Projections of the urban and intra-urban scale thermal effects of climate change in the 21st century for cities in the Carpathian Basin

Tamás GÁL, Nóra SKARBIT, Gergely MOLNÁR and János UNGER[1]

Abstract

This study evaluates the pattern of a night-time climate index, namely the tropical nights (T_{min} ≥ 20 °C) during the 21st century in several different sized cities in the Carpathian Basin. For the modelling, MUKLIMO_3 microclimatic model and the cuboid statistical method were applied. In order to ensure the proper representation of the thermal characteristics of an urban landscape, the Local Climate Zone (LCZ) system was used as land-use information. For this work, LCZ maps were produced using WUDAPT methodology. The climatic input of the model was the Carpatclim dataset for the reference period (1981–2010) and EURO-CORDEX regional model outputs for the future time periods (2021–2050, 2071–2100) and emission scenarios (RCP4.5, RCP8.5). As results show, there would be a remarkable increase in the number of tropical nights along the century, and there is a clearly recognizable increase owing to urban landform. In the near past, the number of the index was 6–10 nights higher in the city core than the rural area where the number of this index was negligible. In the near future this urban-rural trend is the same, however, there is a slight increase (2–5 nights) in the index in city cores. At the end of the century, the results of the two emission scenarios become distinct. In the case of RCP4.5 the urban values are about 15–25 nights, what is less stressful compared to the 30–50 nights according to RCP8.5. The results clearly highlight that the effect of urban climate and climate change would cause serious risk for urban dwellers, therefore it is crucial to perform climate mitigation and adaptation actions on both global and urban scales.

Keywords: climate change, urban climate, Local Climate Zones, urban climate modelling

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Introduction

In our days, the most important environmental phenomenon is climate change. At a global scale, the temperature change is already observable, and by the end of the 21st century it is projected to likely exceed 1.5 °C (Stocker, T.F. *et al.* 2013). The temperature increase has complex environmental effects in global, regional and local (urban) scales, too. The local consequences of these are at least as fundamental as those of a global scale, as the majority of the population is already concentrated in cities. The heat load in cities is supposed to get intensified as global temperature increase will be superimposed on urban temperature modification. Namely, owing to urban heat island (UHI) development the urban nocturnal temperature is usually higher than the rural one (Oke, T.R. *et al.* 2017). Overall, this can have far-reaching health effects (Baccini, M. *et al.* 2008; Bartholy, J. and Pongrácz, R. 2018). Therefore, the studies concerning the impact of global changes on local climate of cities are of a high significance for the urban inhabitants' health and well-being. Therefore, in order to plan and undertake the mitigation actions in particular cities, it is necessary to recognize the possible range of heat load increase there, in terms of both its magnitude and spatial extent.

[1] Department of Climatology and Landscape Ecology, University of Szeged. H-6722 Szeged, Egyetem u. 2. E-mails: tgal@geo.u-szeged.hu, skarbitn@geo.u-szeged.hu, molnarge@geo.u-szeged, unger@geo.u-szeged.hu

In the last few years, local authorities and urban planners in Hungary have begun to pay growing attention to the latest climate change projections. Their interest, of course, focuses on urban-scale features and phenomena, but there are few basic research results for urban areas. Based on these trends, new basic research results are needed to produce climate projections at the local level in order to provide basic information to urban planners on urban climate mitigation strategies or applied research in this field.

The effect of climate change on temperature is presented in IPCC reports (e.g. IPCC 2018). Recent climate model projections apply the Representative Concentration Pathways (Van Vuuren, D.P. *et al.* 2011), and the most commonly used scenarios are RCP4.5 and RCP8.5. These scenarios represent a global temperature increase of 2 °C and 4 °C by the end of the century, but at the regional level, the temperature change is highly variable.

Considering the Carpathian Basin, it is essential to evaluate climate projections for temperature and temperature-related climate indices, as no further climate change mitigation and adaptation plans can be implemented without this information. In case of temperature change there are numerous regional model results (e.g. Jacob, D. *et al.* 2014; Pieczka, I. *et al.* 2018). Based on these results, the temperature changes in this region are 1.5–2 °C (RCP4.5) and 3–4 °C (RCP8.5) by the end of this century.

In order to help the evaluation of the future climate trends it is very suitable to utilize a climate index projection, such as the number of tropical nights (TN, when the daily $T_{min} \geq 20$ °C). This particular index is a good indicator of the annual duration of adverse hot weather conditions, as a high minimum temperature also means a high daily temperature, taking into account the daily temperature cycle (Pieczka, I. *et al.* 2018). For TNs, the projected trends in the Carpathian Basin are as follows: In the period 2021–2040, their numbers are 10–15 (RCP4.5) and 10–20 (RCP8.5), and in the period 2081–2100 they are 20–30 (RCP4.5) and 40–60 (RCP8.5) (Pieczka, I. *et al.* 2018). It is important to highlight that these results are derived from regional climate models and the urban impact does not appear within these model outputs, so an evaluation of a detailed model experiment for urban areas in the Carpathian Basin would provide vital information for climate change related decisions.

It is essential to use an urban climate model to predict the climate in urban areas. Recently, these models have evolved rapidly (Kusaka, H. *et al.* 2001; Martilli, A. *et al.* 2002; Lemonsu, A. *et al.* 2012; Lee, S.-H. *et al.* 2016; Ryu, Y.H. *et al.* 2016). Most of these model development initiatives are related to the Weather Research and Forecasting Model (WRF), Molnár, G. *et al.* (2020) briefly discusses these models. There are only a few other smaller-scale modelling options, e.g. ENVI-met (Bruse, M. and Fleer, H. 1998), Town Energy Balance (Masson, V. 2000) and MUKLIMO_3 models (Sievers, U. 1995). MUKLIMO_3 offers a great possibility for climate projection for urban areas, since combined with the statistical cuboid-method it is capable for time effective simulation. The other advantage of this model is the representation of building arrays. In the urban parametrizations related to WRF the built-up is modelled with the urban canyon concept, however, in MUKLIMO_3 the built-up is regarded as a porous volume. This concept is more close to reality in open urban built-up zones, where urban canyons cannot be defined properly. The computational time efficiency and the replacement of urban canyon concept were the main reasons for using this model.

