., Kim, S., Oh, S., & Lee, D. (2000). Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. *Forest Ecology and Management,* 136(1-3), 173-184.

Kopp, J. & Raška P. (2017). *Ekohydrologický management mikrostruktur v městské krajiny.* Západočeská univerzita v Plzni, Plzeň.

Lehnert, M. (2013a). *Vliv vybraných (geo)faktorů na režim teploty půdy v městské a příměstské krajině Olomouce.* Dissertation. Ostravská univerzita v Ostravě, Ostrava.

Lehnert, M. (2013b). The soil temperature regime in the urban and suburban landscapes of Olomouc, Czech Republic. *Moravian Geographical Reports*, 21(3), 27-36.

Lehnert, M. (2014). Factors affecting soil temperature as limits of spatial interpretation and simulation of soil temperature. *Acta Universitatis Palackianae Olomucensis–Geographica*, 45(1), 5-21.

Lehnert, M., Geletič, J., Dobrovolný, P., & Jurek, M. (2018). Temperature differences among local climate zones established by mobile measurements in two central European cities. *Climate Research*, 75(1), 53-64.

Lehnert, M., Tokar, V., Jurek, M., & Geletič, J. (2020). Summer thermal comfort in Czech cities: measured effects of blue and green features in city centres. *International Journal of Biometeorology*, 1-13. https://doi.org/10.1007/s00484-020-02010-y

Lehnert, M., Vysoudil, M., & Kladivo, P. (2015). Semi-stationary measurement as a tool to refine understanding of the soil temperature spatial variability. *International Agrophysics*, 29(4), 449-457.

Lokoshchenko, M. A., & Korneva, I.A. (2015). Underground urban heat island below Moscow city. *Urban Climate*, 13, 1–13.

Low, J. E., Loveridge, F. A., & Powrie, W. (2013). Measuring soil thermal properties for use in energy foundation design. In *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France (pp. 2-6).

Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K.F., Geletič, J., Giersch, S., & Russo, E. (2020). Overview of the PALM model system 6.0. *Geoscientific Model Development,* 13, 1335-1372.

Masson, V., Heldens, W., Bocher, E., Bonhomme, M., Bucher, B., Burmeister, C., de Munck, C., Esch, T., Hidalgo, J., Kanani-Sühring, F. & Kwok, Y. T. (2020). City-descriptive input data for urban climate models: Model requirements, data sources and challenges. *Urban Climate,* 31, 100536.

Milošević, D., Nagy, I., & Stojanović, V. (2014). Soils in the cities: State, problems and remediation techniques. *Researches Reviews of the Department of Geography, Tourism and Hotel Management,* 43(1), 1–16.

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, 197, 522-538.

Natural Earth (2020): Dataset Admin 0 – Countries (version 4.1.0). Publicly available at: https://www.naturalearthdata.com/

Probert, R. J. (2000): The role of temperature in the regulation of seed dormancy and germination. In: Fenner, M. [ed.]: *Seeds: the ecology of regeneration in plant communities* (pp. 261-292). Wallingford, CABI Publishing.

Resler, J., Eben, K., Geletič, J., Krč, P., Rosecký, M., Sühring, M., Belda, M., Fuka, V., Halenka, T., Huszár, P., & Karlický, J. (2020). Validation of the PALM model system 6.0 in real urban environment; case study of Prague-Dejvice, Czech Republic. Geoscientific Model Development Discussions, 1-57.

Schwarz, N., Schlink, U., Franck, U., & Großmann, K. (2012). Relationship of land surface and air temperatures and its implications for quantifying urban heat island indicators—An application for the city of Leipzig (Germany). *Ecological Indicators,* 18, 693-704.

Shein, E. V., Bannikov, M. V., Troshina, O. V., & Churkina, O. A. (2009): Temperature field of complex soilscapes (by the example of the Vladimir opolie region). *Eurasian Soil Science*, 42(2): 129–136.

Sievers, U., Forkel, R., & Zdunkowski, W. (1983). Transport equations for heat and moisture in the soil and their application to boundary layer problems. *Contributions to Atmospheric Physics*, 56, 58-83.

