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PROJECTED CHANGES IN HEAT LOAD IN CARPATHIAN BASIN CITIES DURING THE 21ST CENTURY

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Summary: In this study the changes in the nighttime heat load in Carpathian Basin cities during the 21st century were examined. To quantify the heat load, the tropical night climate index was used. The MUKLIMO_3 local scale climate model was used to describe the urban processes and the land use classes were defined by the local climate zones. The expected change was examined over three periods: the 1981–2010 was taken as reference period using the Carpatclim database and the 2021–2050 and 2071–2100 future periods using EURO-CORDEX regional model simulation data for two scenarios (RCP4.5 and RCP8.5). To combine the detailed spatial resolution and the long time series, a downscaling method was applied. Our results show that spectacular changes could be in the number of tropical nights during the 21st century and the increasing effect of the urban landform is obvious. In the near future, a slight increase can be expected in the number of tropical nights, which magnitude varies from city to city and there is no major difference between the scenarios. However, at the end of the century the results of the two scenarios differ: the values can be 15-25 nights in case of RCP4.5 and 30-50 nights in case of RCP8.5. The results show that dwellers could be exposed to high heat load in the future, as the combined effect of climate change and urban climate, thus developing various mitigation and adaptation strategies is crucial.

Key words: climate change, urban climate, climate modelling, local climate zones, RCP scenarios, tropical nights

1. INTRODUCTION

Climate change has become the most prominent issue in our days. We are experiencing the effects of this process in our everyday life, for example the increase in the frequency of extreme weather events (e.g. summer heat waves). The global average temperature in the first two decades of the 21st century (2001–2020) was 0.99 °C higher than in the period 1850–1900, and this difference could be between 3.3 °C and 5.7 °C by the end of the century under the most pessimistic scenario (IPCC 2021). However, the temperature change is needed to examine not only at global and regional, but also at local scale since most of the world's population lives in cities and this proportion is likely to increase in the future (UN 2015).

In the cities, a specific local climate is formed as the consequence of the built-up, artificial environment and the human activity (Unger and Gál 2017). The most important aspect of this specific climate is the increased heat load compared to rural areas, the so-called heat island phenomenon, which reaches its maximum intensity during the night (Oke et al. 2017). This local-scale temperature modification is added to the thermal effects of global and regional climate change, which could lead to a remarkable increase in the heat load of cities in the future and will obviously have a negative health impact on their population (Baccini 2008, Bartholy and Pongrácz 2018). Consequently, there is a strong need for studies to assess the potential magnitude and spatial extent of heat load in cities. Following the findings of these studies, various mitigation strategies can be developed. In recent years, urban planners and local authorities have become increasingly interested in the prospects of climate change. Of course, they would focus on the changes expected in cities, but there is little research available on this topic. Thus, in response to these needs, more research is needed to examine the projected changes at the local level for urban planners and local authorities to develop mitigation strategies.

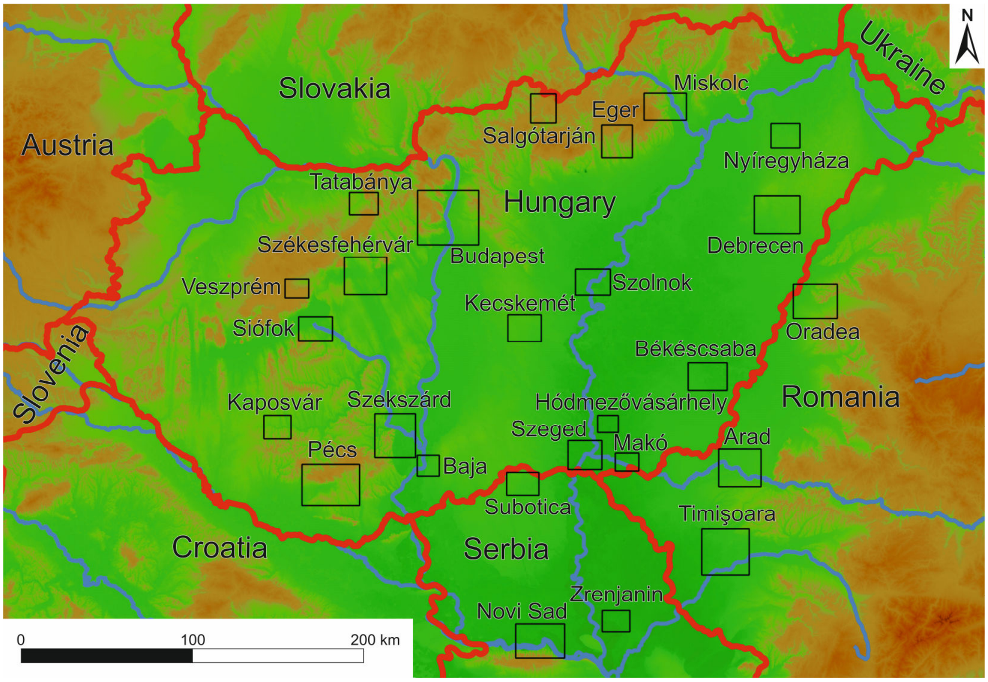

Fig. 1 Location of the studied cities in the Carpathian Basin (the model domains are marked by black frames) (Gál et al. 2021a)

The latest climate projections are based on the Representative Concentration Pathways (van Vuuren et al. 2011) and the most commonly used are the RCP4.5 and RCP8.5. These scenarios estimate a global average temperature change of 2 °C and 4 °C by the end of the 21st century compared to the 1986–2005 period (IPCC 2013). Reviewing the results of regional climate projections for the Carpathian Basin (e.g. Jacob et al. 2014, Pieczka et al. 2018) can be the first step towards the mitigation and adaptation strategies. Based on these research results, the projected temperature change in this region by the end of the century can reach 1.5-2 °C (RCP4.5) and 3-4 °C (RCP8.5). The use of the so-called climate indices can give a clearer picture of the change than the simple temperature values. One such index is the *tropical night*, when the daily minimum temperature exceeds 20 °C. According to Pieczka et al. (2018) the projected numbers of tropical nights in the Carpathian Basin are the following: 10-15 (RCP4.5) and 10-20 (RCP8.5) in 2021–2040, as well as 20-30 (RCP4.5) and 40-60 (RCP8.5) in 2081–2100. However, these results are derived from regional climate model simulations, so they do not include the urban effect. Thus, detailed future information on the thermal conditions of the cities in the Carpathian Basin may be interesting and important.

Consequently, the objectives of this study are to present the expected changes in the number of tropical nights (TNs) in Carpathian Basin cities during the 21st century and summarize some recommendations for local authorities and urban planners about the possibilities of the mitigation and adaptation to the expected climate change in urban areas.

2. MATERIAL AND METHODS

2.1. Study areas

Our study concentrated on 26 cities with different size and geographical backgrounds in the Carpathian Basin (Fig. 1). Most cities are located in low-lying area and have moderate topography. They were selected to cover all major cities in the Carpathian Basin. Among the cities, 20 are located in Hungary, 3 in Romania (Arad, Oradea and Timisoara) and 3 in Serbia (Novi Sad, Subotica and Zrenjanin). However, some western Hungarian cities could not be investigated due to lack of data (see Section 2.4). The list of the studied cities in alphabetic order as well as their population and the altitude of the city center from the EU-DEM database (Bashfield and Keim 2011) are presented in Table 1.

Table 1 The studies cities and their population and altitude

City	Population (thousands)*	Altitude of the city center (m)
Arad	169	115
Baja	36	98
Békéscsaba	59	88
Budapest	1675	120
Debrecen	201	117
Eger	52	156
Hódmezővásárhely	44	81
Kaposvár	63	154
Kecskemét	110	115
Makó	23	83
Miskolc	158	122
Novi Sad	215	81
Nyíregyháza	120	110
Oradea	207	130
Pécs	147	135
Salgótarján	35	242
Siófok	25	107
Subotica	100	109
Szeged	162	85
Székesfehérvár	96	119
Szekszárd	32	94
Szolnok	70	85
Tatabánya	68	144
Timisoara	315	87
Veszprém	55	268
Zrenjanin	80	80

*Hungarian cities: https://nyilvantarto.hu
Romanian and Serbian cities: https://worldpopulationreview.com/

2.2. Land use classification

The land use of the study area is described using the Local Climate Zones (LCZs) system, a widely used classification approach in urban climatology research, which allows the objective separation of different types of urban and rural surfaces (Stewart and Oke, 2012). The zones are separated based on physical characteristics, which describe the thermal responses of the surface. The classification method distinguishes 17 types (zones) (Fig. 2); 10 are characterized by their built-up (LCZ 1-10) and 7 by their land cover (LCZ A-G) features. They are named on the basis of one or more distinctive surface parameters, such as the height and density of the buildings in the case of the built-up zones and the nature of the ground cover in the case of the land cover zones. The area of each zone can extend from a few 100 meters to a few kilometers.

Several methods are known to identify and map LCZs in a given area (Lelovics et al. 2014, Lehnert et al. 2015). In our study, we used the method of Bechtel et al. (2015) to map the zones, which has the advantage of being applicable even with little available surface data. The method is widely used because of its simplicity, requiring only free satellite images (Landsat) and software (Google Earth and SAGA-GIS). The study areas for classification are selected in Google-Earth software and then the classification is performed using SAGA-GIS based on the study areas and satellite images. Then a majority filter is applied to obtain the corresponding area size for each local climate zone. In order to classify the LCZs as accurately as possible, satellite images from different time periods are used. This approach allows the LCZ map to be unaffected by agricultural processes and vegetation cycles. The results of the classification are verified by field surveys to avoid misclassification.