In the case of local-scale climate modelling, the selection of land cover data is crucial. There are a number of possible data sources for this, such as the CORINE land cover, the USGS land use dataset, and the Open Street Map. These databases have their advantages, however, none of them have been designed to represent urban thermal reactions. In the field of urban climatology, the Local Climate Zone (LCZ) classification (Stewart, I.D. and Oke, T.R. 2012) is widely accepted as a representation of urban land use (*Table 1*) and is used to characterize the environment of the measurement sites (e.g. Siu, L.W. and Hart, M.A. 2013; Stewart, I.D. *et al.* 2014; Lehnert, M. *et al.* 2015) or to map

*Table 1. Built and land cover LCZ classes**

Built types	Land cover types
LCZ 1 – Compact high-rise	LCZ A – Dense trees
LCZ 2 – Compact midrise	LCZ B – Scattered trees
LCZ 3 – Compact low-rise	LCZ C – Bush, scrub
LCZ 4 – Open high-rise	LCZ D – Low plants
LCZ 5 – Open midrise	LCZ E – Bare rock / paved
LCZ 6 – Open low-rise	LCZ F – Bare soil / sand
LCZ 7 – Lightweight low-rise	LCZ G – Water
LCZ 8 – Large low-rise	
LCZ 9 – Sparsely built	
LCZ 10 – Heavy industry	

*After Stewart, I.D. and Oke, T.R. 2012.

different urban neighbourhoods (e.g. Lelovics, E. *et al.* 2014; Zheng, Y. *et al.* 2018). Therefore, this scheme can also be used as surface input for numerical modelling (Žuvela-Aloise, M. 2017; Kwok, Y.T. *et al.* 2019). The application of this scheme is advantageous because it is based on the thermal characteristics of the urban areas, i.e. it can be linked to the UHI phenomenon, which is the most important climate modification in these areas. Appropriate application of LCZ in local-scale climate modelling provides a good basis for global comparisons or validation, and the trends obtained from the results can be generalized.

In this study the climate projection outputs of the EURO-CORDEX regional models, the MUKLIMO_3 microclimatic numerical model, and the cuboid method (Früh, B. *et al.* 2011) were used to explore the combined effects of regional climate change and urban climate. The modelling process is based on LCZs as appropriate urban parameterization. Our previous studies of the thermal indices draw attention to the importance of this topic: in case of Szeged there is a remarkable increase in different thermal indices by the end of the century, namely, a strong warming trend can be expected (Skarbit, N. and Gál, T. 2016; Bokwa, A. *et al.* 2018).

The purpose of this study is twofold:

(i) Analysis and comparison of the patterns of the annual values of tropical nights (TNs) quantifying the thermal load of the cities in the Carpathian Basin in the current (1981–2010) and future climate change periods based on two different future emission scenarios (RCP4.5 and RCP8.5).

(ii) Determining the overall additional thermal load in urban areas relative to their natural surroundings for each scenario during these periods.

Study areas

The investigation focuses on different sized cities with different geographical background in the Carpathian Basin, mainly on low-lying areas with moderate relief *(Figure 1)*. The population of the selected 26 cities is between 20,000 and 1,675,000 (*Table 2*).

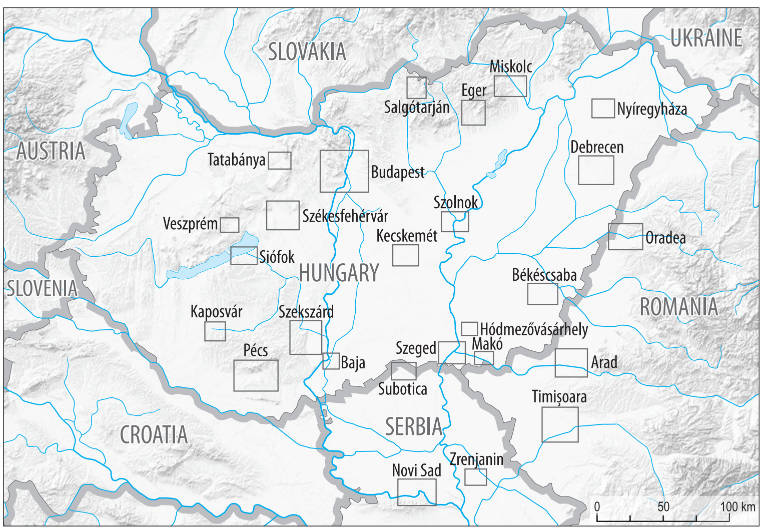

Fig. 1. Locations of the studied cities in the Carpathian Basin (modelling domains marked by black frames)

*Table 2. Population of the studied cities**

City size category by range of population in 1,000 inhabitants	City	Population, 1,000 inhabitants
1 (over 1,000)	*Budapest*	1,675
2 (between 200 and 400)	Timisoara (RO)	315
	Novi Sad (SRB)	215
	Oradea (RO)	207
	Debrecen	201
3 (between 100 and 199)	*Arad* (RO)	169
	Szeged	162
	Miskolc	158
	Pécs	147
	Nyíregyháza	120
	Kecskemét	110
	Subotica (SRB)	100
4 (between 50 and 99)	Székesfehérvár	96
	Zrenjanin (SRB)	80
	Szolnok	70
	Tatabánya	68
	Kaposvár	63
	Békéscsaba	59
	Veszprém	55
	Eger	52
5 (between 20 and 49)	*Hódmezővásárhely*	44
	Baja	36
	Salgótarján	35
	Szekszárd	32
	Siófok	25
	Makó	23

*Results of the cities written in italics are presented in details in this paper. *Source*: For Hungarian cities: https://nyilvantarto.hu, for other cities: https://worldpopulationreview.com/

An analysis of the current and future thermal situation of all 26 cities would go beyond the scope of this paper because of the length limitation. Therefore, we illustrate our results by selecting five city size categories, and we analyse the thermal situation of one city per category in detail (marked by italics in *Table 2*).

