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URBAN HEAT ISLAND STUDIES IN SZEGED, HUNGARY – AN OVERVIEW BASED ON PAPERS PUBLISHED OVER THE PAST FORTY YEARS (1980–2020)

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Summary: The overview summarizes briefly the contents and results of the papers published in journals dealing with urban heat island investigations in Szeged, Hungary between 1980 and 2020. The thermal data they used came from urban station networks, mobile measurements, local-scale simulations as well as aerial and satellite images.

Keywords: urban heat island, Szeged, Hungary

1. INTRODUCTION

This paper lists in chronological order the papers published in journals (in Hungarian and in English) related to the urban heat island (UHI) investigations in Szeged (Hungary) over the last forty years. It summarizes the contents and results of the papers briefly, partly based on their edited, abbreviated abstracts when available. The overview focuses on the period of 1980–2020 taking into account the first published article on the subject (Károssy and Gyarmati 1980).

The studies listed relied essentially on four thermal data sources in Szeged, namely: (i) manually observed data of the first urban network (11 stations) working between 1977 and 1981; (ii) city-wide mobile measurements between 1999 and 2003, as well as in 2008; (iii) automatically observed and stored data of the second urban network (24 stations) working from 2014; (iv) data of local-scale simulations from 2016. There are a few studies which analysed in part other data sources (e.g. aerial and satellite images). From 2013 most studies used the Local Climate Zone (LCZ) system to characterize the different land use/land cover types in and around the urban area.

Szeged is a medium-sized city with a population of around 160 thousands. It is located in the south-eastern part of Hungary (46.3°N, 20.1°E) at 79 m above sea level on a flat flood plain. The River Tisza passes through the city, otherwise, there are no large water bodies nearby. The river is relatively narrow and according to our earlier investigation its influence is negligible (Unger et al. 2000, 2001e). These environmental conditions make Szeged a suitable place for studying of an almost undisturbed urban climate.

Most of the territory of Hungary belongs to Köppen's climatic region Cf (temperate warm climate with a fairly uniform annual distribution of precipitation). Climatic subregions are distinguished using the mean temperature of vegetative season (t_{VS} in °C) and aridity index ($H = Q^*/(L_V \cdot P)$ where Q^* is the annual mean net radiation in MJm^{-2}, L_V is the latent heat of evaporation in $MJkg^{-1}$ and P is the annual mean precipitation in kgm^{-2}). Szeged is in the „warm-dry" subregion by this classification which is characterized by $t_{VS} > 17.5$°C and H > 1.15 (slightly arid). Two half years can be distinguished as the heating (from October until April) and the non-heating (from April until October) seasons. Szeged has an administration area of 281 km^2 but the urbanized area covered only about 40 km^2. The base of its street network is a circuit-avenue system. Different land-use types are present including a densely-built centre with medium-wide streets (LCZs 2 and 3) and large housing estates of high concrete buildings set in wide green spaces (LCZ 5). There are zones used for industry and warehousing (LCZ 8), areas occupied by detached houses (LCZs 6 and 9), considerable open spaces along the riverbanks, in parks, and around the city's outskirts (LCZs D and C) (Unger et al. 2004, 2015).

2. CHRONOLOGICAL LISTING

2.1. Studies based on the data of the first urban station network

Development of urban heat island in the air of Szeged (Károssy, Gyarmati 1980):

This paper used the data series of the 11-station network in Szeged. The temperature values were read manually at 4 times per day. The minimum and maximum temperature values of the cloudless and calm days between 1977 and 1979 were examined. There were 123 days in this period which were all connected with anticyclonic weather types. The authors averaged the temperature values by seasons and drew the isolines of urban-rural differences for both extreme temperatures. The isolines of mean differences took form most typically in winter in both cases (the differences in minimum temperature exceed 3°C in the city centre).

Urban climate measurements in Szeged (Pelle 1983):

This study dealt with the effects of a strong strong cold front of 19th February 1978 for a few days on the urban-rural differences of minimum temperature based on the data series of the above mentioned station network in Szeged. The isotherms of the differences were drawn for each day. On the first day the differences were normally, but on the 20th they suddenly increased (the excess of the centre was over 8°C), then they gradually decreased on the 21st and 22nd. So it could be seen that very remarkable temperature differences can develop in certain macrosynoptical situations between the city and its rural surroundings.

The seasonal system of urban temperature surplus in Szeged, Hungary (Unger 1992a):

This study investigated the magnitude and pattern of the urban temperature surplus based on the station network of Szeged between 1977 and 1980 and focused on the sunny, advection-free days. By the help of the seasonal means calculated from the daily mean temperatures of such days, the seasonal patterns of the temperature excess were presented. Accordingly, the city centre was averagely 1.5−2.1°C warmer than the surroundings, but the urban-rural temperature difference exceed even 2.5°C.

Diurnal and annual variation of the urban temperature surplus in Szeged, Hungary (Unger 1992b):

This paper examined the relationship between the urban morphological types of Szeged and the urban heat excess from 1978 to 1980. The monthly mean temperature differences of several stations representing different built-up areas reflected the built-up densities differently by months and by observation times. The temperature increasing effect of the city appeared in the centre most obviously and the largest differences occurred at 1h at night in early autumn (over 4°C). The row of built-up types as a funcion of decreasing heat excess were as follow: housing estate with tall concrete buildings, loosely built inner area, area between outskirts and housing estate with tall concrete buildings and outskirts.

