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URBAN CLIMATE ANALYSIS BASED ON HIGH SPATIAL AND TEMPORAL RESOLUTION MEASUREMENTS AND MODEL RESULTS

Summary of PhD thesis

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Introduction

The number of urban residents compared to the total population constantly grew in the past and this tendency will continue in the future. Based on the newest prediction this rate will approach 70% in 2050, thus most people will be affected by influences of modified urban environment.

In cities interaction of built area and regional climate results in a specific climate. Compared to natural surfaces, the radiation, energy and water balance components and their rates to each other are altered due to the artificial environment and human activity. These effects result a heat surplus, which is the most typical at nights, when it reaches its maximal magnitude also. This most known phenomenon in urban climatology is called urban heat island (UHI) due to its specific form.

The intensity of UHI, the temperature difference of a rural and an urban measurement point, is influenced by a lot of factors. These are for instance population, wind speed and cloud cover, but the property of built-up in the city is essential. It is worth to examine the effects of building height and density on this heat surplus, since a well-prepared city planning influences it largely.

The calculation of UHI intensity raises the question, whether which area is urban and rural site. Since urban area can be skyscrapers or urban park and correspondingly the rural area can be low plants or dense trees, even an airport. The division of city into different climate zones, which show their effect on the local climate can eliminate this problem. The final result of more attempt by researches in the last decades can be the system of local climate zones (LCZ) created in 2012.This system consists of 10 built-up and 7 land cover types. The name of zones are based on their different surface parameters, which are mostly the height and density of buildings or land cover (e.g. compact built-up and middle building height, briefly compact mid-rise).

Beside the earlier presented problem related to the meaning of rural and urban area, the climate zones make easier to answer the questions of measurement network deploying. The main problem is where we should set the stations to be representative to the land cover of their environment. The system is created to be universal, so it can be used all over the world thus the determined thermal properties of the zones are valid for other settlements also. Consequently, the knowledge obtained by the usage of LCZs encourage the optimal deployment of station, moreover it is useful in the process of city planning.

At the installation of 24-element measurement station network in Szeged a crucial criterion was the representativeness of stations for their local climate zone. The network has outstanding spatial resolution internationally and provides thermal comparison between zones and within several LCZs. The temporal resolution of network is high also, since it measures air temperature and relative humidity every minute. The usage of this detailed data provides accurate knowledge on the spatial and temporal dynamics of UHI, and its pattern depend on LCZs.

The concept of LCZs is based on the different effects of zones on air temperature. Nevertheless, the urban surplus does not reflect only in the air temperature, but on the surface also, which can be quantified by remote sensing. Surface temperature measurements were carried out in Szeged in 2008, thereby they give opportunity to examine the validity of LCZs in case of this parameter. Moreover, besides the temperature values it is worth to analyze the effect of different LCZs on the heat load of human body, which includes combined effect of more climatic variables.

In addition to conditions of present, analysis of future is also necessary, since beside the increasing urban population the problem of global climate change should not be forgotten. Especially the existing urban surplus gives a reason to meet the city aspects of following changes which are awaiting us. This kind of examination helps the creation of adaptation and mitigation strategies in the process of urban planning.

The objectives of dissertation are:

I. Present the occurring thermal differences among the local climate zones.
II. Reveal the intra-zone alterations in temperature in the possible zones.
III. Analyze the spatial and temporal dynamics of urban temperature pattern, and determine the connection with the local climate zones.
IV. Examine the validation of local climate zones in case of surface temperature.
V. Evaluate the human comfort properties of local climate zones, and detect the most exposed zones to heat load.
VI. Predict the expected change in the urban heat load magnitude based on climate model results for the 21^{st} century.

Applied data and methods

One-year data (01.06.2014–31.05.2015) from the measurement network in Szeged was used for the evaluation of thermal properties of local climate zones. The 10-minutes averages of air temperature from the stations as well as cloud and wind speed data from the rural station of Hungarian Meteorology Service (HMS) were applied. All station was needed to analyze the spatial pattern of temperature, and the interpolation was made by kriging method. Four station were eliminated at the inter- and intra-zone examination due to data gaps or the microscale environment did not represent the conditions of local scale.

Three cases were distinguished, first the whole period was considered, regardless the weather situation. Secondly, days with ideal weather situation, when the thermal effect of city can prevail, were chosen based on the so-called weather factor. This factor quantifies the influence of daily cloud and wind on nocturnal cooling. In the third case a night of a chosen day was examined, when the conditions were very appropriate for UHI genesis.

Surface- and air-based measurements from 12th and 14th August 2008 were used for the examination of surface temperature via LCZs. The measurements were carried out between 18.15 and 19.45 UTC, the time correction was made for 19 UTC. The study area was overlap between measured area and local climate zones. The values of total area and surface only (neglect buildings) were examined separately.