Methods

In order to get detailed information about the local scale future changes of thermal effects the MUKLIMO_3 model (Sievers, U. 1995) and cuboid method (Früh, B. *et al*. 2011) were applied to achieve high spatial resolution results inside the cities. The model is non-hydrostatic and calculates atmospheric temperature, relative humidity and wind field in a 3D grid by solving the Reynolds-averaged Navier-Stokes equations. Parametrizations are used for unresolved buildings, short-wave and long-wave radiation, balanced heat and moisture budgets in the soil (Sievers, U. and Zdunkowski, W. 1985). The initial meteorology conditions were ensured by a 1D profile from a reference station within the study area. To run the model, high-resolution orography and land use distribution data were needed. The horizontal resolution of 100 m was adjusted, while the vertical resolution changes in height and more accurate near to the surface, where the essential processes occur. The vertical resolution near to the surface is 10 m and increases by several steps to the top of the model domain where it is 100 m. For most cities 25 vertical layers were enough, however, in some cases, where the topography was more variable we applied more layers (in Budapest 35, Eger 36, Miskolc 38, Novi Sad 33, Pécs 36, Salgótarján 40, Tatabánya 35 and Veszprém 30 layers).

For our analysis, the orography data was provided by EU-DEM. The MUKLIMO_3 applies custom land use categories, thus, any land use classification system is usable if the necessary surface, vegetation and built-up parameters are provided. This property of the model allows applying any urban land use classification as an input for urban landforms. Using this advantage, we could apply the LCZ system to describe the land use.

We used Bechtel-method for LCZ mapping of the selected cities (see *Figure 1*), which applies free-access data and software (Bechtel, B. *et al.* 2015, 2019). This method is the basis of World Urban Database and Access Portal Tools (WUDAPT) which is a scientific initiative aiming to develop a global database for urban climate modelling. For this study, we used several Landsat images from different dates, in order to achieve more reliable LCZ classification. This approach ensures that the yearly changes of agricultural processes or vegetation cycle do not affect the final LCZ maps. The process was verified with field surveys in order to avoid misclassifications.

To represent the thermal effects of climate change several climate indices were calculated and to obtain these climate indices the so-called cuboid method was used, which is a statistical dynamical downscaling method (Früh, B. *et al*. 2011; Žuvela-Aloise, M. *et al*. 2014). This process is basically a tri-linear interpolation of air temperature, relative humidity and wind fields derived by MUKLIMO_3 simulations and produces 30 year mean of annual number of 6 different climate indices. The method assumes that heat load situations can occur in case of specified weather situations, which can be described by the mentioned variables. The necessary inputs for the calculation of these climate indices are a 30-year daily climate dataset from a reference station and 8 single-day MUKLIMO_3 simulations for two prevailing wind direction (16 simulations). In this study the model outputs related to the tropical nights (TNs) are presented.

The process of climate change was examined through two future periods, 2021–2050 and 2071–2100 as well as period 1981–2010 was considered as reference. To obtain input climate data for the cuboid method, the Carpatclim database (Szalai, S. *et al*. 2013) was applied for the reference period. It provides meteorological daily data for the Carpathian Region in spatial resolution of 0.1°. The database does not cover the entire area of Hungary, thus, cities in the western part of the country were excluded from the research.

For the 21st century, data of EURO-CORDEX model simulations with resolution 0.11° were used (Jacob, D. *et al*. 2014). The selection of the simulations was based on whether they include the necessary bias-corrected variables for the cuboid method e.g. air temperature, relative humidity wind speed and direction. Accordingly, 12 simulations were selected, which apply scenarios RCP4.5 and RCP8.5 also. The cuboid method was executed for all model simulations and the results were averaged by the scenarios.

Results and discussion

Examples of urban TN patterns by city categories

Due to its dense built-up and large spatial extent, the number of TNs is relatively high in Budapest in the period of 1981–2010, and the maximum value in the city centre exceeds 20 *(Figure 2*, b*)*. The number of TNs exceeds 10 in the remarkable part of the urban area and 15 in the interior. The pattern of higher values extends to the northeast due to the compact structure of this area (LCZ 3). Relatively high values also appear in the south-eastern part of the city, which may be caused by the prevailing wind direction. The high values of the southern city centre are the results of the LCZ 8, as this type of zone contains large impervious surfaces. This LCZ also appears scattered outside the urban area, with values above 5, especially in the south.

In both scenarios, there are clear changes in the period 2021–2050 compared to the reference period, but there is no considerable difference between them *(Figure 2*, c-d*)*. TN_{max} values are 31 and 35, respectively, according to RCP4.5 and RCP8.5. In most parts of the city, the value of TN in both cases exceeds 15. There are differences between the scenarios in the patterns of the values of 20 and 25, which are more extended into the North, South, and downtown areas for RCP8.5.

At the end of the century, there will be strong changes compared to the period 2021–2050, and the differences between the scenarios will become more remarkable *(Figure 2*, e-f*)*. According to RCP4.5 the number of TNs is over 20 in almost the whole city and the area of TNs over 25 is also expanded (TN_{max} is 42). At the centre, the typical value exceeds 30, but even values above 40 appear in a smaller area. For RCP8.5, TN_{max} is 71 and the number of TNs is over 40 almost throughout the city. The extension of values above 50 is also noteworthy, while in the city centre the number exceeds 60.