Some features of urban influence on temperature extremities (Unger, Ondok 1995):

This paper dealt with the influence of different built-up areas on the spatial distribution of numbers of summer, winter and frost days, as well as of dates of the last and first frost days and the length of the frost-free period based on the data series of the urban network in Szeged. The results revealed that the distribution patterns largely depended on the density and building materials of the built-up areas.

Heat island intensity with different meteorological conditions in a medium-sized town: Szeged, Hungary (Unger 1996a):

In this study the thermal effects of Szeged was investigated based on minimum temperatures of urban and rural stations between 1978 and 1980. The UHI effect was examined by revelation of the relationships between UHI intensity and macrosynoptic types, cloudiness, wind speed as well as the combination of cloud amount and wind speed. Anticyclonic weather situations, little or no cloud coverage, and calm or slight wind were favourable for a strong development of the heat island effect. In the case of extreme UHIs the domination of anticyclonic weather types was almost absolute.

Relationship between urban heat island and wind on the example of Szeged (Unger 1996b):

In this study the relationships between UHI intensity and wind speed/directions were investigated based on measurements of urban and rural stations between 1978 and 1980 in Szeged. As the results showed the relationship between wind speed and UHI was reversed, the stronger the wind, the weaker the intensity. Additionally, the UHI was stronger in the case of western wind, which could be explained by the fact that the rural station was located west of the city.

Urban-rural difference in the heating demand as a consequence of the heat island (Unger, Makra 2007); The effect of urban heat island on heating energy demand in Szeged (Unger 1997):

The database of these studies was provided by an urban-rural meteorological station-pair in the period of 1978−1980 in Szeged. The climatic characteristics of the region in the mentioned three years and in the period of 1961−1990 did not show significant differences, which was certified by the application of a special case of the Student t-test. Therefore, the results, related to the climate-modifying effect of the city, could be extended to a longer period as well. According to the results, the development of the UHI reduced the number of heating days (HD) and heating degree-days (HDD) thus it reduced the duration of the heating season and the quantity of energy consumption in the city. Monthly means of the urban and rural HDs and HDDs showed that the heating season was shorter by more than 3 weeks and the energy demand was about 10% lower in the city than in the rural areas.

2.2. Studies based on mobil measurement data

A model for the maximum urban heat island in Szeged, Hungary (Unger et al. 1999a); The spatial extent of the maximally developed urban heat island in spring in Szeged (Unger et al. 1999b):

In these studies the efforts concentrated on the investigation of maximum development of the UHI in Szeged based on mobile measurements in the spring of 1999. Tasks included the determination of spatial distribution of mean maximum UHI intensity and modelling the existing conditions in the measurement period. Statistical methods were used to examine the effects of invariable parameters (land-use characteristics, distance from the city centre determined in a grid network) and by variable parameters (wind speed, temperature) on thermal conditions. The results indicated isotherms increasing in rather regular concentric shapes from the suburbs toward the inner urban areas. Strong relationship existed between urban thermal excess and land-use features. In addition, meteorological conditions determined to a great extent the UHI intensity at the time of its maximum development.

Land-use and meteorological aspects of the urban heat island (Unger et al. 2001b):

This study examined the influence of urban and meteorological factors on the near-surface air temperature field of Szeged, using mobile and stationary measurements under different weather conditions between March and August 1999. Tasks included the determination of the spatial distribution of seasonal mean maximum UHI intensity and modelling of existing conditions. Multiple correlation and regression analyses were used to examine the effects of urban parameters (land-use characteristics and distance from the city centre determined in a grid network) and of meteorological parameters (wind speed, temperature) on thermal conditions in the study area. The results indicated isotherms increasing in regular concentric shapes from the suburbs towards the inner urban areas where the mean maximum UHI intensity reaches more than 3°C in the studied periods. Strong relationship existed between urban thermal excess and distance, as well as built-up ratio. In contrast, meteorological conditions did not have any significant effect on the UHI intensity at the time of its maximum development.

Urban heat island development affected by urban surface factors (Unger et al. 2000); Urban temperature excess as a function of urban parameters in Szeged, Part 1: Seasonal patterns (Unger et al. 2001c); Urban temperature excess as a function of urban parameters in Szeged, Part 2: Statistical model equations (Unger et al. 2001a):

These studies examined the spatial and quantitative influence of urban factors on the air temperature pattern of Szeged using mobile measurements under different weather conditions between March 1999 and February 2000. Their efforts concentrated on the UHI in its peak development during the diurnal cycle. Tasks included the determination of spatial distribution of mean daily maximum UHI intensity, using of standard kriging procedure and the determination of statistical model equations in the one-year study period, as well as in the heating and non-heating seasons. Multiple correlation and regression analyses were used to reveal the effects of urban surface parameters (land-use characteristics and distance from the city centre determined in a grid network) on the UHI patterns. The results indicated isotherms increasing in regular concentric shapes from the suburbs toward the inner urban areas with a seasonal variation in the UHI magnitude. As the patterns showed, strong relationship existed between urban thermal excess and built-up density. In the city centre, the mean UHI intensity reached more than 2.6°C (year), 3.1°C (non-heating) and 2.1°C (heating). According to the model equations, strong relationships existed between urban thermal excess and distance, as well as built-up ratio, but the role of water surface was negligible.