Sobocká, J. (2010). Specifics of urban soils (Technosols) survey and mapping. *19th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia* (pp. 56-59).

Sobocká, J., Saksa, M., Feranec, J., Szatmári, D., Holec, J., Bobáľová, H., & Rášová, A. (2020). Mapping of urban environmentally sensitive areas in Bratislava city. *Journal of Soils and Sediments,* https://doi.org/10.1007/s11368-020-02682-4.

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society,* 93(12), 1879-1900.

Šulgin, A. M. (1972). *Klimat počvy i jego regulirovanije*. Leningrad, Gidrometeoizdat.

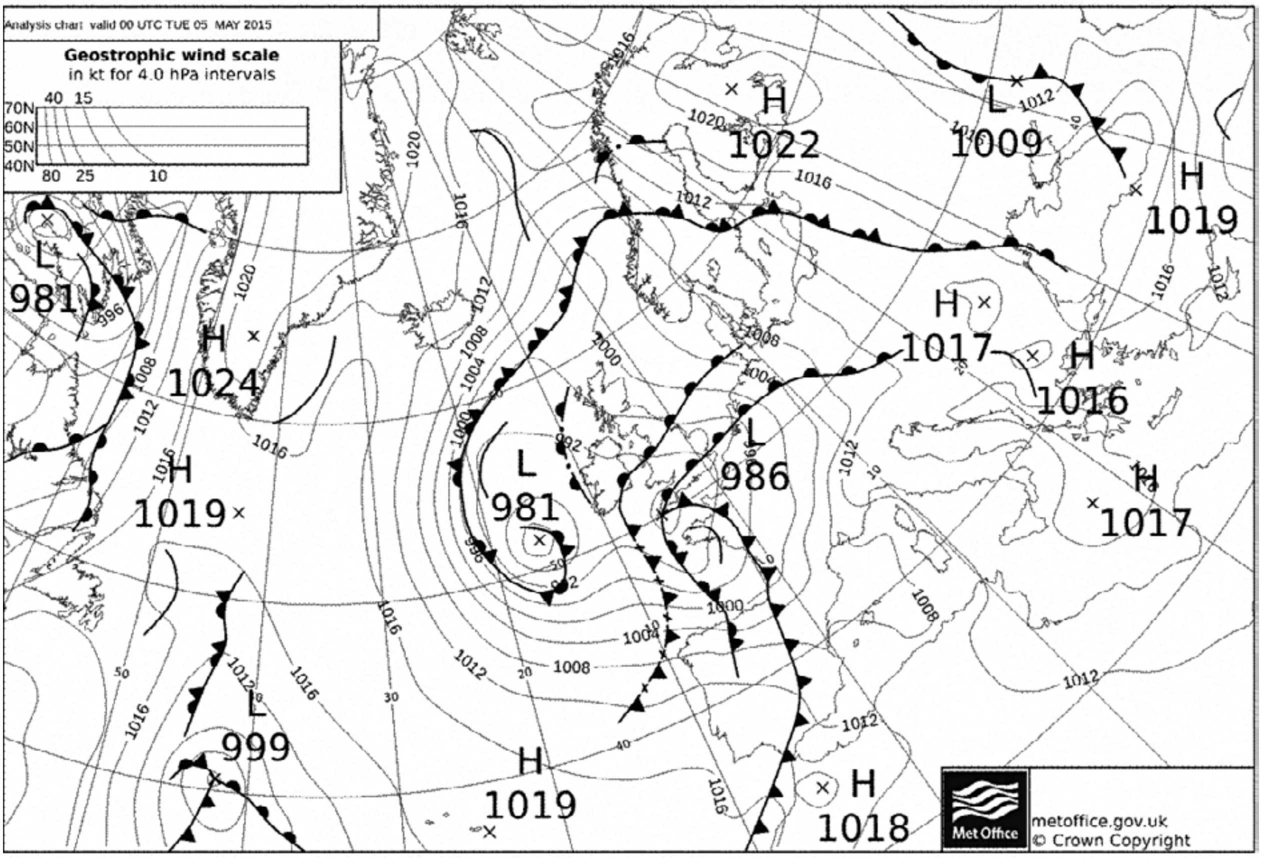
Tang, C. S., Shi, B., Gao, L., Daniels, J. L., Jiang, H. T., & Liu, C. (2011). Urbanization effect on soil temperature in Nanjing, China. *Energy and Buildings,* 43(11), 3090-3098.