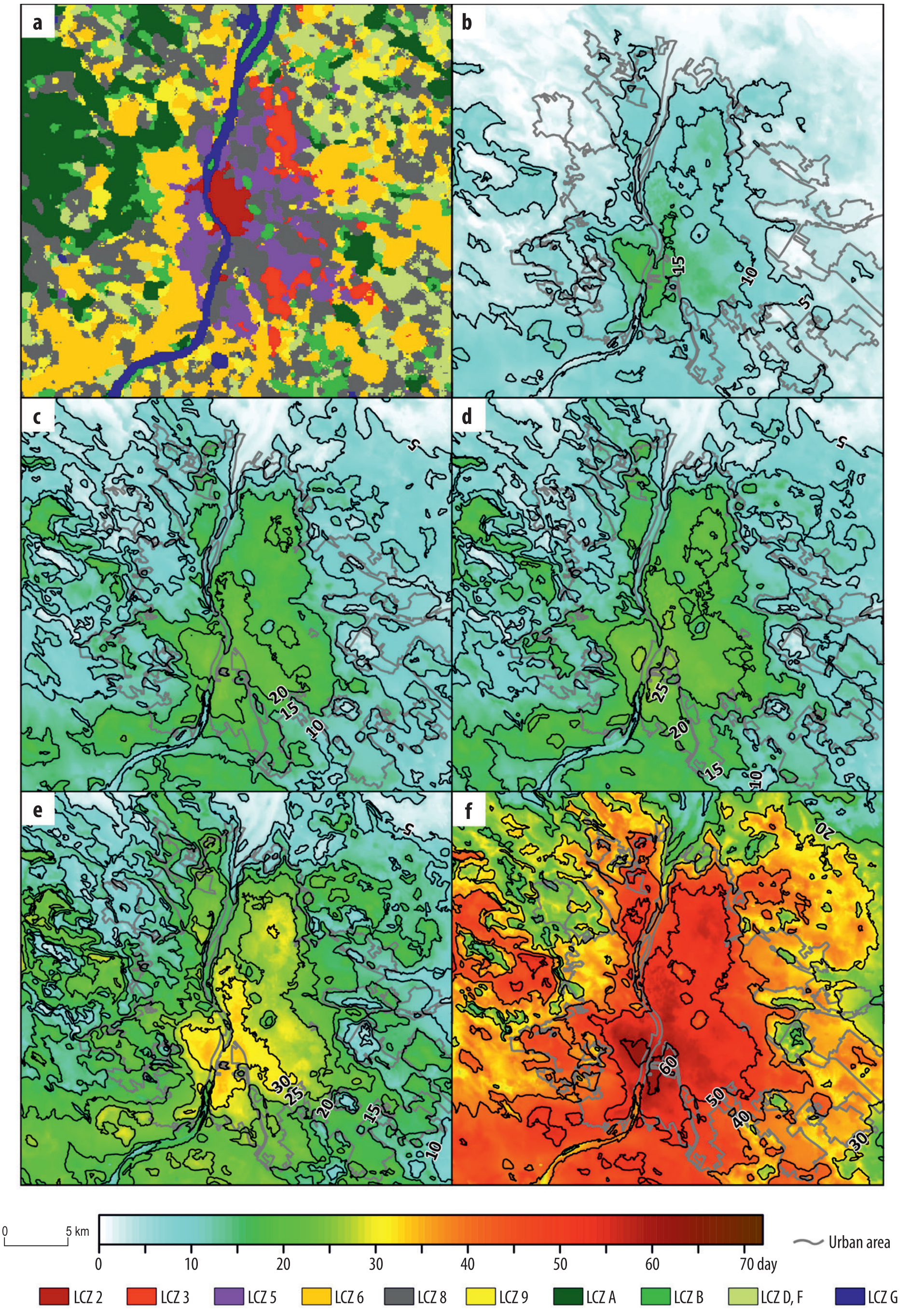

Fig. 2. LCZ map (a) and patterns of the tropical nights in Budapest (Hungary) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind direction are NW and E.

In the case of Debrecen, the smaller population and areal extent compared to the capital is reflected in the number of TNs. Its value exceeds 5 in the more densely built-up western part of the city and in the LCZ 8 between 1981 and 2010 *(Figure 3*, b*)*. In the city centre, values above 10 occur mostly in the area of compact LCZs, but values above 15 can also be observed in a relatively small area (with a maximum of 16). The effect of the second dominant wind direction (north-east) also appears in the pattern.

There will be minimal changes in the period 2021–2050, the scenarios show similar results, and the change between them is negligible *(Figure 3*, c-d*)*. The only considerable change is the increased area of TNs over 10 and 15, which appear with slightly different magnitudes by scenarios. The maximum values are 17 and 19 according to the different RCPs.

Remarkable changes is observed in the period of 2071–2100 and the differences between the scenario values are relatively large *(Figure 3*, e-f*)*. According to RCP4.5, in most parts of the city the values are over 10 and the number of TNs in the interior exceeds 15, while in LCZ 2 it exceeds 20 (TN_{max} is 25). For RCP8.5, the values are more than twice as high: in most parts of the city, the number of TNs exceeds 30, while in the centre it is greater even 40 (TN_{max} is 51).

Considering Arad, which represents the next category of cities, the magnitude of TNs is similar, but slightly lower than in Debrecen. During the reference period, the number of TNs exceeds 5 in densely built-up areas and 10 in the small area of LCZ 8 (TN_{max} is 11) *(Figure 4*, b*)*. The effect of the prevailing wind directions is reflected in the north-west extent of the pattern.

In the case of this city, too, the near future will not bring major changes and the difference between the scenarios is minimal, the maximum values are 13 and 14 *(Figure 4*, c-d*)*. The change compared to the reference period is the increase in areas above 5 and 10. This increase occurs especially around the green area in the south-east and in the north-western parts of the city.

In 2071–2100, the changes according to RCP4.5 are noticeable, but not salient *(Figure 4*, e*)*. The pattern is similar to the previous period, but the values are higher of about 5 (TN_{max} is 21). The other change is the appearance of values above 5 in the western part of the study area, which may be the result of the prevailing wind directions and the dense tree zone (LCZ A). For RCP8.5, the changes are twice as high *(Figure 4*, f*)* in almost the entire city and in densely built-up areas the number of TNs exceeds 30 and 40, respectively (TN_{max} is 50).