Temperature cross-section features in an urban area (Unger et al. 2001e); Urban temperature surplus: cross-sectional studies in Szeged (Unger, Sümeghy 2001):

These studies examined the connection between the built-up urban surface and air temperature in Szeged. Data were collected by mobile measurements under different weather conditions between March 1999 and February 2000. The efforts concentrated on investigating the maximum diurnal development of the UHI along an urban cross-section. According to the results, the UHI intensity changed according to seasons, as a consequence of the prevailing weather conditions. The role of cloudiness and wind speed on the temporal variation of the largest UHI was clearly recognized during most of the time in the studied period. The seasonal profiles followed remarkably well the general cross-section of the typical UHI described by Oke (1987) who defined its characteristical parts as 'cliff', 'plateau' and 'peak'. The usefulness of the normalized values in the investigaton was proved, as the form of the seasonal mean UHI profile was independent of the seasonal climatological conditions, and was determined to a high degreee by urban surface factors. As a conclusion, a modified model describing the metropolitan temperature variable for cities situated in simple geographical conditions was suggested: it was equal to the sum of components of the basic climate of the region and of the production of urbanization in surface, where this last term was a multiplication of weather and urban surface factors.

Seasonal case studies on the urban temperature cross-section (Sümeghy, Unger 2003a); Temperature modification effect of settlements – Heat island investigations in Szeged (Sümeghy, Unger 2003b):

In these papers the investigations concentrated on the spatial distribution and temporal dynamics of the nocturnal UHI, using mobile measurements under different weather conditions in the periods of March 1999–February 2000 and April 2002 – March 2003 in Szeged. Task also included the revelation of building-up and building-down of the UHI along an urban cross-section studying example cases by seasons and the explanation of their features using land-use and meteorological parameters. The UHI profiles were rather perfect with the highest values in the city centre and a few hours after sunset. However, some assimetry occurred in the isotherms because they were always shifted a bit to the eastern edge of the transect. It could be attributed to the influence of the highest built-up density of this neighbourhood. For example, in the case of the summer night using normalized UHI values some interesting features in the profiles emerged. Presumably, the changes in the magnitudes of UHI in the western and eastern suburbs were caused by the cooler rural air transport (first from NW then from E-NE) according to the changed wind direction. The phenomenon of the two peaks was observed in the course of the fall measurement and it could be explained only by the temporary weakening of the wind.

Connection between phenological phases and urban heat island in Debrecen and Szeged, Hungary (Lakatos, Gulyás 2003):

The study presumed that the urban climatic modification (UHI) affects the phenological and phenometrical properties of the urban vegetation. The phenological and temperature observations were taken in grid networks in the spring of 2003 in Szeged and Debrecen. As a good observable plant, Forsythia suspensa was the object of the examination because this plant occurred in 60-70% of the city areas. The timing of the different phenological phases was monitored in a daily fashion. According to the results there was close connection between the spatial distributions of the timing of these phenological phases and the UHI intensity. The strongest correlation occurred between the UHI intensity and the date of 100% flowering.

A multiple linear statistical model for estimating mean maximum urban heat island (Bottyán, Unger 2003); A statistical approach for estimating mean maximum urban temperature excess (Bottyán et al. 2003):

These studies examined the spatial and quantitative influence of urban factors on the air temperature field of Szeged using mobile measurements under different weather conditions in the periods of March 1999 − February 2000 and April−October 2002. Tasks included: (1) determination of spatial distribution of mean diurnal maximum UHI intensity and some urban surface parameters (built-up and water surface ratios, sky view factor, building height) using the standard Kriging procedure, as well as (2) development of statistical models in the heating and non-heating seasons using the above mentioned parameters and their areal extensions. Model equations were determined by means of stepwise multiple linear regression analysis. In both seasons the patterns of the mean UHI intensity had concentric shapes with some local irregularities. The intensity reached more than 2.1°C (heating season) and 3.1°C (non-heating season) in the centre of the city. As the measured and calculated UHI intensity patterns showed, there was clear connection between the spatial distribution of the the urban thermal excess and the examined land-use parameters, so these parameters played an important role in the evolution of the strong UHI intensity field. From the above mentioned parameters the sky-view factor and the building height were the most determining factors which were in line with the urban surface energy balance. Therefore, by means of these models there would be possibilities to predict mean maximum UHI intensity in other cities, which have land-use features similar to Szeged.

Intra-urban relationship between surface geometry and urban heat island: review and new approach (Unger 2004):

This paper provided a comprehensive review of the intra-urban sky view factor (SVF)–temperature relationship. Then a new approach to reveal the real connection between SVF and air temperature in an entire city was presented. The results found in the literature were rather contradictory, possibly due the fact that previous investigations were limited to the central or specific parts (e.g. inner city, urban canyons) of cities and used few sites and measurements. Comparisons were often based on element pairs measured at selected sites. In some cases areal means were also discussed, but always in connection with one of the variables examined. For comparison, this study in Szeged utilized large number of areal means of SVF and air temperature. The values were related to almost a whole city and based on numerous measurements. The results showed a strong relationship in the intra-urban variations of these variables, i.e. urban surface geometry was a significant determining factor of the air temperature distribution inside a city if the selected scale was appropriate. Therefore, investigations of a sufficient number of appropriate-sized areas covering the largest part of a city or the entire city are needed to draw well-established conclusions.