Vysoudil, M., Geletič, J., Lehnert, M., Lipina, P., Pavelková Chmelová, R., & Řepka, M. (2012). Podnebí Olomouce. Univerzita Palackého v Olomouci.

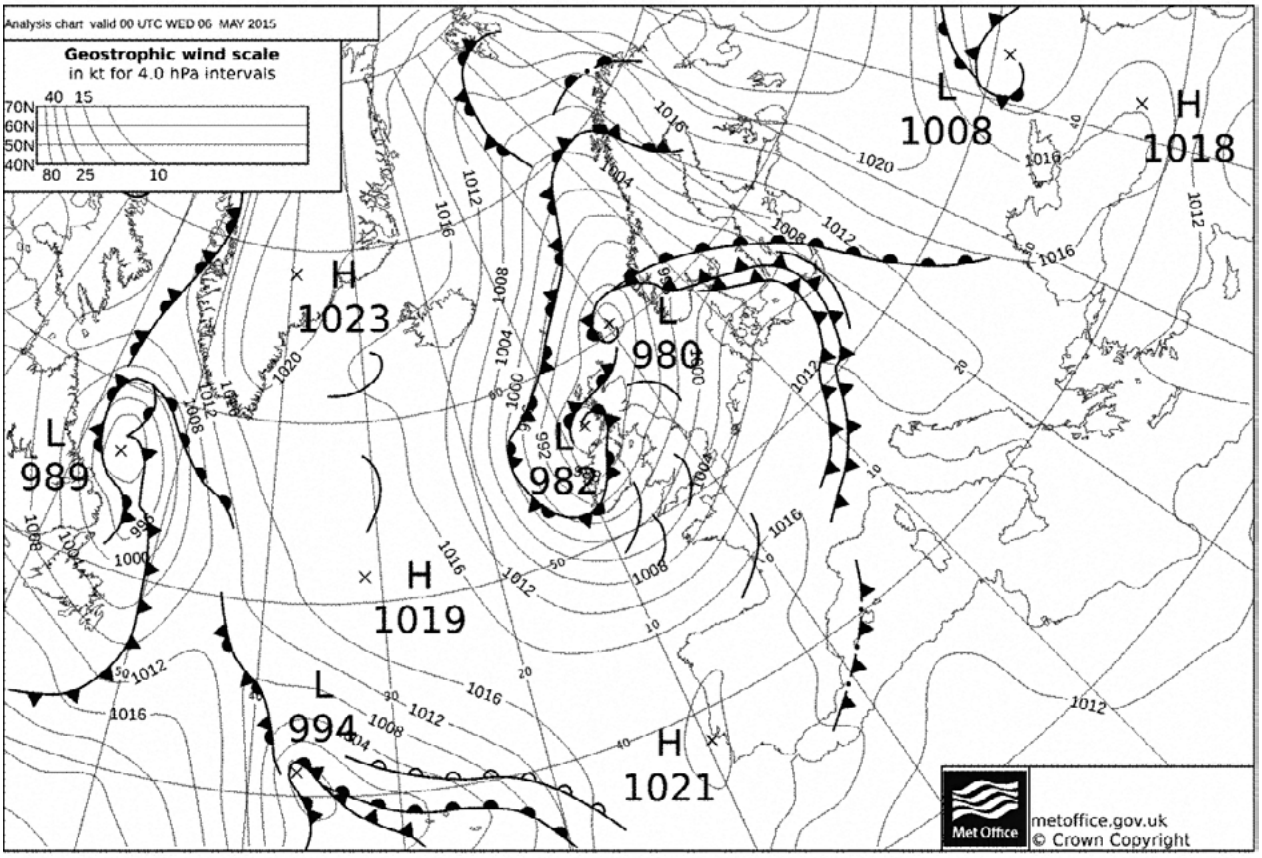
Zheng, D., Hunt, E. R., Running, S. W. (1993): A daily soil temperature model based on air temperature and precipitation for continental applications. *Climate Research*, 2(3): 183–191.