Although the population of Zrenjanin is lower than that of the previous two cities, the number of TNs in the reference period is higher due to its location at a lower latitude *(Figure 5*, b). In almost the entire area of the city the value exceeds 5, except for the southern part. In the LCZ 8 and LCZ 5 it is over 10, while LCZ3 it has more than 15 (TN_{max} is 23).

In the period 2021–2050 the pattern values exceed 5 and 10, especially according to RCP8.5 *(Figure 5*, c-d*)*. In addition, values above 15 appear scattered across the western and southeastern areas. The TN_{max} is 21 and 24 for the different RCPs. The lack of increase of the maximum values in case of RCP4.5 is the result of the application of different climate input for the reference and future periods (Carpatclim and EURO-CORDEX).

Considering the results between 2071 and 2100, the changes are of a similar magnitude as in previous cities *(Figure 5*, e-f*)*. At RCP4.5, the number of TNs is over 15 throughout the city. Besides, values above 20 appear scattered throughout the pattern, especially in LCZ 8 and LCZ 5. In the core (dominated by LCZ 3), the values exceed 25 and even 30 in a small area (TN_{max} is 31). The outcomes of RCP8.5 during this period show far high values, which are slightly more than twice as high as those of RCP4.5: almost the entire area of the city has more than 40 TNs and values above 50 appear in the previously mentioned zones and are above 60 in the city core (TN_{max} is 62).

Hódmezővásárhely is the smallest among the example cities, however, this is not reflected in the number of TNs (*Figure 6*, b*)*.

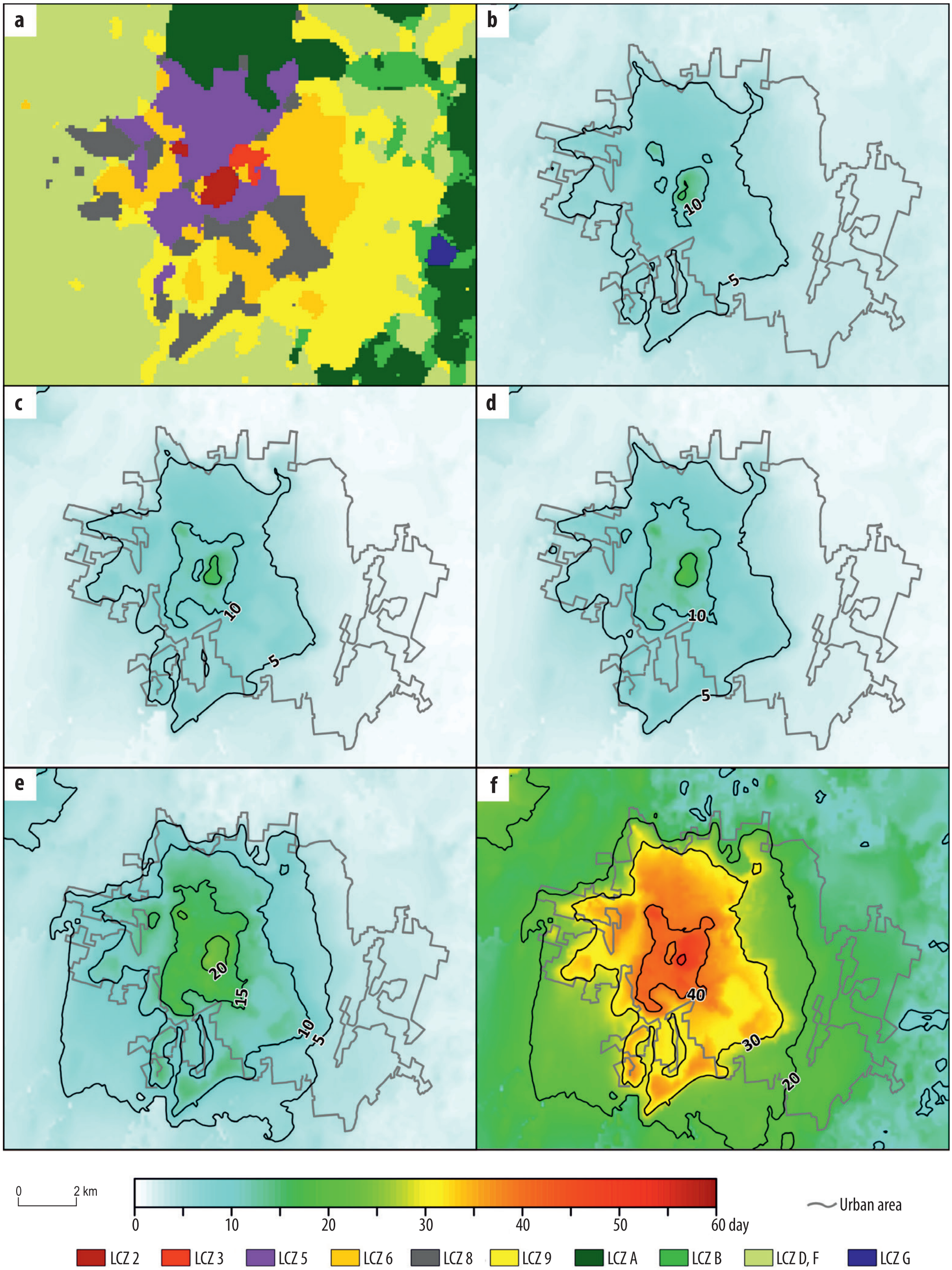

Fig. 3. LCZ map (a) and patterns of the tropical nights in Debrecen (Hungary) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind directions are S and NE.