In order to evaluate the thermal sensation of local climate zones the 10-minute averages of physiologically equivalent temperature (PET) were used for the longest period at the start of analysis (01.06.2014–31.01.2017). PET is the temperature (in °C) of a standardized fictitious environment in which the human body in order to maintain its energy balance, gives the same physiological responses as in complex real-world conditions. The determination of its values was simulated by the RayMan model. The aim was the determination of properties in local scale, thus data independent from effects of microscale environment, namely global radiation and wind speed from HMS rural station, were used. In case of wind speed roughness parameter and the empirical reduction constants related to the given side were taken into consideration. Temperature and relative humidity are more homogenous, thus they were used from selected sites in each local climate zones except LCZ 8 (large low-rise), where both stations had large data gaps. Seasons when weather is suitable for outdoor activities were focused on, which were transitional seasons and summer. The temporal variations of 10-day mean PETs were evaluated in two phases, at the early afternoon between 13 and 14 LST and at the evening for 2 hours from sunset. Furthermore human comfort conditions of summer heat wave period were examined. Thermal sensation characterization for Hungarian habitants were applied to determine the pleasant and favorable time periods.

The simulation of present and prediction of future heat load in the city was carried out in two steps. The outputs of local scale model MUKLIMO_3 are: temperature (T), relative humidity (RH), wind speed (v) and direction for equidistant grid in 100 m horizontal resolution. After that a dynamical-statistical downscaling technique called the cuboid method yields different climate indices for longer climate periods in the same horizontal resolution. The method assumes ideal conditions for heat load can be determined with the usage of only three parameters (T, RH, v). The minimum and maximum values of them, namely the 8 corners of cuboid should encompass these ideal situations. Simulations with MUKLIMO_3 were carried out for these 8 corners and 2 prevailing wind directions (NE and NW).

The usage of climate indices facilitates the presentation of effects of climate change for inhabitants and decision-makers. 30-year averages were applied to analyze this alteration. Period 1981–2010 was used as reference, while the 21st century was presented through periods 2021–2050 and 2071–2100. T, RH and wind field data are needed from a reference station to run the cuboid method. For period 1981–2010, measured database from NOAA was used and EURO-CORDEX climate simulations were applied, which employ the latest RCP scenarios, for the future. In case of climate model data 14 simulations were used, which contained the necessary data (T, RH, v). From them, 7-7 referred to RCP4.5 and RCP8.5 and they were averaged to get the final results.

Time period 1999–2010 was considered for the validation with the usage of rural and urban measurements in order to evaluate results properly. The urban measurements in Szeged started in 1999, thus the mentioned period was chosen.

Results and conclusion

I. Occurring thermal differences among local climate zones were determined (*Gál et al.*, 2016; *Skarbit et al.*, 2017**).**

1. In case of daily mean and minimum temperature the sequence of zones is unequivocal, the values decrease from compact and medium to sparse and low built-up LCZs. Considering the daily maximum temperature there is no clear tendency. The largest differences among the built-up zones are in summer minimum temperatures. On ideal summer days, the differences are considerable only at nights.
2. In average conditions the highest nocturnal UHI intensity occurs in summer in the compact zones, while the lowest is in winter in LCZ 9 (sparsely built). On ideal days the differences among seasons are not remarkable and the highest and lowest intensity appears in different seasons via LCZs. The alteration among seasons and parts of day is the largest in compact zones, and LCZ 9 modifies it least.
3. The number of "cold" and "warm" indices increase and decrease respectively from the compact zones to the rural LCZ D (low plants). The largest differences occur in case of indices based on minimum temperature.

II. Intra-zone thermal differences were explored in zones with more than one station (LCZ 5, 6 and 9) (*Skarbit et al.*, 2017).

4. On summer ideal days appreciable differences appear only in the nocturnal mean temperature. This time the intra-zonal temperature differences in LCZ 5 (open midrise) and 9 are lower than 1 °C, but in LCZ 6 (open lowrise) the greatest reaches 1.5 °C. In case of maximal UHI intensity the highest differences among stations occurs in

LCZ 6 on ideal days (2 °C). The presented differences can be related to the effects of microscale environment of stations and the prevailing NW wind direction. Additionally, they do not exceed the magnitude of differences among the zones.

III. **Spatial and temporal dynamics of urban temperature pattern were analyzed** (*Gál et al.*, 2016; *Skarbit et al.*, 2017; *Unger et al.*, 2017).

5. The average annual UHI reaches its maximal intensity 2 hours after sunset, which is 2 °C in the city center. Its decline starts at 10–11 hours after sunset and completely disappears at +12th and +13th hours. In ideal conditions the maximal intensity (above 3.5 °C) occurs at 5 hours after sunset and the weakening of UHI starts at +7th and +8th hours slowly. The decrease accelerates 10 hours after sunset and the temperature differences are minimal also at +12th and +13th hours.
6. The maximal intensity of UHI exceeds 5 °C at night of an ideal summer day in the area of compact zones and central parts of LCZ 5. The UHI stretches northwest direction in LCZ 8, while the values in east and south (LCZ 6 and 9) are lower. A cold advection can be noticed in the western part of the city in the area of LCZ 9.
7. The most intensive nocturnal cooling occurs at sunset and 1 hour after on ideal days. The magnitude of temperature gradient is below −2.5 °C at rural, and above −2 °C at urban areas. The values are around 0 °C at the remaining part of night and until sunrise there is no relevant change. The warming process starts at 10 hours after sunset. At this time the gradient in the city is below 0.5, after 1–1.5 °C, while it is above at the rural area, respectively. The differences among gradients of local climate zones appear at sunset and sunrise and they are higher in case of

ideal days, while between them they are minimal. The annual variation between the compact zones and LCZ 9 and D is 0.5 °C, approaches 2 °C on ideal days and reaches 3 °C at the night of examined summer day.