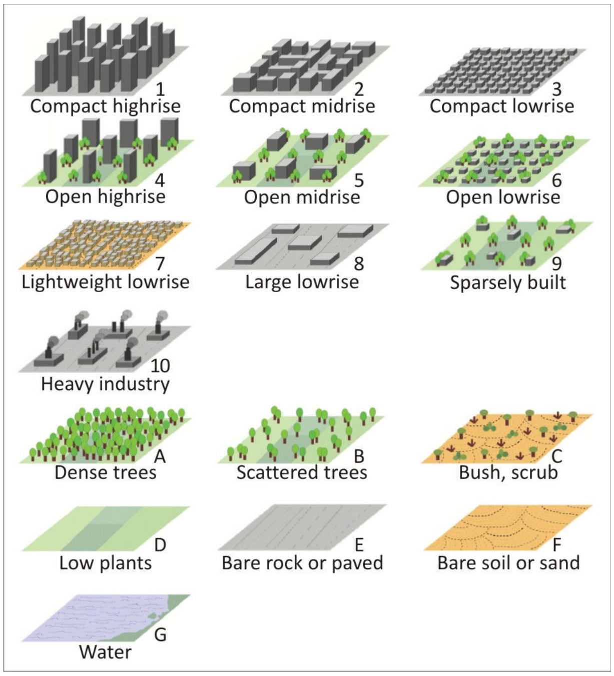

Fig. 2 The concept of local climate zones and the apellation of zones based on Stewart and Oke (2012)

2.3. Heat load modelling

Urban conditions were described using the local scale climate model MUKLIMO_3 (Sievers 2012, 2016). The model is non-hydrostatic and simulates air temperature, humidity and wind conditions on a 3-dimensional grid by solving the Reynolds-averaged Navier–Stokes equations. As initial meteorology conditions, temperature and humidity profiles from a reference station are required. Furthermore, high-resolution orography and land use distribution data are needed as input data. In case of the orography data, the EU-DEM database was used. The model allows specifying any land use category if the required surface, vegetation and built-up parameters are known. This property makes it possible to apply the local climate zone concept to determine the land use of the cities. The horizontal resolution is 100 m, while the vertical resolution varies with altitude and it is denser near the surface, where the dominant processes occur.

In our study, the heat load was quantified using the tropical night climate index, thus it can be used to illustrate the effect of the heat load at night. This is particularly important in case of urban heat surplus, since the difference in air temperature between urban and rural areas is most pronounced during the nocturnal hours.

This index was calculated for three 30-year periods: the 1981–2010 reference period, the 2021–2050 and the 2071–2100. The computational capacity requirements of combining such longer periods with detailed spatial resolution are very high. To overcome this, the so-called cuboid method was used, which is a statistical-dynamical downscaling method (Früh et al. 2011, Žuvela-Aloise et al. 2014). It can be considered as a trilinear interpolation technique of air temperature, relative humidity and wind fields of MUKLIMO_3 simulations. The method assumes that heat load situations occur in specific weather situations, which can be provided by 8 different simulations. These simulations have to be performed for two prevailing wind directions, which were determined for each city.

Table 2 Details of the applied EURO-CORDEX climate model simulations

	Institute	**Global climate model**	**Regional climate model**
1.	CLMcom	CNRM-CM5	CCLM4
2.		EC-EARTH	
3.		HadGEM2	
4.		MPI-ESM-LR	
5.	DMI	EC-EARTH	HIRHAM5
6.	KNMI	EC-EARTH	RACMO22E
7.		HadGEM2	
8.	SMHI	CNRM-CM5	RCA4
9.		EC-EARTH	
10.		IPSL-CM5A-MR	
11.		HadGEM2	
12.		MPI-ESM-LR	

2.4. Datasets

The cuboid method requires daily temperature, relative humidity, wind speed and wind direction data from a reference station for the examined period. The input data for the 1981–2010 reference period was taken from the Carpatclim database (Szalai et al. 2013). The database contains daily meteorological data for the Carpathian region with a resolution of 0.1° between 44°N and 50°N latitude and 17°E and 27°E longitude for the period 1961–2010.

However, it does not cover the whole territory of Hungary, so no analyses have been performed for the cities in the west.

Climate data for the 21st century was provided by EURO-CORDEX model simulations with a resolution of 0.11° (Jacob et al. 2014). The simulations were selected based on whether they contained the data required for the cuboid method. Based on this, we used the outputs of 12 simulations applying the RCP4.5 and RCP8.5 scenarios (van Vuuren et al. 2011) (Table 2). The cuboid method was run for each simulation, and the final results were the averages of their outputs over each period by scenarios.

3. RESULTS: CHANGE IN THE NUMBER OF TROPICAL NIGHTS

3.1. Arad

In the reference period, the number of TNs exceeds 5 only in the densely built-up parts of Arad (Fig. 3b). These areas are the LCZ 3 in the city center and the LCZs 5 and 8 type built-ups in the northwest part. For LCZ 8, the number of these nights can even exceed 10. The higher number of TNs in the northwest is due to the effect of the prevailing S and SE wind directions, which shift the warm air of the inner area to this part of the city (Gál et al. 2021a).

In the near future, no major changes are expected and the difference between the scenarios are minimal (Figs. 3c and d). The extent of the areas where the number of TNs exceed 5 or 10 is likely to increase.

This process in case of scenario RCP8.5 (Fig. 3d) affects more areas is spectacular mainly around the green area in the southeastern part of the city (Gál et al. 2021a).

In 2071–2100, the number of TNs may continue to increase based on scenario RCP4.5, but the change compared to the previous period is not large, approximately 5 nights (Fig. 3e). It can be observed that values above 5 may also appear west of the city, which can be attributed to the prevailing wind directions and the nearby dense tree land cover. In a remarkable part of the city the number of TNs could exceed 10, in the city center 15, while in some smaller parts of LCZ 8 built-up areas even 20.

Based on RCP8.5 the change could be more than twice as large (Fig. 3f). The number of TNs could be above 30 in almost the entire city and above 40 in the densely built-up areas (Gál et al. 2021a).

3.2. Baja

In the 1981–2010 reference period the number of TNs is below 5 in most parts of Baja (Fig. 4b). Values above this occur in the central area of the city, extending westwards and eastwards, and in the eastern and southeastern areas of the city. The higher values in the center are due to the compact zones, and further west to the LCZs 5 and 8. The TNs above 5 in the eastern parts of the city are also due to the LCZ 8 type built-up in this area.

In period 2021–2050, based on the more optimistic scenario RCP4.5 the number of TNs can be over 5 in the entire city except the western part (Fig. 4c). Values above 10 may occur in the compact built-up city center, west of it in LCZs 5 and 8, as well as in the previously mentioned LCZ 8 built-up areas in the eastern and southeastern parts of the city.

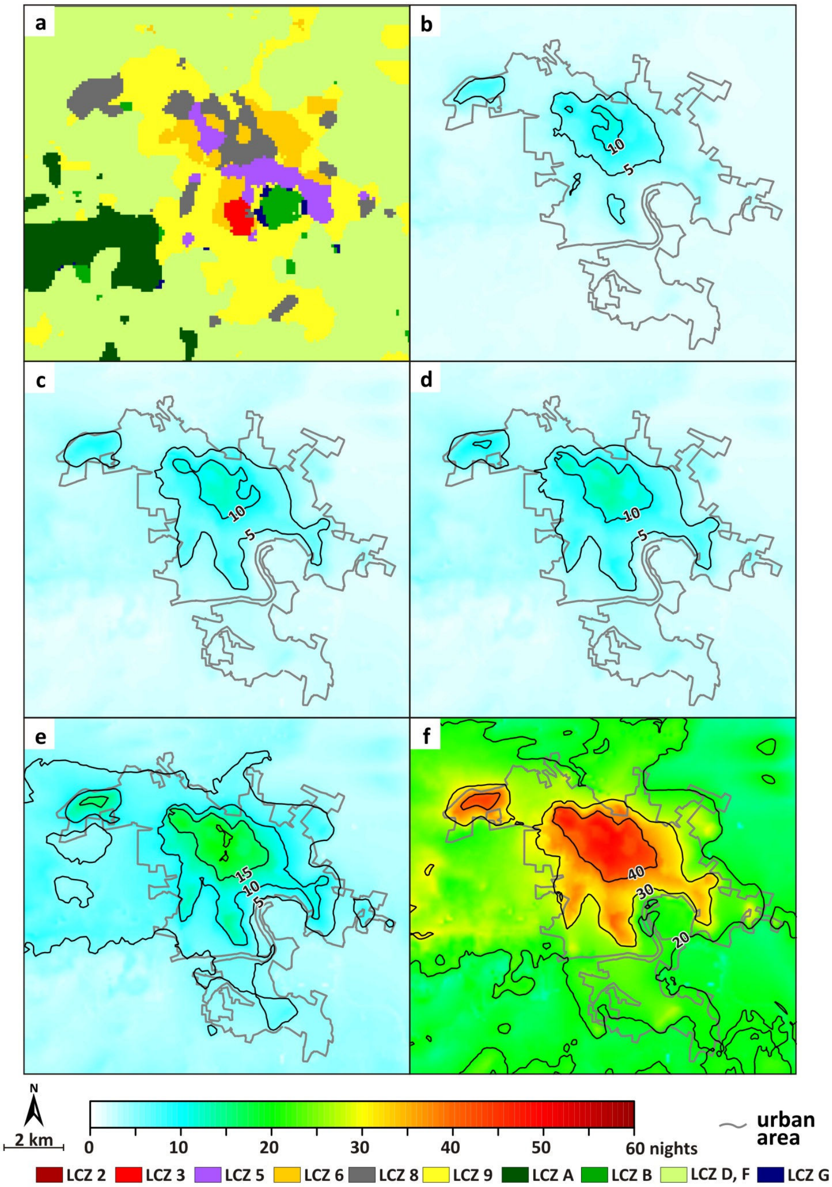

Fig. 3 LCZ map of Arad (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and SE (Gál et al. 2021a).