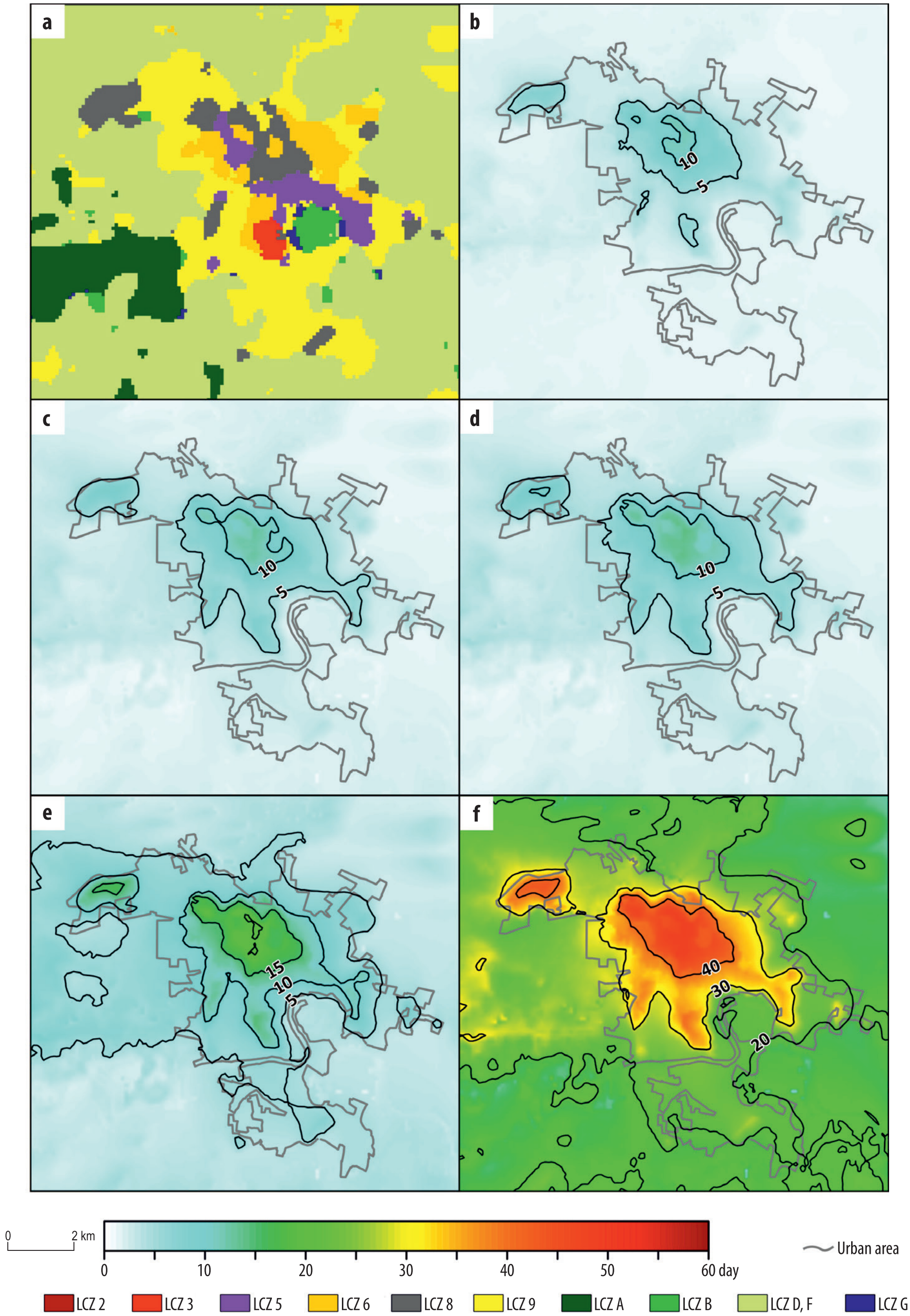

Fig. 4. LCZ map (a) and patterns of the tropical nights in Arad (Romania) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind directions are S and SE.