IV. **The conception of local climate zones was extended to the surface temperature** (*Skarbit et al.*, 2015).

8. Among the built-up zones, the highest values appear in compact zones and LCZ 5, while the lowest in LCZ 9. Values of LCZ 8 exceed LCZ 6, owing to the easier warm-up of flat roof buildings and higher rate of impervious surface. A typical surface temperature value is more frequent in the compact zones than in the sparsely built ones. Therefore the observed sequence of local climate zones for air temperature is valid for surface temperature also. It occurs remarkably in case of surface values neglecting buildings.

V. **Human comfort conditions of local climate zones were determined on annual and seasonal level** (*Unger et al.*, 2018).

9. Values of physiologically equivalent temperature decrease from compact to open zones independently of part of day and seasons. Consequently, ideal zones to mitigate heat stress are LCZ 6 and 9. Appropriate zones for outdoor activities are LCZ 6 and 9 in the daytime and LCZ 2 and 3 (compact mid- and low-rise) in the evening. "Cold" thermal sensation categories are more frequent in open, while "warm" categories in compact zones.
10. In early afternoon in spring, the pleasant thermal conditions start at the end of March, beginning of April and finish at the end of May depending on LCZs. In autumn, it starts at the beginning of season and ends in mid- or late October. At the evening, the ideal period for outdoor activities starts in the middle of March in the built-up and

three weeks later in the natural zones. In autumn the order is opposite, the natural zones from the end of September, and the built-up zones from the beginning of October are not appropriate. Consequently, in the transitional seasons the period of favorable outdoor thermal conditions is longer in the built-up LCZs than in the natural ones. In summer none of zones is suitable for outdoor activities in the afternoon, however at night all of them, especially the densely built ones are pleasant. In case of heat waves all of dwellers are exposed to remarkable heat stress for 6-8 hours in daytime.

VI. **Distribution and future change of heat load quantifying climate indices were simulated** (*Skarbit, Gál*, 2016).

11. Remarkable differences occur in the number of indices via LCZs in the present and the future also, the number of days is higher in the densely built-up zones. The values of every indices are likely to increase in the future. This change is slightly noticeable in period 2021–2050 and the difference between the scenarios is negligible. At the end of the 21st century (2071–2100) the modification is notable according to RCP4.5, however its magnitude is much larger based on RCP8.5. The greatest changes appear in case of indices with stricter criterion (summer evening, tropical night), which can be connected to the development of heat waves and notable increase of heat load.
12. The model gives more accurate result in the urban area than in the natural surfaces. The most correct estimation is given for indices defined by minimum and maximum temperature. Accordingly, accurate result can be got in the crucial period of urban climate examination, namely at night. In case of indices related to time, overestimation can be detected, therefore the cooling after sunset is slower according to the model.

Publications related to thesis

1. *Skarbit N, Gál T, Unger J*, 2015: Airborne surface temperature differences of the different local climate zones in the urban area of a medium sized city. In: 2015 Joint Urban Remote Sensing Event. Paper 7120497. 4 p.

2. *Gál T, Skarbit N, Unger J*, 2016: Urban heat island patterns and their dynamics based on an urban climate measurement network. Hungarian Geographical Bulletin, 65(2), 105–116.
   Specialization and rank of journal:
   Earth and Planetary Sciences (miscellaneous) Q3
   Geography, Planning and Development Q3

3. *Skarbit N, Gál T*, 2016: Urban heat island patterns and their dynamics based on an urban climate measurement network. Hungarian Geographical Bulletin, 65(2), 181–193.
   Specialization and rank of journal:
   Earth and Planetary Sciences (miscellaneous) Q3
   Geography, Planning and Development Q3

4. *Skarbit N, Stewart ID, Unger J, Gál T*, 2017: Employing an urban meteorological network to monitor air temperature conditions in the 'local climate zones' of Szeged, Hungary. International Journal of Climatology, 37, 582–596.
   IF=3,76
   Specialization and rank of journal:
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5. *Unger J, Skarbit N, Gál T*, 2017: Szegedi városklíma mérőállomás-hálózat és információs rendszer. Légkör, 61, 114–118.

6. *Unger J, Skarbit N, Gál T*, 2018: Evaluation of outdoor human thermal sensation of local climate zones based on long-term database. International Journal of Biometeorology, 62(2), 183–193.
   IF=2,204
   Specialization and rank of journal:
   Atmospheric Science Q2
   Ecology Q2
   Health, Toxicology and Mutagenesis Q2