Modelling of the annual mean maximum urban heat island with the application of 2 and 3D surface parameters (Unger 2006); Modelling the maximum development of urban heat island with the application of GIS based surface parameters in Szeged (Part 1): Temperature, surveying and geoinformatical measurement methods (Balázs et al. 2005); Modelling the maximum development of urban heat island with the application of GIS based surface parameters in Szeged (Part 2): Stratified sampling and the statistical model (Gál et al. 2005):

The primary aim of these studies was to reveal quantitatively what effect urban structure had on the development, magnitude and spatial distribution of the annual mean maximum UHI using a selected representative sample area in Szeged. In order to quantify the effect mentioned above, besides the earlier applied SVF and different built-up parameters, a relatively new surface parameter (weighted volumetric compactness) was used to characterise the volume, structure and thermodynamical role of buildings. The calculation of this new parameter required a large-sized digital database that includes building's 3D measurement. Because this would take a long time, the research concentrated on a smaller but representative sample area, as the first step: the compactness of approximately 11,000 buildings in one third of the city was determined by geoinformatical analysis. A stepwise multiple linear regression model was used to determine to what extent each parameter added to the annual mean UHI intensity. According to the results, there were clear connections between the spatial distribution of the UHI and the examined parameters (built-up and water surface ratios and weighted volumetric compactness), so these parameters played important role in the evolution of the UHI intensity field. The connection between compactness and the annual mean ('all weather') UHI intensity is stronger than with the SVF. Using the final model equation, the absolute deviations of the generated UHI (calculated for an independent one year period) remained under 0.5°C throughout almost the entire investigated area. The estimated UHI pattern with its characteristic features showed clear similarities to the real conditions.

Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database (Unger 2009); Relationship between the urban surface and the heat island in Szeged, Part 1: GIS procedure for quantifying surface geometry (Unger et al. 2006b); Relationship between the urban surface and the heat island in Szeged, Part 2: connection between surface geometry and temperature distribution (Unger et al. 2006a):

These studies provided a review on methods of SVF determination and intra-urban surface geometry–air temperature relationship. Then, a software-based method of SVF estimation from a 3D database, describing urban surface elements, was applied. Finally, related investigations in Szeged and importance of the results obtained were discussed. Previous investigations were limited to only specific urban parts or some canyons and used small numbers of sites and few occasions of measurements. This study utilized large number of areal means of SVF and temperature related to a large sample area and based on numerous measurements. The investigation revealed a strong relationship between these variables. Thus, surface geometry was a significant determining factor of the temperature distribution if the selected scale was appropriate.

Simulation of the mean urban heat island using 2D surface parameters: empirical modeling, verification and extension (Balázs et al. 2009):

In this paper the spatial distribution of the annual mean UHI intensity was simulated applying empirical models based on datasets from urban areas of Szeged and Debrecen, using simple and easily determinable urban surface cover variables. These two cities have similar topographic and climatic conditions. Temperature field measurements were carried out, Landsat satellite images were evaluated, and then one- and multi-variable models were constructed using linear regression techniques. The selected multiple-parameter models were verified using independent datasets from three urban settlements near Debrecen. In order to obtain some impression of the mean UHI patterns in other cities with no temperature measurements available, the best model among the obtained ones was extended to four urban areas situated in geographical environments similar to Szeged and Debrecen. The main shortcoming of typical empirical models, namely that they were often restricted to a specific location, was overcome by the obtained model since it was not entirely site but more region specific, and valid in a large region (Great Hungarian Plain) with several cities.

Computing continuous sky view factor using 3D urban raster and vector data bases: comparison and application to urban climate (Gál et al. 2009):

The use of high resolution 3D urban raster and vector databases in urban climatology was presented. The study applied two different methods to the calculation of continuous SVFs, compared their values and considered their usefulness and limitations in urban climate studies. It evaluated the relationship between urban geometry, quantified by SVF, and intra-urban nocturnal temperature variations using areal means in the whole urban area of Szeged. Results from the vector and raster models showed similar SVF values. The usefulness of application of areal means in SVF−temperature relations was confirmed. The vector and the raster approaches to the derivation of areal means of SVF were both showed to be powerful tools to obtain a general picture of the geometrical conditions in urban environments.

Analysis of the relationship between urban land use and urban heat island using GIS methods in Szeged (Mucsi et al. 2009):

In this paper, instead of traditional per-pixel classifiers, Normalized Endmember Spectral Mixture Analysis was applied to map urban land cover using Landsat TM data acquired over the city of Szeged. Impervious surface, one of the most important elements of VIS model, has been recognized as a key indicator in assessing urban environment. Fractional images of impervious surfaces developed from LTM images (acquired in 1986 and 2007) were compared. The urban land cover map was the base of the spatial analysis of UHI, which demonstrated a very strong connection between the spatial distribution of main urban land cover classes and the spatial characteristics of UHI. In addition to 2D spatial analysis, the investigation was extended to include 3D urban surface analysis to assess the effect of urban surface geometry onto the UHI using geoinformatic methods. According to the results, there was a strong relationship in the intra-urban variations of surface geometry and heat island intensity.

Modeling of the urban heat island pattern based on the relationship between surface and air temperatures (Unger et al. 2010); City of sunlight after sunset – mapping of urban heat island using aerial remote sensing method in Szeged (Rakonczai et al. 2009):

The aim of these studies was to develop a new method for early nighttime near-surface air temperature pattern estimation based on surface temperature data in urban areas. The surface temperature data were collected by an airplane-based thermal infrared sensor at an altitude of 2000 m above ground level. The study area was covered by hundreds of images with a spatial resolution of about 2 m. The measured values were calibrated with data of in situ surface measurements of different land use types. Large temperature differences where found between green areas and densely built-up parts of the city. The structure of the city was reflected in the temperature map; roads and squares showed very high temperatures, while parks and waterbodies were up to 20 degrees cooler. Simultaneous air temperature measurements were carried out using a car-based temperature sensor along an almost 12 km long N-S urban transect. The measured points were located using a GPS device. Data were processed with GIS methods, including newly developed algorithms. In order to find the relationship between air and surface temperature a wider environment, the source area which determines the air temperature at a given point and time was taken into account. Using a source area with a radius of 500 m, a strong relationship was detected between the two parameters. Namely, the temperatures of the surfaces found in the surroundings (weighted by the distance) determine the temperature of the air parcel located at a given point. The obtained regression equation was applied to extend the results in order to model the air temperature field in a larger urban area of Szeged.