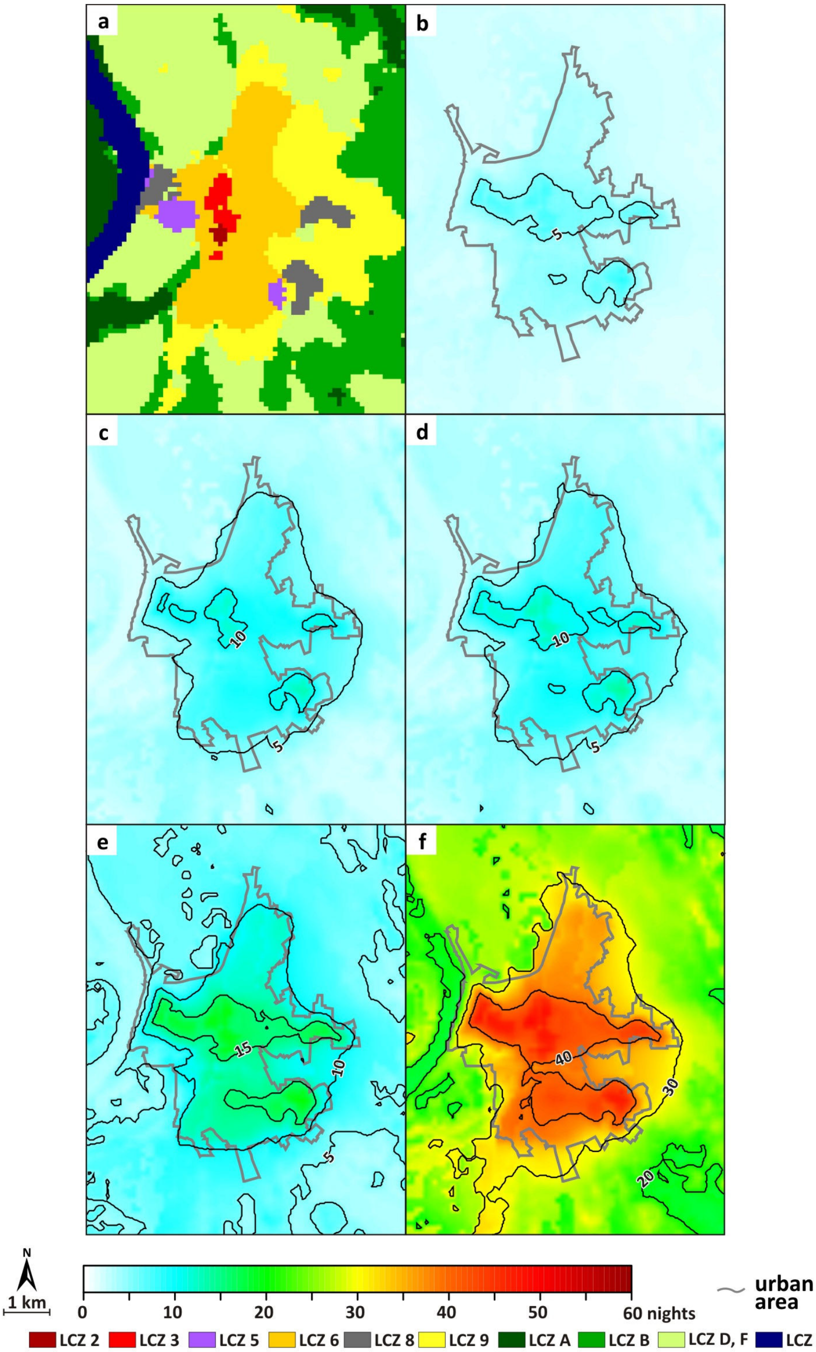

Fig. 4 LCZ map of Baja (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and SE.

Based on the more pessimistic RCP8.5 scenario the number of TNs could be similar to RCP4.5 (Fig. 4d). There are only minor differences between the two scenarios. Under RCP8.5, the area where the values are over 5 is extended in the western part of the city. However, the spectacular difference is in the spatial extent of values above 10, since all the areas already mentioned in case of RCP4.5, could be larger, and in two additional areas (south and east of the city center) values could be above 10.

Clearly a larger change could happen at the end of the century. Already under the more optimistic RCP4.5, the annual number of TNs could be above 10 in almost the entire city (Fig. 4e). In addition, values above 15 may occur in two larger areas: in the city center, covering almost the entire width of the city, and in the southeast in a larger contiguous area.

The changes under RCP8.5 could be much greater since based on this scenario the number of TNs could exceed 30 in almost the entire city by the end of the century (Fig. 4f). At the same time, values above 40 could also occur in most parts of the city, including the entire central and south-southeastern parts, which could form a large contiguous area.

3.3. Békéscsaba

In the reference period 1981–2010, the annual number of TNs in most parts of Békéscsaba, except the less built-up south-southeastern areas of the city, is above 5 (Fig. 5b). In addition, the number of TNs is above 10 in several areas of the city: in the compact city center, in the extensive LCZ 8 in the north, and in the LCZs 5 and 8 further south.

In period 2021–2050 the more optimistic RCP4.5 scenario assumes no major change compared to the reference period (Fig. 5c). Values above 5 are still expected in most parts of the city, the only change could be the increasing of the extent of areas where the values are above 10. In addition to these areas, the number of TNs could exceed 10 in the western part of the city, in LCZ 8.

Based on the RCP8.5 scenario, the area where the TNs are above 5 may increase in the southern and eastern parts of Békéscsaba in the near future (Fig. 5d). In addition, values above 10 may occur in a contiguous area in the northern and central parts of the city. Furthermore, the number of TNs could exceed 15 in a small compact built-up area.

By the end of the century, even the RCP4.5 scenario could show significant changes (Fig. 5e). By this time, the number of TNs could be above 5 in almost the entire city, and in a significant part of it above 10. In addition, in the northern and central parts of the city, values above 15 may occur in a larger contiguous area, and in the west in the LCZ 8 type built-up. In addition, TNs could be above 20 in smaller areas in the more densely built-up parts of the city center.

The RCP8.5 scenario foresees drastic changes by the end of the century (Fig. 5f). By then, the number of TNs could be above 20 in almost the whole area of Békéscsaba and above 30 in a large part of the city. Within this, in the northern and central areas, as well as in the western part, the values can even exceed 40.

3.4. Budapest

The number of TNs in Budapest is relatively high in the 1981–2010 period due to its dense built-up; the maximum value is more than 20 in the city center (Fig. 6b). Values above 10 are typical in a large part of the built-up area and above 15 in the inner areas. Higher values are found in the northeastern part of the city, where the LCZ 3 type built-up is typical, and in the southern and southeastern parts of the city, due to the prevailing wind direction and the LCZ 8 type built-up (Gál et al. 2021a).

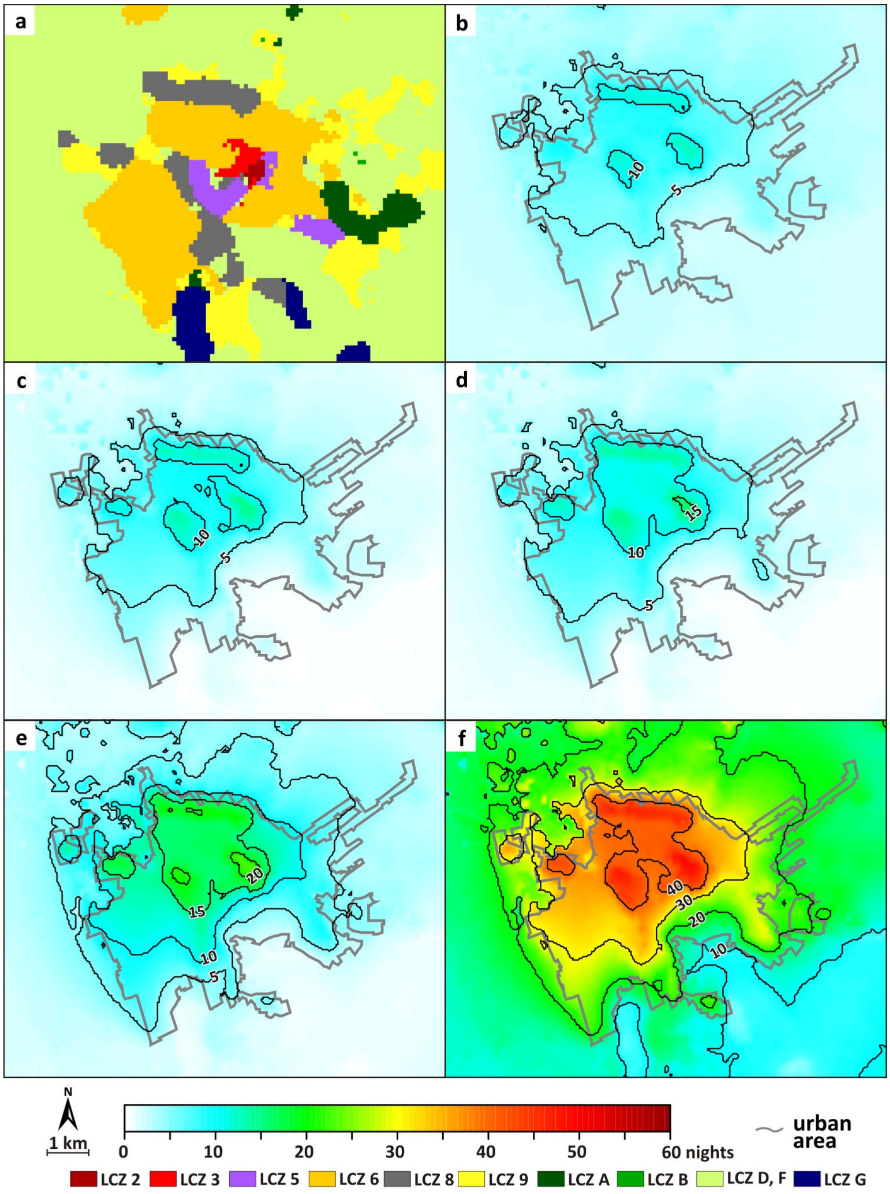

Fig. 5 LCZ map of Békéscsaba (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and SW.

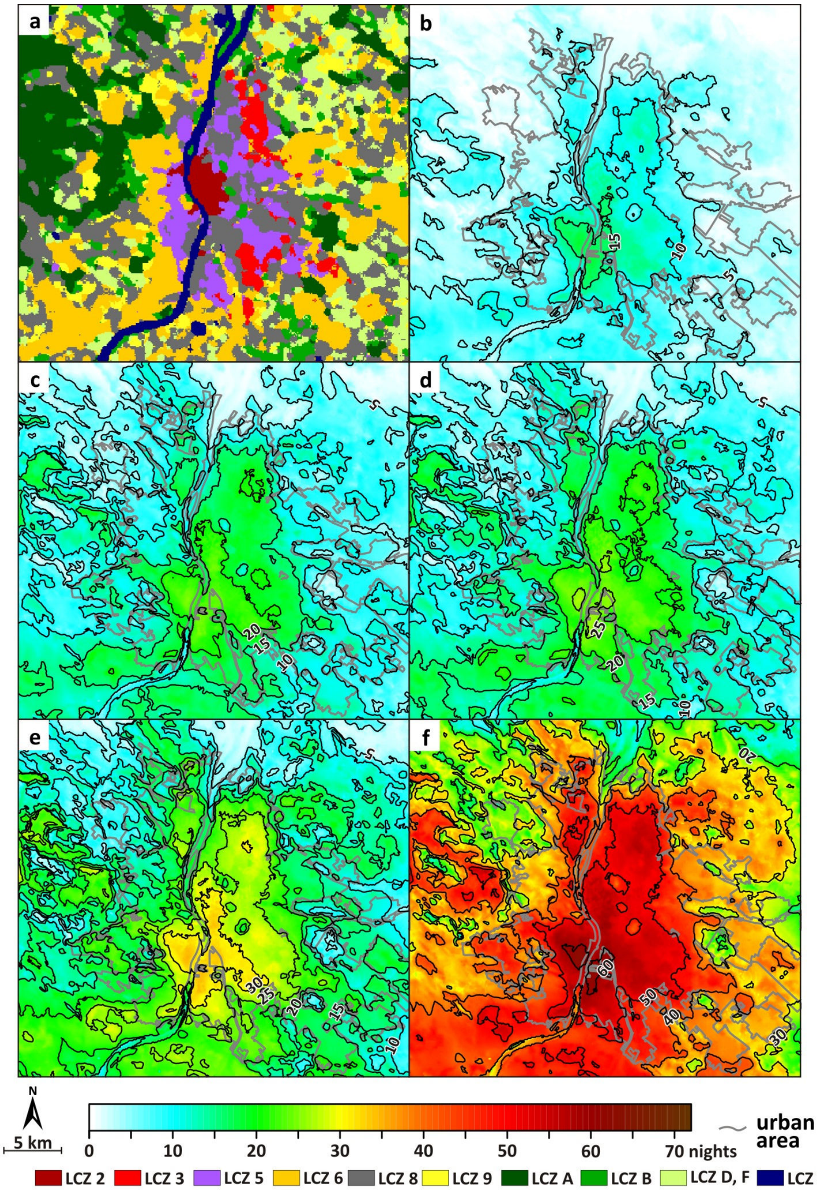

Fig. 6 LCZ map of Budapest (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and E (Gál et al. 2021a).