Appendix A

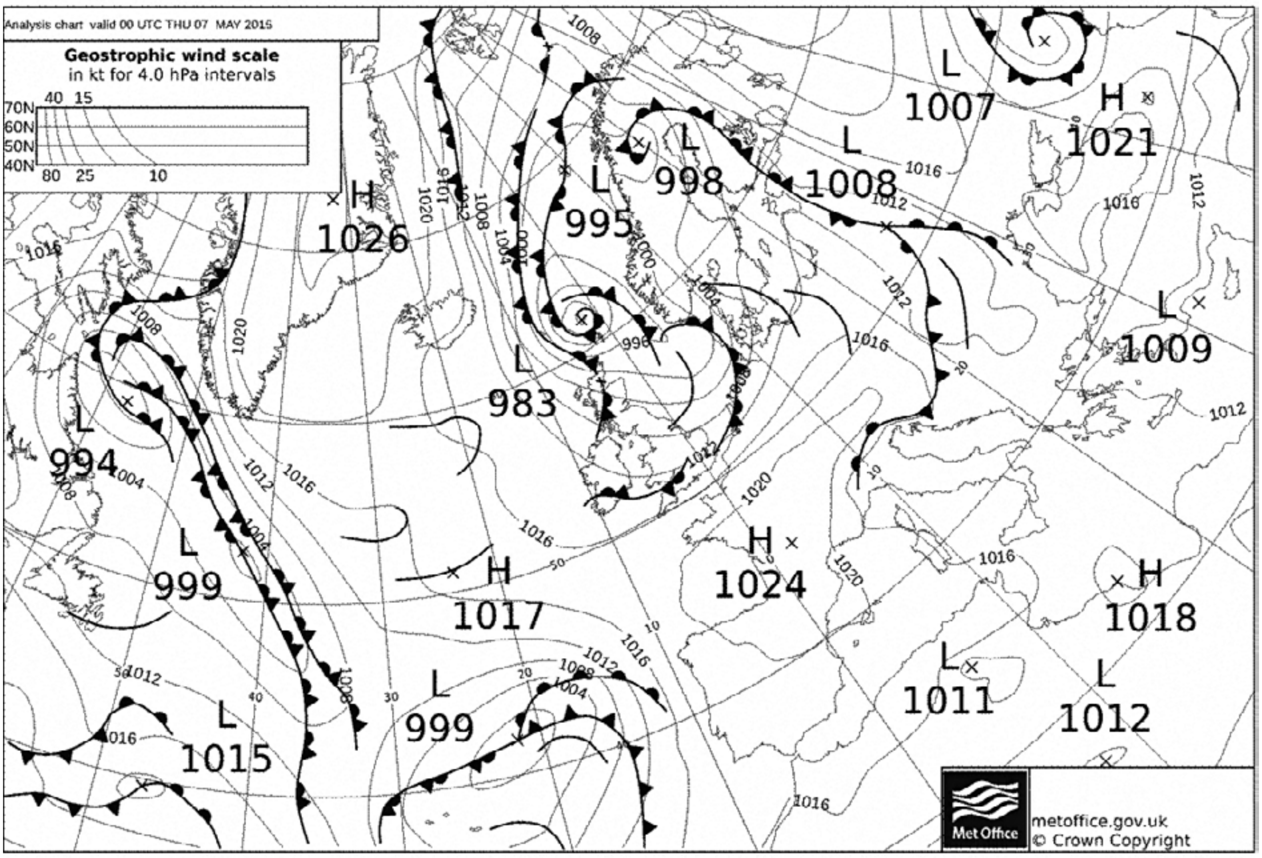
Synoptic charts for Europe, 5–7 May, 2020 (Source: UK Met Office in https://www.wetterzentrale.de/reanalysis.php)



5 May, 2020 (00 UTC)



6 May, 2020 (00 UTC)



7 May, 2020 (00 UTC)