Comparison and generalisation of spatial patterns of the urban heat island based on normalized values (Unger et al. 2010); Investigation of the structure of an urban heat island using normalized intensity (Sümeghy, Unger 2004); Classification of the urban heat island patterns (Sümeghy, Unger 2003c):

The studied medium-sized cities (Szeged and Debrecen, Hungary) are located on a low and flat plain. Data were collected by mobile measurements in grid networks under different weather conditions between April 2002 and March 2003 in the time of daily maximum development of the UHI. Tasks included: (i) interpretation and comparison of the average UHI intensity fields using absolute and normalized values; (ii) classification of individual temperature patterns into generalized types by cities using normalization and cross-correlation. According to the results, spatial distribution of the annual and seasonal mean UHI intensity fields in the studied period had concentric shape with some local irregularities. The UHI pattern classification reveals that several (eight) types of the structure could be distinguished in both cities. Shifts in the shape of patterns in comparison with the centralized pattern were in connection with the prevailing wind directions.

Evaluation of the thermal features of the local climate zones – a Szeged case study (Lelovics et al. 2013):

In this study the connection between air temperature of the urban area and its built-up features was examined in Szeged. Air temperature was measured along a N-S transect during anticyclonic situations in a mobil measurement campaign in 2008. The urban built-up features were characterized with the usage of LCZ system. The largest temperature values occurred in two areas: area at the edge of the LCZ 2 with densely located 3-4-storey buildings, and the parking lot of a shopping center at the border of LCZ 5 and LCZ 6 appeared as exceptionally warm spots.

Refining the concept of urban heat island using Local Climate Zone classification – examples from Szeged (Unger et al. 2014):

This study first presented the new LCZ classification system which reflected the climatic characteristics of the surfaces as well as its types and aspects of their separation based on quantified parameters. Secondly, it developed GIS methods wich calculate these parameters for given areas. The database for these methods contained topographic map, 3D building and 2D road databases, as well as remotely sensed information from RapidEye satellite image. Thirdly, it determined the LCZ types occuring in the urbanized area of Szeged and were represented by circle areas with a diameter of 250 m. As a final step, it compared their thermal reactions based on the earlier temperature measurement campaigns. As a result, six built and one land cover LCZ types were distinguished in the studied urban area. Clear temperature differences occurred between these types. These differences were very significant on a day with favorable (calm and clear) weather conditions and they were more moderate using annual averages. These comparisons confirmed the usefulness of these type of classification: the thermal influence of any change or difference in landscapes were better expressed using LCZ difference concept than a simple but generally not clear urban-rural approach, and additionally, it provided an opportunity for intra- and inter-urban comparisons.

2.3. Studies based on the data of the second urban station network

Development, data processing and preliminary results of an urban human comfort monitoring and information system (Unger et al. 2015):

In this study the development and operation of an urban climate monitoring network and information system in Szeged and the related preliminary research results were discussed. The selection of the representative sites of the network was based primarily on the pattern of the LCZs in and around the city. After the processing of the incoming data (air temperature and relative humidity, as well as global radiation and wind speed), a human comfort index was calculated from the four meteorological parameters with a neural network method, then the measured and calculated parameters interpolated linearly into a regular grid with 500 m resolution. As public information, maps and graphs about the thermal and human comfort conditions appeared in 10-minute time steps as a real-time visualisation on the internet. As the preliminary case studies showed, the largest intra-urban thermal differences occurred in the nocturnal hours reaching even 5ºC in early spring. In the spatial distribution of human comfort conditions, there were distinct differences in the strength of the loading or favorable environmental conditions between the neighborhoods during the daytime. Finally, the utilization possibilities of the results were detailed.

Intra-urban temperature observations in two Central European cities: a summer study (Lelovics et al. 2016):

This paper presented an urban climatological application of the urban monitoring systems – recently implemented in Szeged and Novi Sad, Serbia – using the first set of data collected during the summer of 2014. In order to ensure a representative number and placement of stations, the selection of measurement sites was based on LCZ maps developed for both cities. This study concentrated only on the intra-urban temperature pattern characteristics expressed by the thermal reactions of the different LCZs in both cities. The daily temperature indices (e.g., summer days) had the highest values in the densely built-up LCZs. The diurnal cycle of surplus temperatures by LCZ classes under anticyclonic weather conditions was found to be similar in the two cities with higher absolute values in the case of Novi Sad. During summer, the diurnal variation of conventional UHI intensity confirmed the general knowledge that it remained positive with highest values at night, while negative values occurred predominantly during the day.

Urban heat island patterns and their dynamics based on an urban climate measurement network (Gál et al. 2016):

In this paper the spatial pattern of UHI and its dynamical background were analysed. Furthermore, the annual, seasonal and diurnal characteristics of UHI were examined according to the LCZs. The analysis was performed using one year (between June 2014 and May 2015) dataset from the measurement network of Szeged. This network consisted of 24 stations measuring air temperature and relative humidity. In the installation of the network the representativeness played an important role in order to that the stations represents their LCZs. The thermal reactions were examined during average and ideal conditions using the so-called weather factor. The results showed that the UHI was stronger in the compactly built zones and there were great differences between the zones. The greatest values appeared in summer, while the difference was small in winter. The UHI started to develop at sunset and existed through approximately 9–10 hours and differences were about 2°C larger in case of ideal days, when the conditions (wind, cloud cover) were appropriate to the strong development of the UHI. The cooling rates showed that the first few hours after sunset were determinative for the developing of UHI. In addition, the effect of UHI on annual mean temperature was also significant.