There are strong changes in the period 2021–2050 compared to the reference period, but there are no remarkable differences between the scenarios (Figs. 6c and d). In most parts of the city the number of TNs could exceed 15. The difference between the scenarios are in the size of the areas where values above 20 and 25 appear.

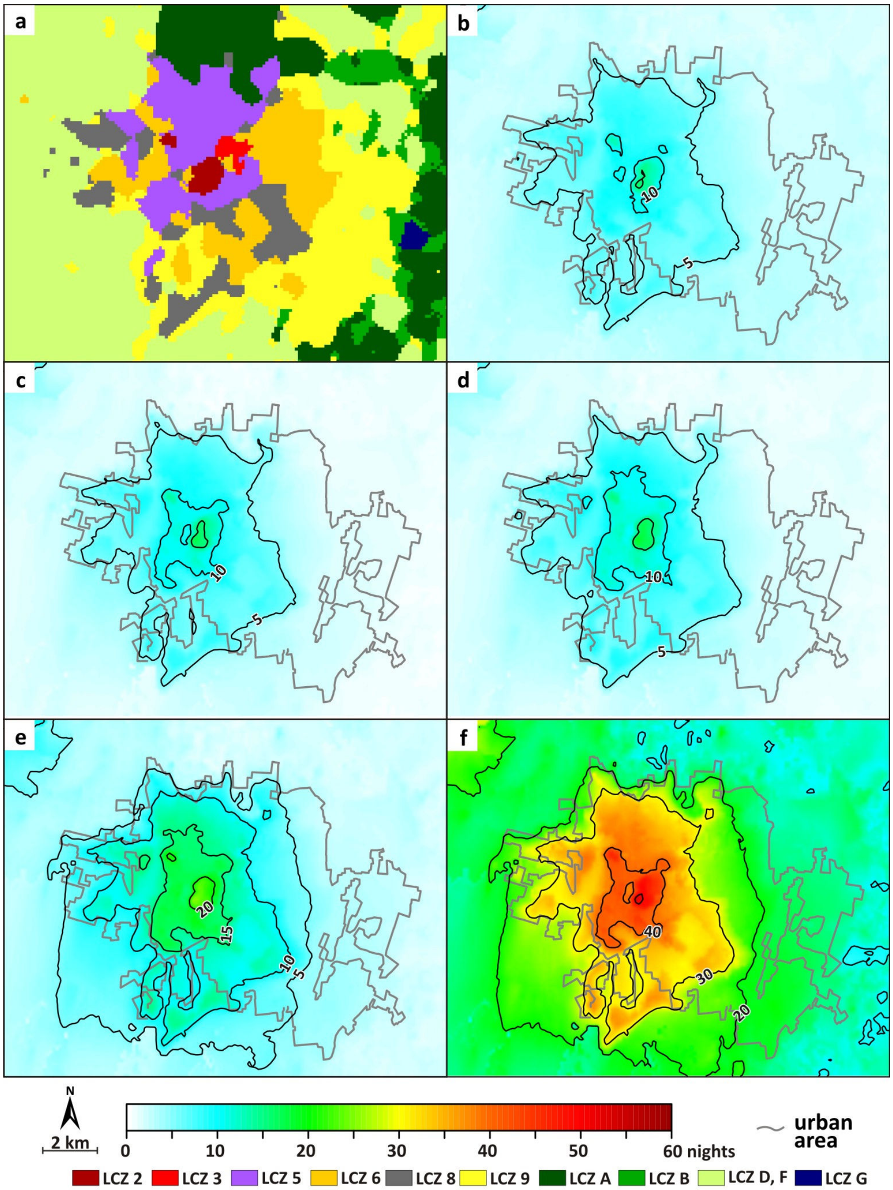

Fig. 7 LCZ map of Debrecen (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and NE. (Gál et al. 2021a).

In case of the RCP8.5 scenario, there are more areas with TNs exceeding 20 in the north and south of the city and above 25 in the city center (Fig. 6d) (Gál et al. 2021a).

At the end of the century major changes are expected compared to the previous period, and there is a large difference between the scenarios (Figs. 6e and f). In the RCP4.5 scenario, TNs could be above 20 in almost the whole city and above 25 in the interior. In the city center, the typical value could be above 30, but in a small area it could exceed even 40 (Fig. 6e).

For RCP8.5, the number of TNs may be above 40 in almost the entire city, with values above 50 in a larger contiguous area, while in the city center the number of tropical nights may exceed even 60 (Fig. 6f) (Gál et al. 2021a).

3.5. Debrecen

In the 1981–2010 period the number of TNs is above 5 in the densely built-up western part of Debrecen and in the LCZ 8 type built-up areas (Fig. 7b). In the city center values above 10 are typical mainly in compact built-up areas, but values above 15 also occur in a small area. The spatial distribution of TNs also shows the influence of the second prevailing wind direction (northeast) (Gál et al. 2021a).

In the period 2021–2050 minimal changes are expected and the scenarios show similar results, the difference between them is minor (Figs. 7c and d). Values above 10 and 15 could appear in a larger area, especially in case of the RCP8.5 scenario (Fig. 7d). The changes could occur mainly in the LCZ 5 and compact zones (Gál et al. 2021a).

Notable changes are expected for the period 2071–2100 and there are large differences between the scenarios (Figs. 7e and f). In case of RCP4.5 scenario, the number of TNs in most parts of the city could be above 10 (Fig. 7e). In the central areas of Debrecen it could exceed 15, and 20 in the LCZ 2 type built-up.

Under the RCP8.5 scenario, the values are more than twice as large (Fig. 7f). In the largest part of the city, the number of TNs could exceed 30, while over 40 in the city center and 50 in a smaller area (Gál et al. 2021a).

3.6. Eger

In the period 1981–2010 the number of TNs in the whole area of Eger is low, it is between 0 and 1 (Fig. 8b).

In the near future, both scenarios expect a slight increase in TNs, but neither scenario expects the values to reach 5 (Fig. 8c and d). More TNs are expected in the southern areas of the city than in the northern areas.

At the end of century, based on scenario RCP4.5, the number of TNs may exceed 5 south of the city center in the LCZs 3, 5 and 8 type built-ups (Fig. 8e).

According to scenario RCP8.5 major changes could occur, since the number of TNs could be above 10 in the central and above 20 in the south part of the city (Fig. 8f).

3.7. Hódmezővásárhely

In Hódmezővásárhely the number of TNs in the period 1981–2010 exceeds 5 in almost the entire city (Fig. 9b). The values are above 10 in the southeastern part of the city, in LCZ 8 and in the city center, in LCZ 5 (Gál et al. 2021a).

For 2021–2050, there may be some minor changes: TNs above 5 and 10 appear in more areas (Figs. 9c and d). The main difference between the scenarios is the extent of areas with TNs above 10.

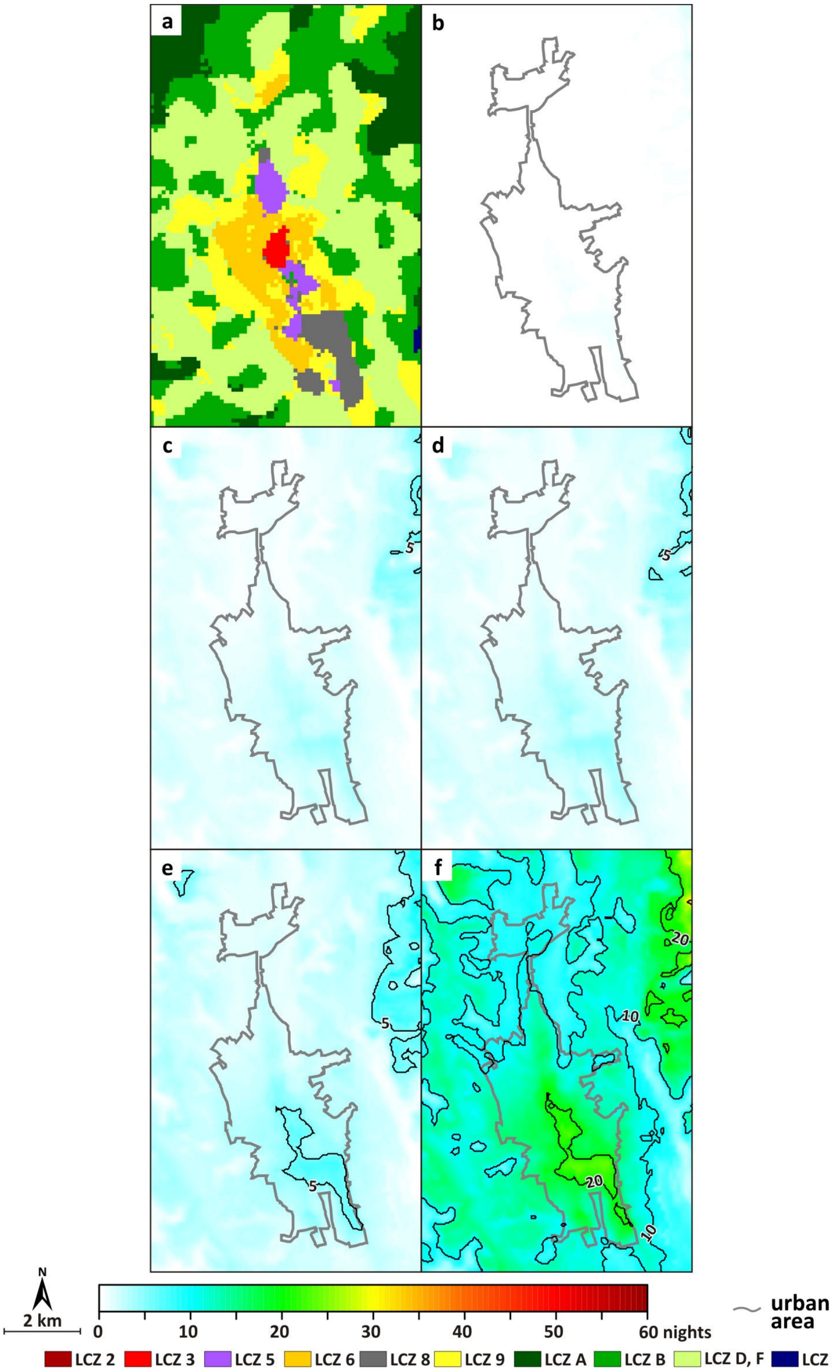

Fig. 8 LCZ map of Eger (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are SE and S.