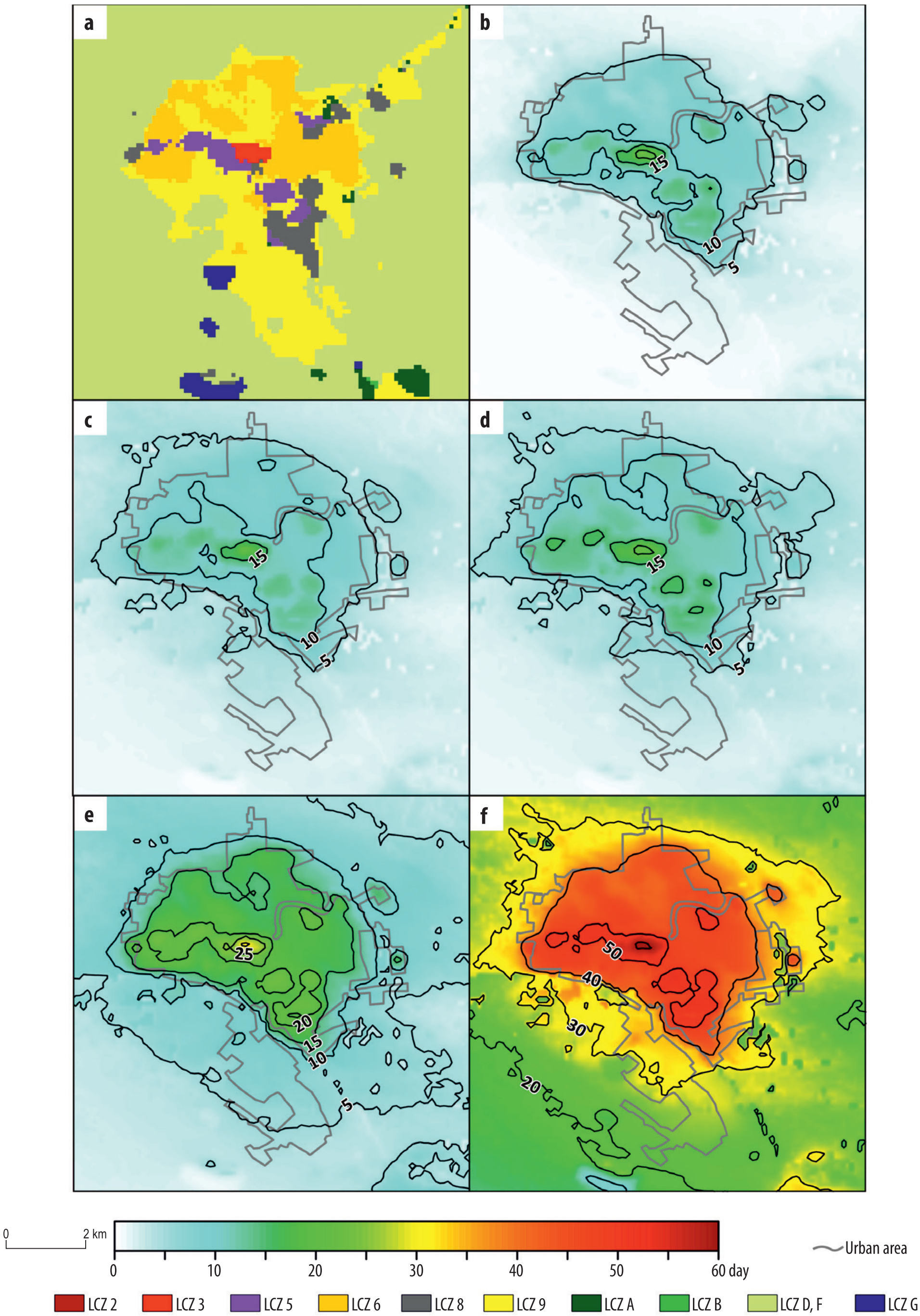

Fig. 5. LCZ map (a) and patterns of the tropical nights in Zrenjanin (Serbia) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind directions are SE and NW.

In the reference period, the city boundary almost coincides with line 5, while in LCZ 8 the numbers exceed 10 (TN_{max} is 11).

In the near future, minor changes will take place, which is reflected in the expansion of value areas above 5 and 10 *(Figure 6,* c-d*)*. The main difference between the scenarios is the increased area of values above 10, which is even greater for RCP8.5: not only LCZ 5 and LCZ 8 are affected, but also the N-NE part of the city. The maximum values according to RCP4.5 and RCP8.5 are 12 and 13, respectively.

For 2071–2100, the change in RCP4.5 is not outstanding: the number of TNs exceeds 10 in the entire urban area and is greater than 15 in most of the city, which means the densely built-up south-west, the south-east LCZ 8 and the aforementioned north-northeast *(Figure 6,* e*)*. The TN_{max} does not exceed 20, which is exceptional among the presented cities. For RCP8.5, the values in the whole urban area exceed 30 and are higher than 40 in the previously mentioned areas, and exceed 45 in the south-west and south-east (TN_{max} is 48) *(Figure 6,* f*)*.

Urban-rural heat load differences

According to *Table 3*, the number of TNs in the reference period does not exceed 5 in the rural areas. In the urban areas the dispersion is high: the values are between 5 and 10 in most cities, while they exceed 10 in larger cities and 15 only in the southernmost ones (Novi Sad and Zrenjanin). In the period 2021–2050, there will be minimal changes compared to 1981–2010, and the difference between the scenarios is also minimal. For RCP4.5, rural values are still below 5 with the exception of 3 cities, while urban values are between 10 and 15. The deviation of the TNs of RCP8.5 from RCP4.5 during this period is only 1–2 nights. Remarkable changes appear in 2071–2100 especially in case of RCP8.5 and the difference between the scenarios is enormous. While the rural TNs of RCP4.5 are below 5 in most cases and do not exceed 15, RCP8.5 values are basically between 15 and 25 (except extreme cases). The urban TNs of RCP4.5 are usually between 15 and 25, however, for RCP8.5 there are very few cities where this number does not exceed 30. Typical TN values are between 40 and 50, but in four cases the number exceeds even 50 (e.g. Budapest).

The differences among the cities are mostly determined by the location, size, topography and built-up (LCZ) types. The highest values appear for larger and/or southern cities such as Budapest, Novi Sad and Zrenjanin. For smaller cities and/or cities with higher altitudes and latitudes (e.g. Salgótarján), the TN values are generally lower.

The results – particularly the rural values in *Table 3* – can be compared to Pieczka, I. *et al.* (2018), which is the only example of tropical night extrapolation in the Carpathian Basin. According to Pieczka, I. *et al.* (2018), in case of period 2021–2040 and 2081–2100 the values are 10 and 15–30 days higher, respectively. There are some possible explanations of these differences. Firstly, the time periods are different, and in case of 2081–2100 it could cause major differences since in theory the first 10 years should be less warm than the last 20 within the period of 2071–2100. Secondly, in our study the outputs of 12 different regional models were applied meanwhile and Pieczka, I. *et al.* (2018) presented the results only of a single model. As the temperature extrapolation of the models are also different, it could also explain partly of the above mentioned differences. Finally, the values presented in *Table 3* are the spatial mean of LCZ D areas within the domains, therefore several local and micro-scale climate effects (nearby water surfaces or forest areas, small scale terrain forms) occur, which are not implemented in regional scale models. Consequently, the comparison of these values is not entirely correct.

The built-up environment causes remarkable differences in the number of TNs between the rural and urban area. *Table 3* clearly shows that the maximum difference in each city depends on the size and location of the city and the time period and scenario. These results clearly support the motivation for local-scale climate modelling, as regional-scale