Employing an urban meteorological network to monitor air temperature conditions in the 'local climate zones' of Szeged, Hungary (Skarbit et al. 2017); Urban climate measurement network and information system in Szeged (Unger et al. 2017):

The average annual and seasonal air temperature conditions in the LCZs of Szeged were analysed. The basis of the analysis was a 1-year dataset from 2014 to 2015 from 20 station of the urban meteorological network. The network and its corresponding LCZ classes put temperature studies in Szeged into a new spatial framework to assess local climate and

UHI conditions. The stations were installed at locally representative sites using a Geographic Information System method based on the standard surface parameters of the LCZ classification. The network was purposely designed to monitor thermal differences among LCZ classes. Detailed site metadata were provided for each of the stations used in the analysis. The results showed that the densely built-up LCZs had higher annual and monthly mean and minimum air temperatures than structurally open and more vegetated classes, with nocturnal differences of >4°C observed under calm, clear skies. Among select temperature indices measured in the urban LCZ classes, frost days, cooling degree-days, and tropical nights differed markedly from the background rural LCZs. This difference suggested that local climatologies existed within the city, and that these had implications for thermal comfort, urban energy use, and urban agriculture. In addition, the dynamics of the UHI pattern was also presented at a night with ideal weather conditions. Finally, the evaluation of heating and cooling rates in Szeged showed an important role for LCZs in UHI analysis.

Comparison of regional and urban outdoor thermal stress conditions in heatwave and normal summer periods: A case study (Unger et al. 2020):

This study compared the diurnal variation of thermal stress conditions during a heatwave period (HW) to the ones during a normal summer period in the region and within the urban area of Szeged based on urban monitoring network data. Thermal stress categories of human bioclimatological index PET were adapted to the local population. Variation of the nocturnal intra-urban PET-patterns was analyzed along with the evolving UHI. A definite regional difference was found in the thermal stress conditions between the two periods, which was at least one PET-category in the daytime, while slightly less during the night. The nocturnal stress was higher in the inner city parts for both periods and the evolving UHI patterns determined the PET-patterns in a great extent. The UHI proved to be much stronger in the HW period. In summary, during the HW the nocturnal thermal stress on the urban inhabitants, especially those living in 'hot spot' neighborhoods, was significantly higher than what could be deducted from temperature data measured near the city. These types of results could provide valuable information for urban planners and decision-makers for evolving strategies against the adverse effects of urban climate and climate change to create livable settlements.

2.4. Studies based on local-scale simulation data

Projection of intra-urban modification of nighttime climate indices during the 21st century (Skarbit, Gál 2016):

This paper evaluated the alteration of certain nighttime climate indices namely warm nights ($T_{min} \geq 17$°C) and tropical nights ($T_{min} \geq 20$°C) during the 21st century in Szeged. In this study the MUKLIMO_3 model was used, which ensured the modelling of the local scale processes in the examined area. In the model for the land use the LCZ system was applied. In order to analyze longer periods the cuboid method was applied, which is a dynamical-statistical downscaling technique. The calculated indices for 1981–2010 were based on measurements and for 2021–2050 and 2071–2100 from the EURO-CORDEX datasets. The study presented the results of Representative Concentration Pathways scenarios namely RCP4.5 and RCP8.5 and they showed that the highest values appeared in the city centre and the number of the days clearly increased in the 21st century especially according to scenario

RCP 8.5. The values depended on the built-up types and there were more days towards to the densely built-up LCZs. Moreover, considering the relative changes of the zones, larger changes appeared in sparsely built-up zones and natural surfaces.

Urban climate in Central European cities and global climate change (Bokwa et al. 2018):

This paper was the final report of the „Urban climate in Central European cities and global climate change" project with the aim to raise the public awareness on those issues in five Central European cities: Szeged, Brno (Czech Republic), Bratislava (Slovakia), Kraków (Poland) and Vienna (Austria). Within the project, complex data concerning local geomorphological features, land use and long-term climatological data were used to perform the climate modelling analyses using the model MUKLIMO_3. According to the predictions presented, an increase in heat load, expressed in mean annual number of summer days, was expected in urban areas of Central Europe. Mean values for particular study areas were expected to increase by 2100, comparing to 1971–2000, by 20–50 days, depending on the scenario used. The regional pattern of the predicted values of mean annual number of summer days showed dependence on latitude, i.e. for cities located in the northern part of the study area, the values were lower than for cities located in the south. The difference for mean values, for particular study areas, reached about 40 days. The local patterns showed the impact of both land use/land cover and relief. The largest values of mean annual number of summer days were observed in areas with intense built-up which were located in the valley floors. In rural areas, larger values occurred in the valleys than in the hill tops. The differences between the places with the lowest value and the largest value in particular cities reached 60–100 days, depending on the scenario used.