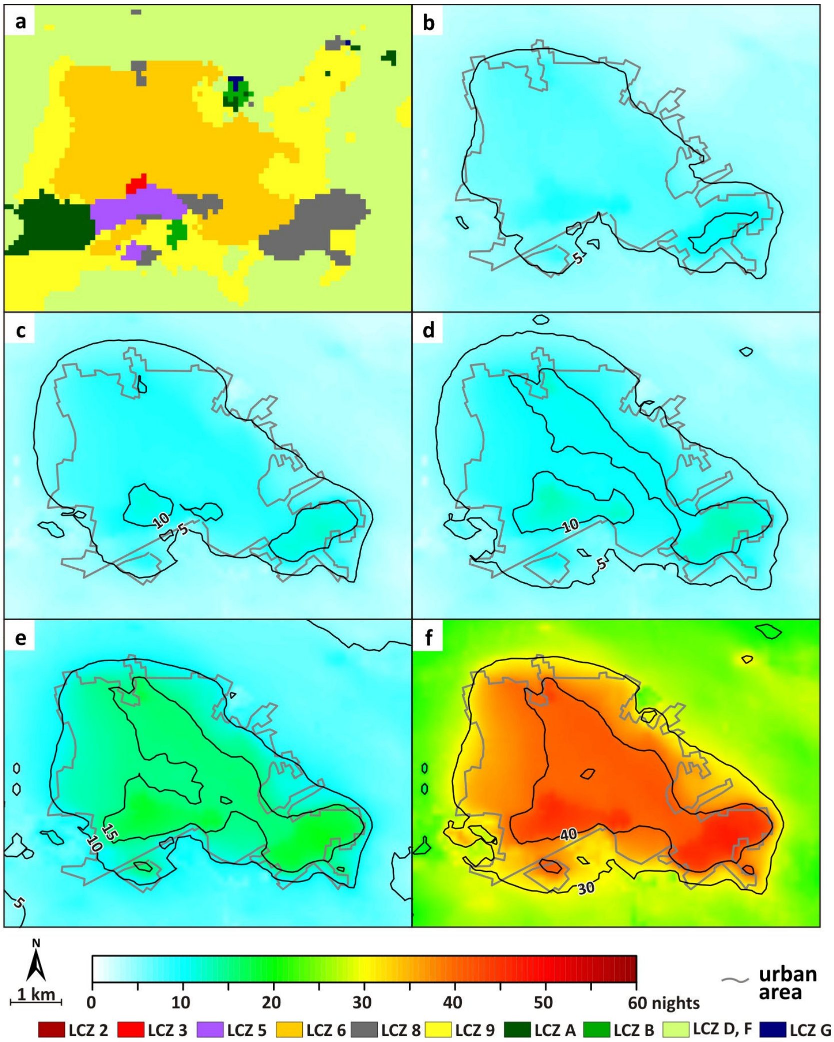

Fig. 9 LCZ map of Hódmezővásárhely (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and NW (Gál et al. 2021a)

In the RCP8.5 scenario, in addition to the LCZs 5 and 8 type built-up areas, values over 10 could be found also in the north-northeastern part of the city (Fig. 9d) (Gál et al. 2021a).

In the period 2071–2100, the RCP4.5 scenario projects the number of TNs to be above 10 in the whole city (Fig. 9e). In most parts of Hódmezővásárhely, such as in the densely built-up areas, and in the north-northeastern part of the city, this value may exceed 15.

In case of RCP8.5 scenario, the number of TNs could be above 30 in the whole city, but in most parts of the city, even higher values of above 40 are expected (Fig. 9f) (Gál et al. 2021a).

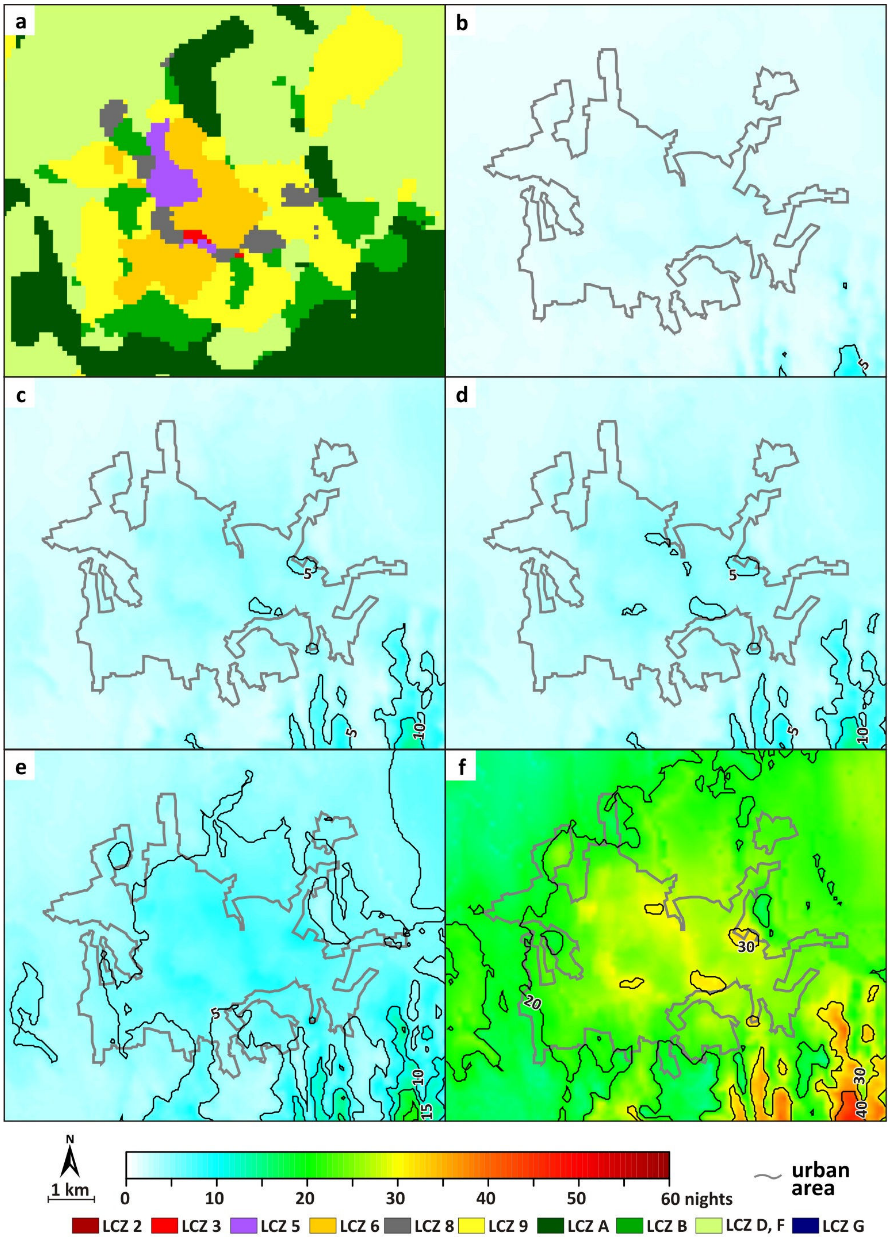

Fig. 10 LCZ map of Kaposvár (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and SW.

3.8. Kaposvár

In the reference period 1981–2010 the number of TNs in the whole area of Kaposvár is below 5 (Fig. 10b).

In the near future, both scenarios predict an increase in the number of TNs, but it is likely to remain below 5 in most parts of the city (Figs. 10c and d). Values above 5 can be only expected in the more densely built-up area and in LCZ 8.

There is a small difference between the scenarios, since in case of RCP8.5 the number of TNs exceeds 5 in more areas (Fig. 10d). Besides, higher values can be expected in the compact built-up city center and in the northern part.

At the end of the century, the number of TNs could be above 5 in almost the entire area of Kaposvár based on scenario RCP4.5 (Fig. 10e). Exceptions are only some outlying urban areas, mainly in the western and southern parts.

According to scenario RCP8.5, remarkable changes could occur, since the number of TNs can be above 20 in the entire city and above 30 in several smaller areas (Fig. 10f). Values over 30 typically appear in the densely built-up areas mentioned in the previous period.

3.9. Kecskemét

In the period 1981–2010 the number of TNs in the central and eastern parts of Kecskemét is over 5 (Fig. 11b). This due to the dominant LCZs 5 and 8 type built-up in these areas and the prevailing NW and W wind directions. In the compact zones (LCZs 2 and 3) of the city center the values exceed 10.

In the near future, the two scenarios give similar pictures (Figs. 11c and d), with an increase in areas where the number of TNs is over 5. This trend is particularly visible in the western part of the city in LCZs 5 and 8, but can also be observed in the eastern areas. In addition, values over 5 can also appear in the LCZ 8 type built-up area to the south. Furthermore, values above 10, which so far only appeared in the city center, can occur south and east in LCZ 8. In the compact zones, the number of TNs can exceed 15.

By the end of the century, major changes can take place. Based on the more optimistic RCP4.5 scenario, the number of TNs can remain below 5 in only a few smaller western areas (Fig. 11e). Furthermore, the value can be above 10 in all denser built-up areas, and above 15 in the case of those, which are close to the city center. In the downtown compact zones, the number of TNs can exceed 20, while in a smaller area it is over 25.

According to the RCP8.5 scenario, there could be huge changes in the number of TNs by the end of the century (Fig. 11f): the annual number could be above 20 in almost the whole area of Kecskemét, and the areas with values above 30 could also be remarkable. In most of the more densely built-up areas, i.e. in the central and eastern part of the city, the number of TNs could exceed 40, while in a small area of the city center it could be over 50.