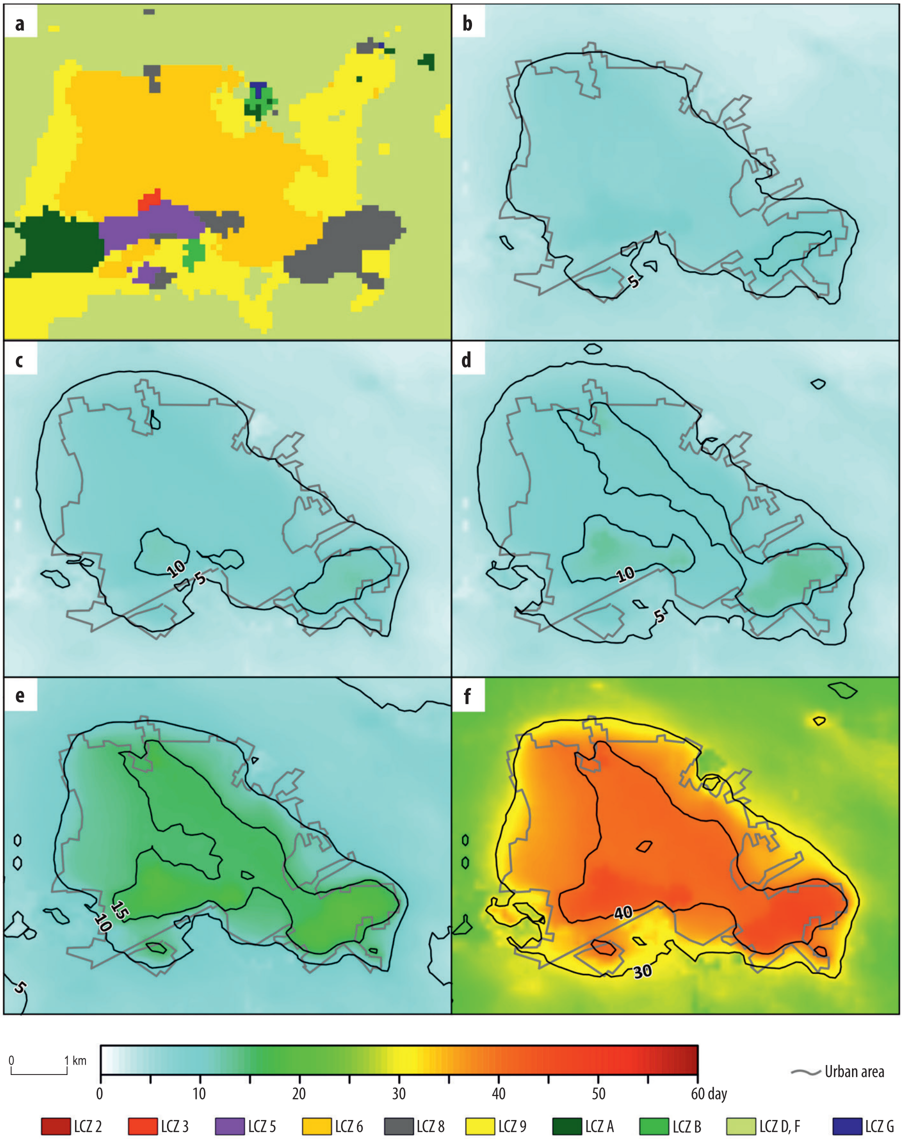

Fig. 6. LCZ map (a) and patterns of the tropical nights in Hódmezővásárhely (Hungary) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind directions are S and NW.

modelling can only determine rural conditions, whereas at the local scale, urban and intra-urban conditions can also be explored. The knowledge gained in this way is very valuable, as this type of projection of the increasing heat load in cities varying from district to district during the century, allows the authorities and partly the individuals to take appropriate preventive measures to mitigate the expected negative effects.

*Table 3. General information on the urban-rural difference in the mean number of tropical nights during the 21st century by cities**

City category	Period / Scenario	1981–2010		2021–2050 RCP4.5		2021–2050 RCP8.5		2071–2100 RCP4.5		2071–2100 RCP8.5	
		R	U	R	U	R	U	R	U	R	U
1	*Budapest*	3	13	8	20	8	22	12	29	31	54
2	Timisoara (RO)	3	13	2	12	2	13	4	20	20	50
	Novi Sad (SRB)	5	18	6	17	7	19	11	26	32	53
	Oradea (RO)	2	6	2	6	2	7	4	11	18	34
	Debrecen	2	12	1	13	2	15	3	21	15	46
3	*Arad* (RO)	1	5	2	6	2	7	3	11	18	35
	Szeged	1	11	2	15	2	16	3	22	15	47
	Miskolc	1	3	1	6	1	7	3	14	14	35
	Pécs	2	6	5	13	5	14	9	21	28	48
	Nyíregyháza	1	9	1	10	1	12	2	17	11	40
	Kecskemét	1	10	1	14	2	15	3	22	16	47
	Subotica (SRB)	1	10	1	10	1	11	2	16	12	38
4	Székesfehérvár	2	7	3	10	4	11	6	17	24	41
	Zrenjanin (SRB)	1	17	2	16	3	18	5	26	23	56
	Szolnok	2	9	2	14	2	15	3	21	17	46
	Tatabánya	0	0	2	3	2	4	4	7	17	24
	Kaposvár	1	2	2	4	2	5	4	8	19	29
	Békéscsaba	2	10	1	11	1	12	2	18	13	43
	Veszprém	0	1	2	4	2	5	4	8	17	28
	Eger	0	0	1	3	1	3	2	5	10	19
5	*Hódmezővásárhely*	3	8	3	11	3	12	5	18	22	44
	Baja	2	6	3	11	3	12	5	18	24	46
	Salgótarján	0	0	1	2	1	3	2	4	11	17
	Szekszárd	2	6	3	10	3	10	6	16	20	36
	Siófok	3	9	6	13	6	14	11	22	36	54
	Makó	2	5	2	7	2	8	4	13	19	37

*Values are spatial means of different LCZs: R = LCZ D, U = the warmest LCZ in the given city. City categories and cities written in italics are explained in *Table 2*.

Conclusions

In this study the future changes in the number of TNs were examined through three time periods in several cities in the Carpathian Basin. The results reveal that both the size and latitude of cities affect the values that are higher in southern and larger cities. Inside the cities the built-up types, the location and prevailing wind directions are determinative factors. In general, the change in the number of TNs and the difference between the scenarios are not remarkable in 2021–2050, the substantial change will occur in 2071–2100, especially for RCP8.5.

Our results show the extent to which different built-up types modify (actually amplify) differently the effects of climate change. In this way, they provide detailed information on future processes not only for the regions (rural areas), but also for the cities, which are already, but will continue to be, the primary sites of human activity. Therefore, these results can serve as a guide for urban planners and local authorities to create neighbourhoods that are more liveable and better adapted to future changes.

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