Heat load assessment in Central European cities using an urban climate model and observational monitoring data (Bokwa et al. 2019):

Diurnal variability of spatial pattern of air temperature was studied in five cities in Central Europe: Bratislava (Slovakia), Brno (Czech Republic), Kraków (Poland), Szeged and Vienna (Austria), during one of the heatwaves in 2015 (4–14 August), with the application of MUKLIMO_3 model. 8th August was chosen to study in detail the urban heat load at 10.00, 16.00, 22.00 and 4.00 CEST. LCZ concept was used to supply data for the model and for the interpretation of the results obtained. Model outcomes were validated with measurement data from 86 points belonging to the networks which operated in the cities studied. The results obtained showed that among urban LCZ, the highest heat load was observed for LCZ 2 and LCZ 3 from 16.00 to 4.00, while at 10.00 there was no such clear pattern. Unlike forested areas, open green areas can contribute to the generation of high air temperature: > 35°C during daytime and > 30°C during nighttime. Important factors controlling the intra-zonal and inter-zonal variability of air temperature in particular LCZs were the local environmental conditions. During the daytime, diversified relief in the area of the city and its vicinities generated higher heat load in the valleys' floors than in areas located above, both in rural and urban areas. The same landforms experience lowered heat load during the nighttime due to air temperature inversions effect.

Projection of present and future daily and evening urban heat load patterns (Unger et al. 2020):

In this modeling study the recent and future daily and evening thermal climate of a Central-European city (Szeged) was investigated in terms of heat load modification by applying MUKLIMO_3 model to project daily and evening climate indices. For surface parameterization the LCZ scheme was used. The investigation encompassed three climatological time periods (1981–2010, 2021–2050 and 2071–2100) and two emission scenarios for future climate (RCP4.5 and RCP8.5). The results showrd that highest index values appeared in the city centre and stretch to the NW direction (LCZs 2, 3 and 8) and they decreased towards to the vegetated rural surfaces (mainly LCZ D). That is, the values depended on the zone types and there were more days towards to the densely built-up LCZs. Also, a general temporal change could be detected as the index patterns showed the substantial increasing tendency for both indices towards the end of this century. This temporal change suggested a two-way conclusion: first, the increasing number of hot days means a strongly deteriorating change of unfavourable thermal conditions, and second, the change in the number of the evening index provides more opportunities for regeneration and leisure-time activities outdoors in the already thermally less stressful evening hours for the urban inhabitants. This study gave very illustrative examples on the expected climate changes during this century and these examples show that there were several sides to these changes in urban environments. Furthermore, they clearly proved that global or regional scale climate predictions without urban climate interactions do not have enough detailed information.

Analysis of urban heat island with meteorological forecast model in Szeged (Molnár et al. 2017):

Aim of the research was the application of Weather Research and Forecasting (WRF) model in urban scale in order to predict the UHI effect. Therefore, high-resolution, nested simulations were carried out in case of a Szeged in 2015. In this area, a detailed measurement dataset was available for the model validation process. In numerical weather predictions models the applied urban land use information was crucial. Consequently, it was essential to improve the details of canopy parameterization if the static data did not manage to represent precisely the urban forms in a specific area. High-resolution remote sensing products of Landsat 8 OLI/TIRS satellite and multiple GIS techniques were applied to determine the sufficient canopy values. Several simulations were made with different model setups and input geographical databases to fine-tune the model performance for optimal agreement with measured UHI parameters. The results suggested that the model reproduced reasonably well the UHI effect related to measurements in case of uninterrupted (anticyclonic) weather conditions.

Evaluation of a WRF-LCZ system in simulating urban effects under non-ideal synoptic patterns (Molnár et al. 2018):

The modelling of meteorological variables under non-ideal (e.g. characterized by cyclonal activity) synoptic patterns is always challenging. It is particularly true, when the simulations are performed on local or neighborhood scale. In this study the spatio-temporal distribution of UHI of Szeged was predicted by the WRF model during two period with different meteorological background. During the first, a thick and permanent fog layer was located over the Carpathian Basin. The second one was dominated by a Mediterranean low that has caused high sums of precipitation. The comparison of modelled and observed variables suggested that the computed outputs showed robust consistency with the observations during the rainfall event. On the foggy days, however, WRF had difficulties to capture the daily variability of UHI intensity. It was due to the large underestimations of moisture circumstances.

Modeling of urban heat island using adjusted static database (Molnár et al. 2019a):

In this study the WRF model was applied to examine the spatial and temporal formation of UHI phenomenon in Szeged. In order to achieve a more accurate representation of complex urban surface properties in WRF, a modified static database (consists of land use and urban canopy parameters) had been developed using satellite images and building information. In the new database, the number of urban grids increased by 76% related to the default case. The urban landscape in WRF became more complex after employing two urban land use classes instead of only one. The modification of the default parameters of a single layer urban scheme revealed that urban fractions decreased in all urban categories, while street widths increased resulting in narrower urban canyons. For testing the impact of the modifications on near-surface temperature estimation, a four-day heatwave period was selected from 2015. The model outputs had been evaluated against the observations of the local urban climate monitoring system (UCMS). WRF with the modified parameters simulated most of the features of UHI reasonably well. In most cases, biases with the simulations of the adjusted static database tended to be significantly lower than with the default parameters. Additionally, during a longer time period (i.e., the summer of 2015) the extreme values of near-surface air temperature and maxima of UHI intensities were evaluated on the basis of an urban and a rural site of UCMS. It was concluded that the maxima and minima of observed near surface air temperature were underestimated (overestimated) by about 1–3°C at the urban (rural) site. The maxima of UHI intensities indicated cold biases on 86 of 91 days.