3.10. Makó

In the 1981–2010 reference period, the number of TNs in Makó exceeds 5 only in the central area with LCZs 3 and 5, and remains below 5 in the rest of the city (Fig. 12b).

In period 2021–2050, both scenarios show an increase in the area with more than 5 TNs (Figs. 12c and d). This may occur mainly in the LCZ 6 in the western and central areas of the city and in the LCZ 8 in the northeastern part of the city.

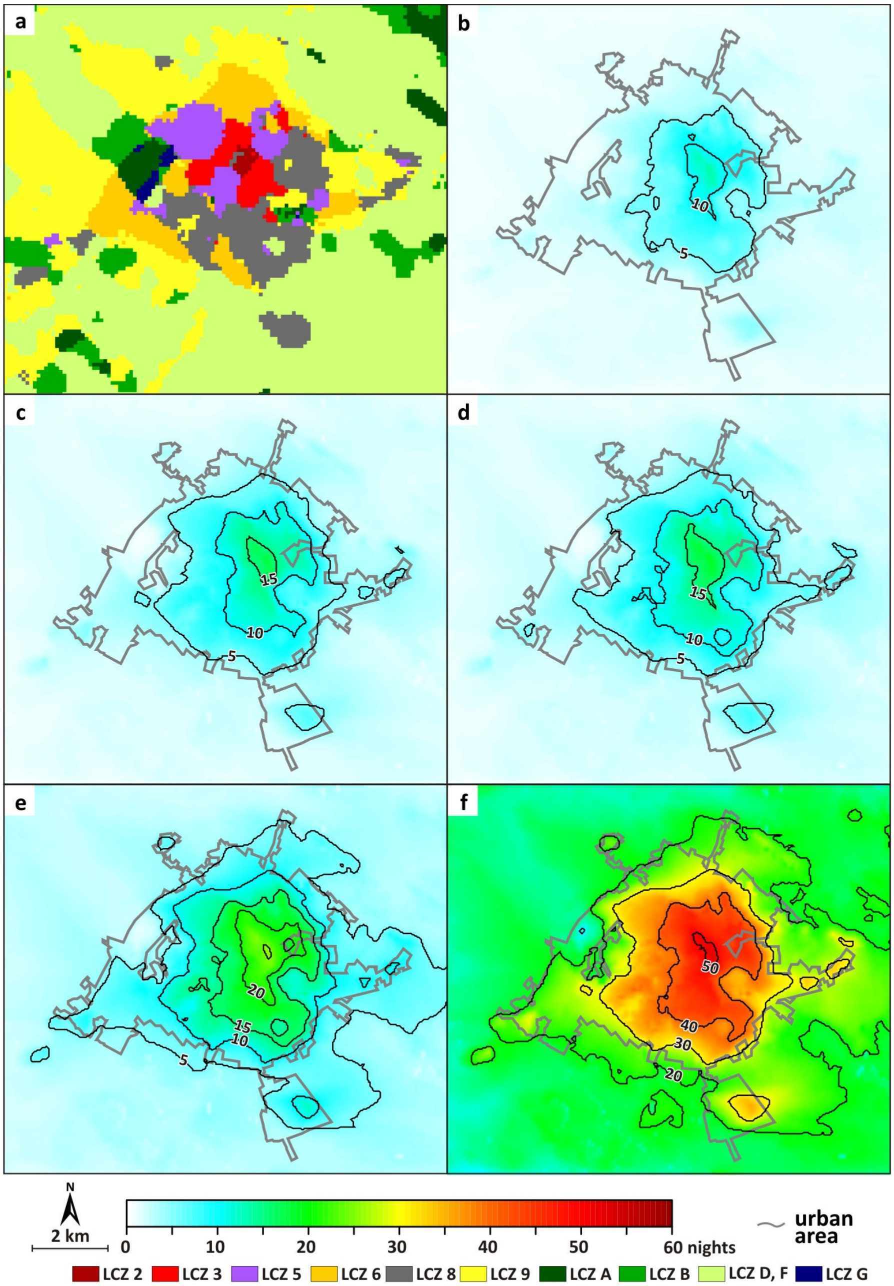

Fig. 11 LCZ map of Kecskemét (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and W.

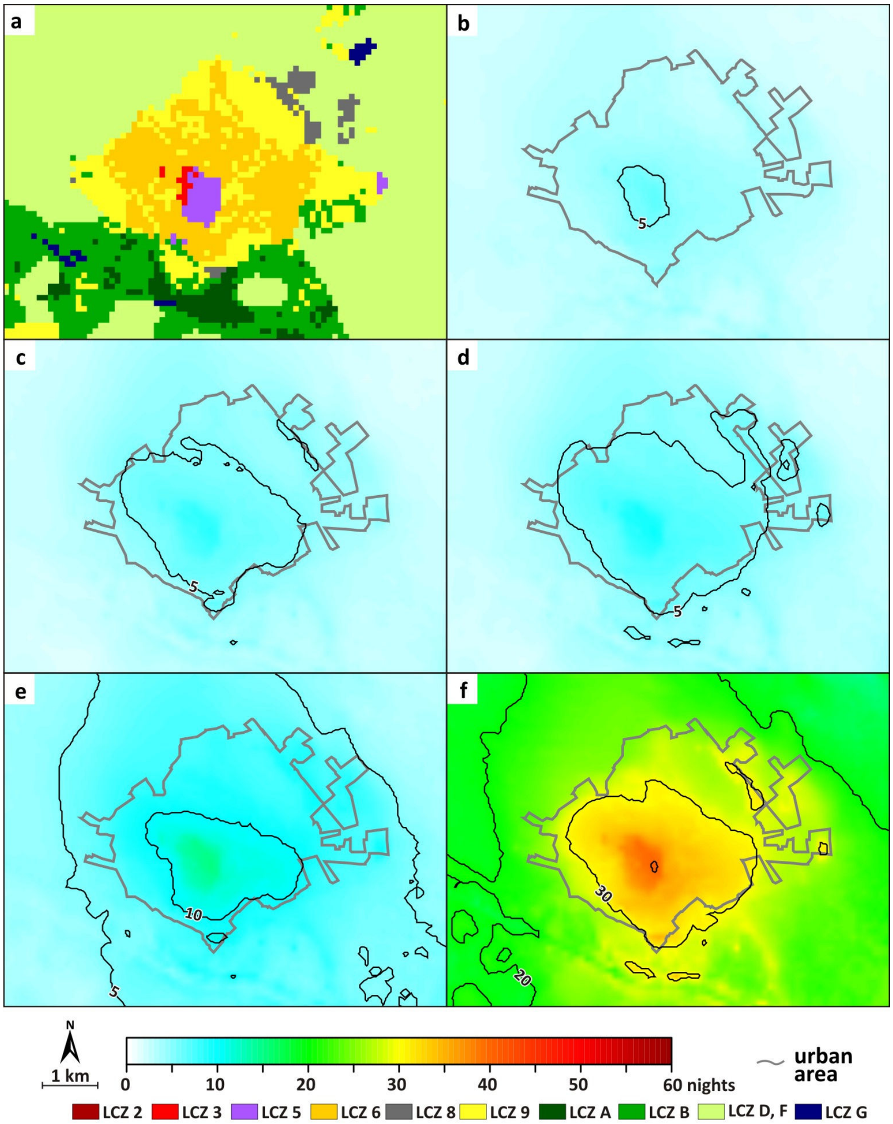

Fig. 12 LCZ map of Makó (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and NW.

Under the RCP8.5 scenario, this change could affect even more areas, especially in the eastern part of the city (Fig. 12.d).

For the period 2071–2100, the RCP4.5 scenario projects the number of TNs to be above 5 for the whole city (Fig. 12e). In addition, in a significant area, this value could be above 10, including LCZs 3 and 5 in the city center, as well as the southeastern urban parts.

Based on the more pessimistic RCP8.5 scenario, more marked changes may occur, with TNs exceeding 20 in the whole area of Makó (Fig. 12f). Furthermore, in most parts of the city, for the denser built-up areas, this number can be above 30, while in a small area of the city center it can exceed 40.

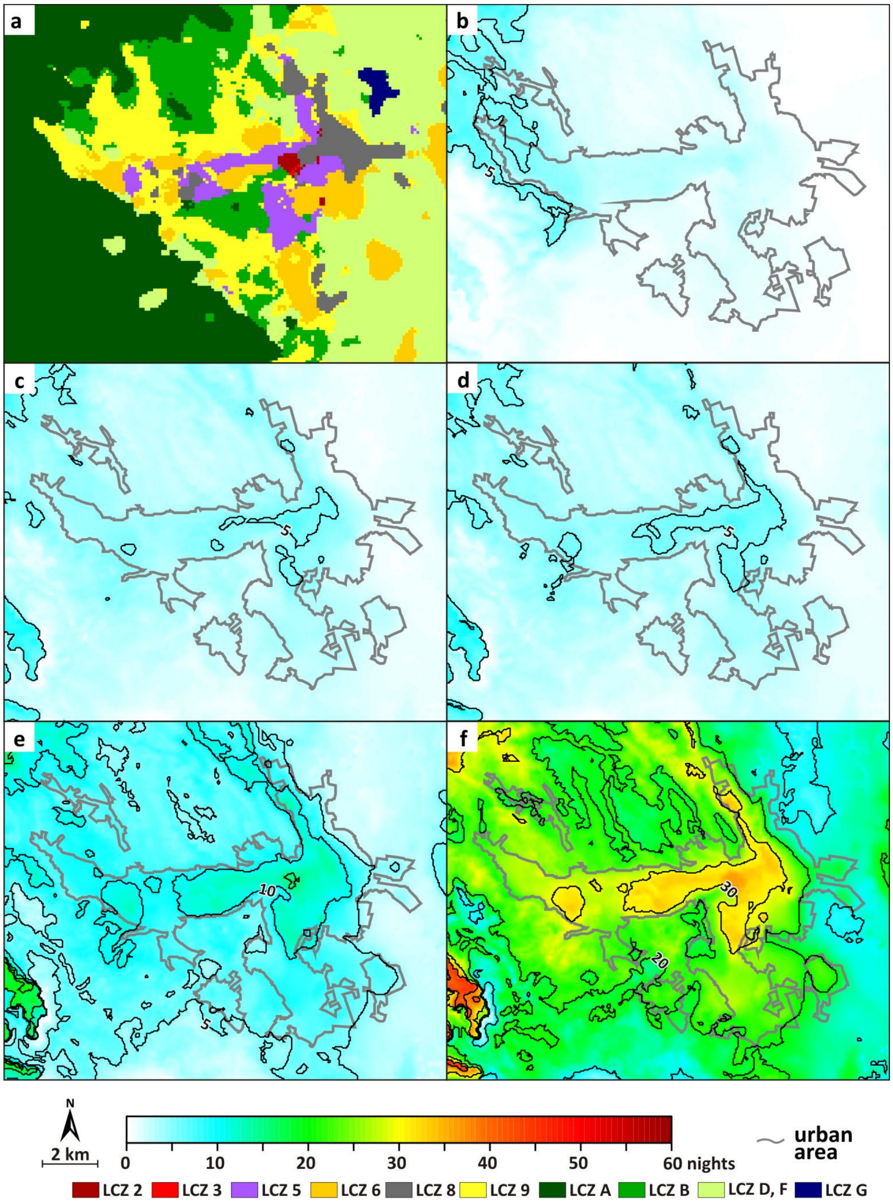

Fig. 13 LCZ map of Miskolc (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and SE.