Integration of an LCZ-based classification into WRF to assess the intra-urban temperature pattern under a heatwave period in Szeged, Hungary (Molnár et al. 2019b):

In this study the LCZ system was incorporated into the WRF model in order to facilitate proper land surface information for the model integrations. After the calculation of necessary input canopy parameters, based on local static datasets, simulations were performed to test the model's performance in predicting near-surface air temperature (T_a) and UHI intensity (ΔT) under a heatwave period in July 2017. The modelled values were evaluated against the observations of the local urban climate monitoring system. The results suggested that WRF with a single-layer canopy scheme and the LCZ-based static database was able to capture the spatiotemporal variation of the aforementioned variables reasonably well. The daytime T_a was generally overestimated in each zone. At nights, slight overestimations (underestimations) occurred in LCZ 6, LCZ 9, and LCZ D (LCZ 2 and LCZ 5). The mean ΔT was underestimated in the nighttime; however, the daytime ΔT was estimated accurately. The mean maxima (minima) of ΔT were underestimated (overestimated) with around 1.5–2°C, particularly in LCZ 2 and LCZ 5. Some components of the surface energy budget were also computed to shed light on the inter-LCZ differences of T_a. It was concluded that the nocturnal ground heat flux was about five times higher in urban LCZs than in the rural LCZ D, which resulted in a reduced cooling potential over the urbanized areas.

How does anthropogenic heating affect the thermal environment in a medium-sized Central European city? A case study in Szeged, Hungary (Molnár et al. 2020):

Since the estimation of anthropogenic heating was always problematic in medium-sized cities because of data lacking, the study intended to test how much the omission of such data influences the physical consistency in a numerical model (WRF). It was hypothesized that anthropogenic heating was an important input for the model, even in a relatively small urban area, therefore three different approaches were adapted to quantify its spatiotemporal distribution over Szeged. Four numerical experiments were performed in the WRF coupled with the single layer canopy scheme, which included the calculated fluxes and an anthropogenic flux-free reference case. By comparing the experiments, there were the opportunity to determine the effects of different anthropogenic heating scenarios on certain meteorological variables near the surface and in the overlying urban boundary layer. The maximum anthropogenic heat release was estimated to be ranging between 0.6 and 31.2 Wm^{-2}, with higher values on winter days. This heat surplus contributed to a maximum increase of 1.5°C in the simulated near-surface air temperature. Depending on the rate of anthropogenic heat release, the urban boundary layer became deeper, and the mixing of heat and momentum was more efficient. The results demonstrated that without the consideration of anthropogenic heating, numerical simulations performed to cities similar to Szeged cannot be physically complete.

2.5. Studies based in part on other data sources

Airborne surface temperature differences of the different Local Climate Zones in the urban area of a medium sized city (Skarbit et al. 2015):

This paper presented a case study about the surface temperature characteristics of the different LCZs in Szeged. For the evaluation high resolution surface temperature data acquired by a low-cost small-format digital imaging system, measured in early night hours were applied. The map of LCZs for the study area was derived by an automatic GIS method for LCZ classification. The results showed that the different LCZ classes had different surface temperature characteristics. Among the densely populated LCZ classes the open low-rise had the lowest surface temperature, thus it could be the most favorable urban built-up type if the aim is the decrease the effect of the urban heat load.

Using local climate zones to compare remotely sensed surface temperatures in temperate and hot desert cities (Fricke et al. 2020a); Exploring thermal differences in cities with different climates based on LCZ classification concept and satellite data (Fricke et al. 2020b):

Surface classification using the LCZ system provided an appropriate approach for distinguishing urban and rural areas, as well as comparing the surface urban heat island (SUHI) of climatically different regions. The goal of the study was to compare the SUHI effects of two Central European cities (Szeged and Novi Sad, Serbia) with temperate climate (Köppen-Geiger's Cfa), and a city (Beer Sheva, Israel) with hot desert climate (BWh). LCZ classification was completed using World Urban Database and Access Portal Tools methodology and the thermal differences were analysed on the basis of the land surface temperature data of the Moderate Resolution Imaging Spectroradiometer sensor, derived on clear days over a four-year period. This intra-climate region comparison showed the difference between the SUHI effects of Szeged and Novi Sad in spring and autumn. As the pattern of Normalised Difference Vegetation Index (NDVI) indicated, the vegetation coverage of the surrounding rural areas was an important modifying factor of the diurnal SUHI effect, and could change the sign of the urban-rural thermal difference. According to the inter-climate comparison, the urban-rural thermal contrast was the strongest during daytime in summer with an opposite sign in each season.

Model development for the estimation of urban air temperature based on surface temperature and NDVI – a case study in Szeged (Guo et al. 2020):

Predictive models for urban air temperature (T_{air}) were developed by using urban land surface temperature (LST) retrieved from Landsat-8 and MODIS data, NDVI retrieved from Landsat-8 data and T_{air} measured by 24 stations in Szeged. The investigation focused on summer period (June−September) during 2016−2019. The relationship between T_{air} and LST was analyzed by calculating Pearson correlation coefficient, root-mean-square error and mean-absolute error using the data of 2017−2019, then unary (LST) and binary (LST and NDVI) linear regression models were developed for estimating T_{air}. The data in 2016 were used to validate the accuracy of the models. Correlation analysis indicated that there were strong correlations at night and relatively weaker ones during the daytime. The errors between T_{air} and $LST_{MODIS\text{-}Night}$ was the smallest, followed by $LST_{MODIS\text{-}Day}$ and $LST_{Landsat\text{-}8}$, respectively. The validation results showed that all models could perform well, especially during nighttime with an error of less than 1.5°C. However, the addition of NDVI into the linear regression models did not significantly improve the accuracy of the models, and even had a negative effect. Finally, the influencing factors as well as temporal and spatial variability of the correlation between T_{air} and LST were analyzed. $LST_{Landsat\text{-}8}$ had a larger original error with T_{air}, but the regression model based on Landsat-8 had a stronger ability to reduce errors.

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