3.11. Miskolc

In the 1981–2010 reference period, the annual number of TNs in Miskolc is below 5 in almost the entire city (Fig. 13b). Values above this occur only on the western edge of the city.

In the near future, the RCP4.5 scenario indicates that the number TNs in the city center could be above 5 in the compact (LCZs 2 and 3) and in LCZ 8, as well as in several smaller areas scattered in some more densely built-up parts of the city, typically in LCZ 5 (Fig. 13c).

In case of scenario RCP8.5, the downtown area, where the number of TNs more than 5 is larger, and also extends longer towards the outer areas of the city (Fig. 13d).

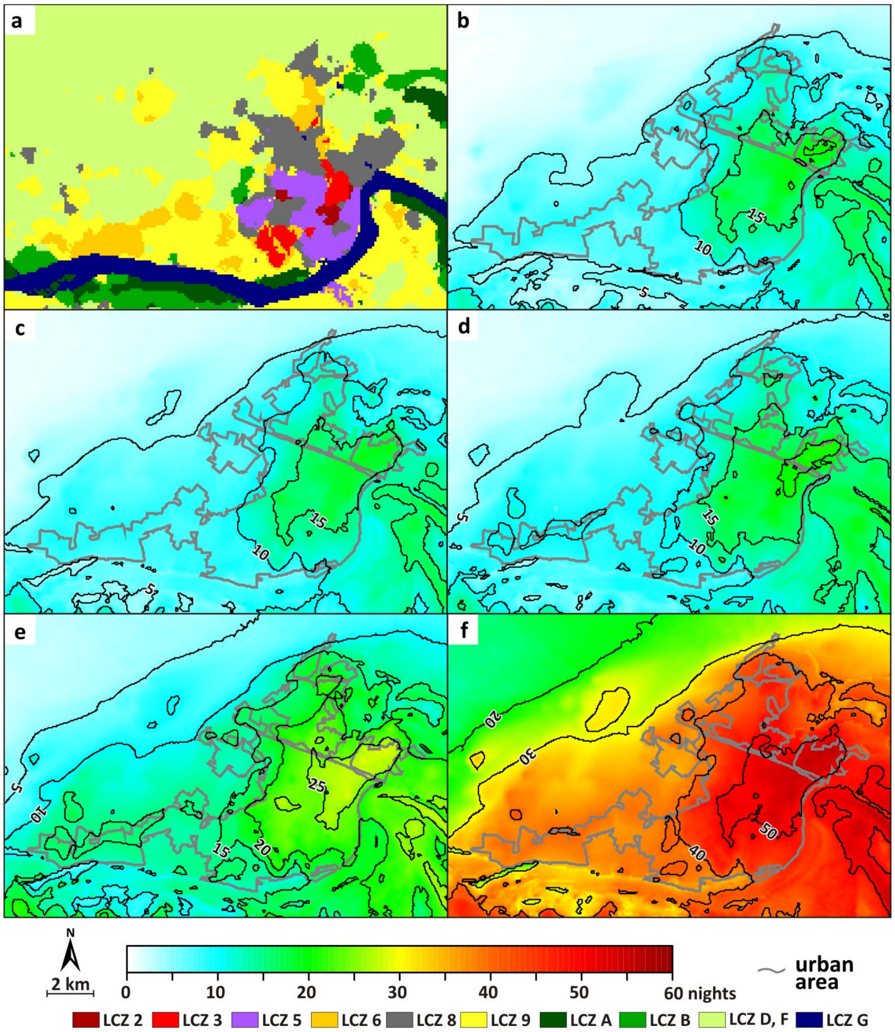

Fig. 14 LCZ map of Novi Sad (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are W and NW.

At the end of the century, the RCP4.5 scenario projects TNs to be above 5 in the whole of Miskolc, except in some eastern parts (Fig. 13e). However, in the largest, mainly densely built-up parts of the city (LCZs 5 and 8), this number could exceed 10. Furthermore, in LCZ 2 in the inner city, the number of TNs during this period can be as high as 15.

Based on the RCP8.5 scenario, the number of TNs may be over 20 in almost the entire area of Miskolc (Fig. 13f). Furthermore, in more densely built-up parts of the city, where the previous scenario gave values above only 10, in this scenario they can exceed 30, i.e. more than one month.

3.12. Novi Sad

Already in the 1981–2010 reference period, the number of TNs is higher in Novi Sad compared to the other studied cities (Fig. 14b). This value is above 5 in the whole city, but above 10, except the less built-up areas to the west. The number of TNs is over 15 in the central part of the city, which is mostly covered by LCZ 5, and in LCZ 8 in the north and northeast. In the northeastern part of Novi Sad, in a small area, it even exceeds 20.

In the near future, the RCP4.5 scenario shows minimal deviation in the number of TNs compared to the reference period (Fig. 14c).

Under the RCP8.5 scenario, change is already possible, but not significant (Fig. 14d). More and more areas may experience TNs above 10 or 15, and the change may affect the western and southern parts of Novi Sad the most. Values above 20 observed in the reference period may already appear in a larger area in the LCZs 5 and 8 in the northeast.

By the end of the century, the RCP4.5 scenario projects TNs to be above 10 in the entire city, and above 15 except a few small areas (Fig. 14e). In the densely built-up areas of the city, the values can be above 20, while they can be above 25 in the compact parts of the city center and to the northwest at LCZ 8.

Under the RCP8.5 scenario, significant changes can take place, as by this time the number of TNs may be over 30 in the entire city (Fig. 14f). However, in most parts of the city, including all densely built-up areas and some less densely built-up areas, values above 40 may be typical. Moreover, in the central areas of the city, and in a larger contiguous area northeast and south of it, the number of TNs may exceed 50.

3.13. Nyíregyháza

In the reference period 1981–2010, the number of TNs in the center and in the northwestern part of Nyíregyháza exceeds 5, mainly in the areas of LCZs 5 and 8 (Fig. 15b). Values above 5 can also be found to the east in two smaller areas, where these built-up types are also prevalent. In the city center, in the compact zones, values above 10 already appear during this period.

In the near future, both scenarios suggest only minor changes (Figs. 15c and d). Areas where the number of TNs exceeds 5 and 10, may increase further. This trend is more pronounced in the case of the more pessimistic RCP8.5, manifests itself in the spread of areas characterized by values above 10 in the city center (Fig. 15d).

By the end of the century the RCP4.5 scenario predicts that the number of TNs could be above 5 in most areas of Nyíregyháza (Fig. 15e). The only exceptions to this are the lesser built-up areas on the outskirts of the city. In most parts of the city center, typically in the LCZ 5 type built-up areas, the number may be over 10, while in the compact central part it may be above 15.

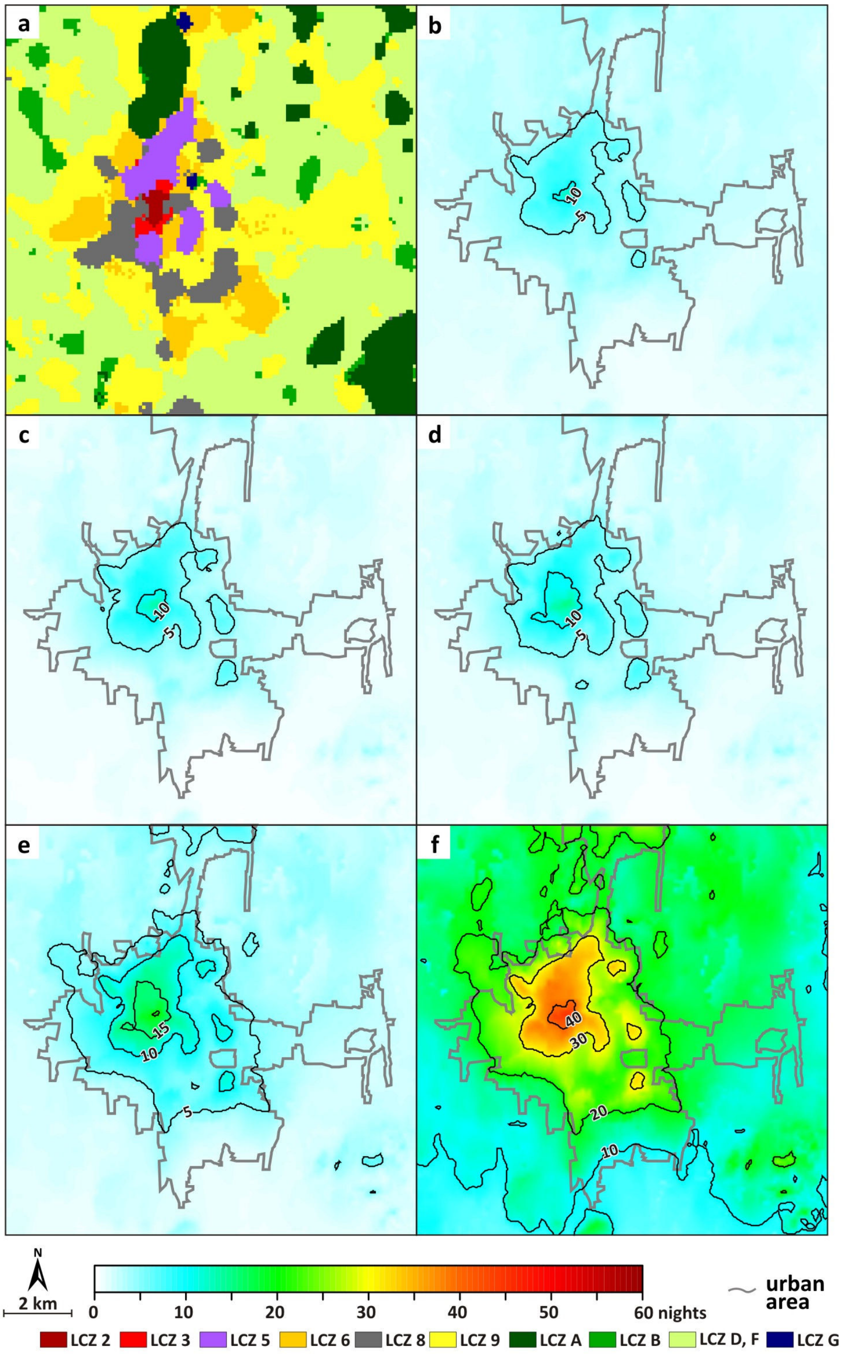

Fig. 15 LCZ map of Nyíregyháza (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are SW and S.

According to the RCP8.5 scenario, the number of TNs in most of Nyíregyháza may be over 20, but it may also exceed 10 in the whole city (Fig. 15f). It can be seen that in the areas where the more optimistic scenario only gave a value above 10, in this case the number of TNs could exceed 30. Even higher values (above 40) may occur in the area of compact zones.

3.14. Oradea

In the reference period 1981–2010, the number of TNs in the central and north-western areas of Oradea exceeds 5 (Fig. 16b). This can be attributed to the prevailing south and southwest wind direction as well as to the built-up types; the central LCZ 3 and northwest LCZs 5 and 8 type built-ups.

In the near future, only minor changes can occur and there is a high degree of agreement between the scenarios (Figs. 16c and d). The extent of areas characterized by TNs above 5 increases slightly to the south, especially in case of RCP8.5 scenario (Fig. 16d). In the north-western part of the city, in the LCZs 5 and 8, the number of TNs can exceed 10.

Values above 10 may appear in a slightly larger area according to the more pessimistic RCP8.5.

By the end of the century, the RCP4.5 scenario projects the number of TNs to be above 5 in almost the entire urban area, excluding some southern parts (Fig. 16e). Values above 10 may occur in the city center in LCZ 3 and in the northwestern part of the city, and values above 15 may also appear in the latter, typically in the areas with the LCZs 5 and 8 type built-ups.

Under the RCP8.5 scenario, large changes can occur, as in this case the number of TNs can exceed 20 in almost the entire urban area (Fig. 16f). There may be values above 30 in the center and in the northern part of the city, especially for LCZs 3 and 6. In the north-west, in LCZs 5 and 8 the number of TNs may already exceed 40.

3.15. Pécs

In the 1981–2010 reference period, the number of TNs in most parts of Pécs does not reach 5 (Fig. 17b). Values above this occur in the densely built-up areas of the city center (LCZs 2, 3, 5 and 8) as well as in a small area to the east.

In the case of Pécs, spectacular changes can already take place in the period 2021–2050 (Figs. 17c and d). During this period, the number of TNs in the entire city may be above 5. However, in much of the city, in a contiguous area, this value can be above 10. This area includes the more densely built-up parts of the western and central parts of the city, as well as the northeastern part of the city, where the higher values are due to the nearby dense forest land cover (LCZ A). The difference between the two scenarios is minimal during this period.

For the RCP8.5 scenario, values above 10 may appear over a larger area, and values above 15 can occur in compact areas of the city center (LCZs 2 and 3) (Fig. 17d).

In the period 2071–2100 the more optimistic RCP4.5 scenario suggests that the number of TNs in the whole area of Pécs may be over 10 (Fig. 17e). With the exception of the southern and outermost urban areas, this value can be above 15, and in the city center and a smaller eastern area, it can be already over 20.

According to the RCP8.5 scenario, the number of TNs in the whole area of Pécs may be over 30, but in most parts of the city, with the exception of the southern and outer areas, it may also exceed 40 (Fig. 17f).

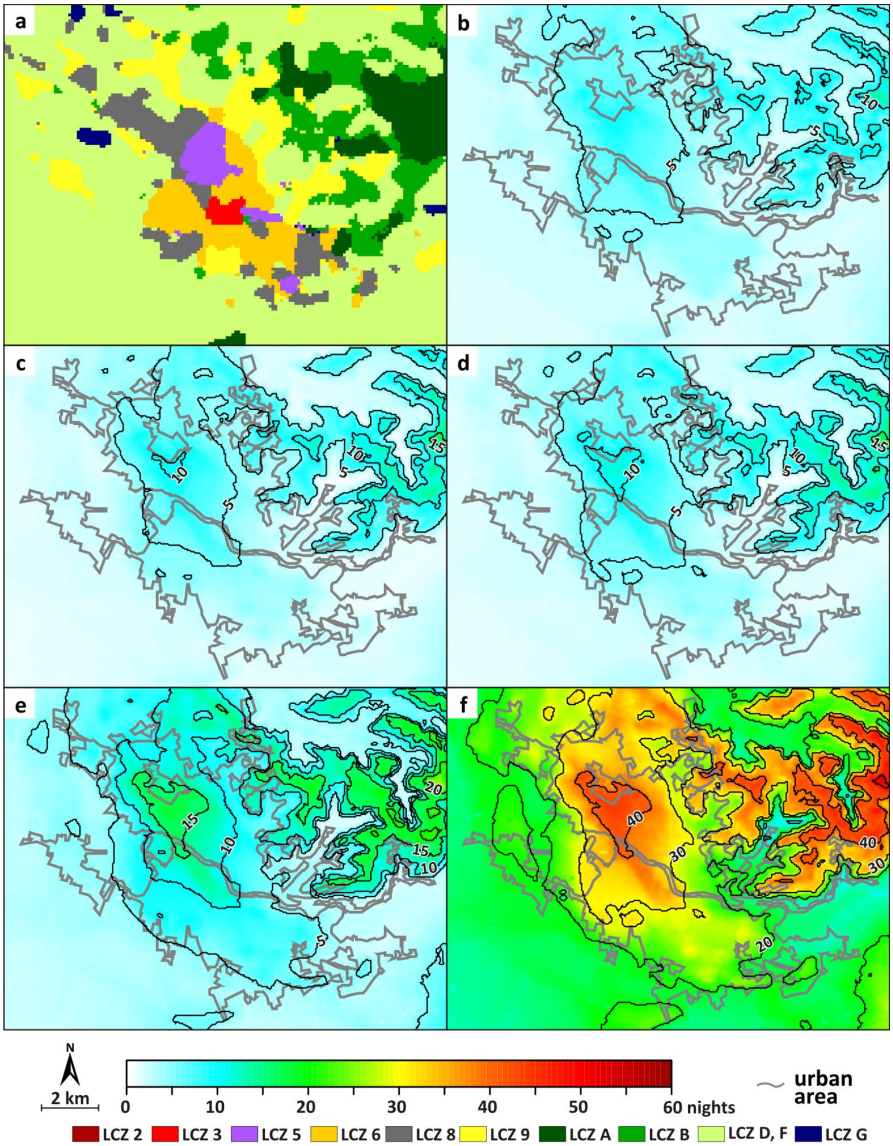

Fig. 16 LCZ map of Oradea (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and SW.

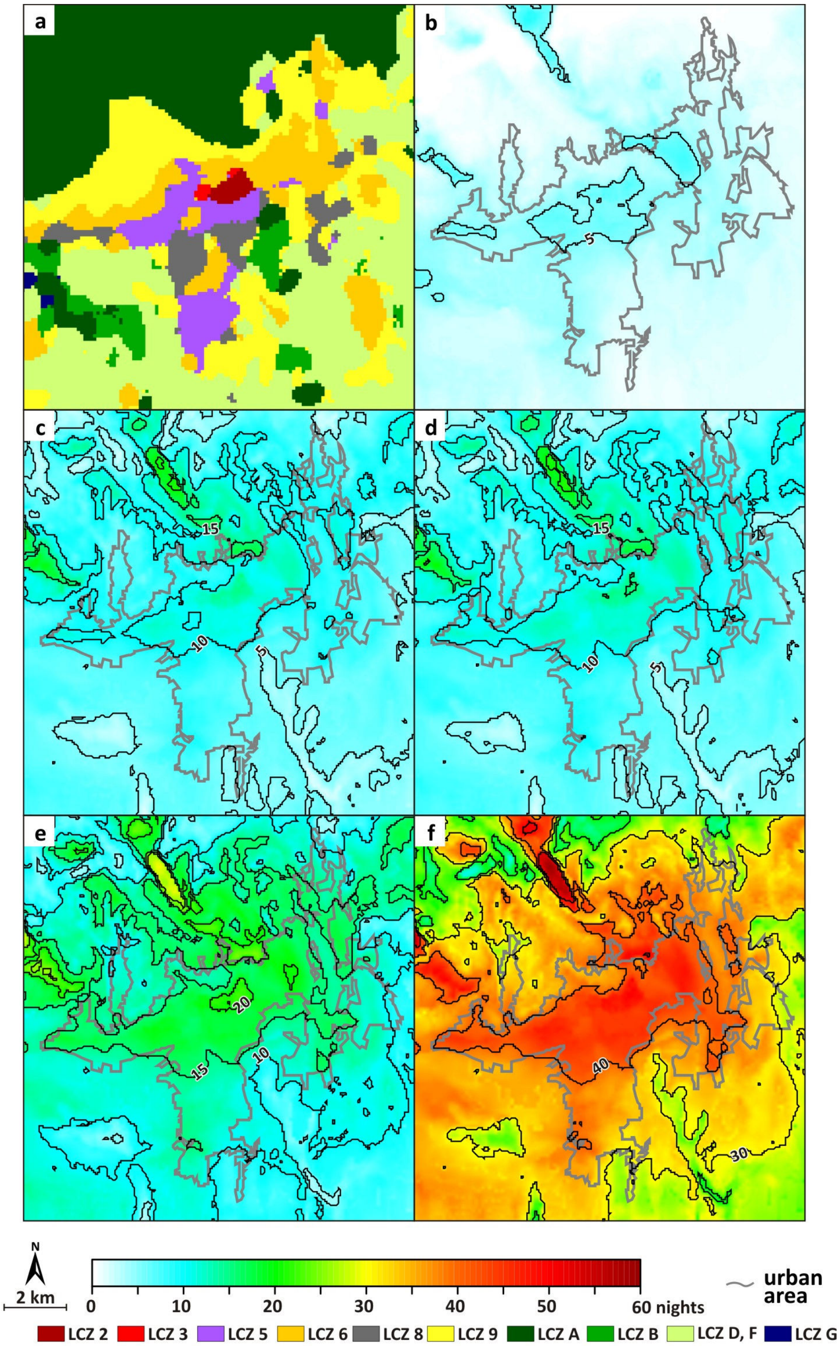

Fig. 17 LCZ map of Pécs (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and SE.

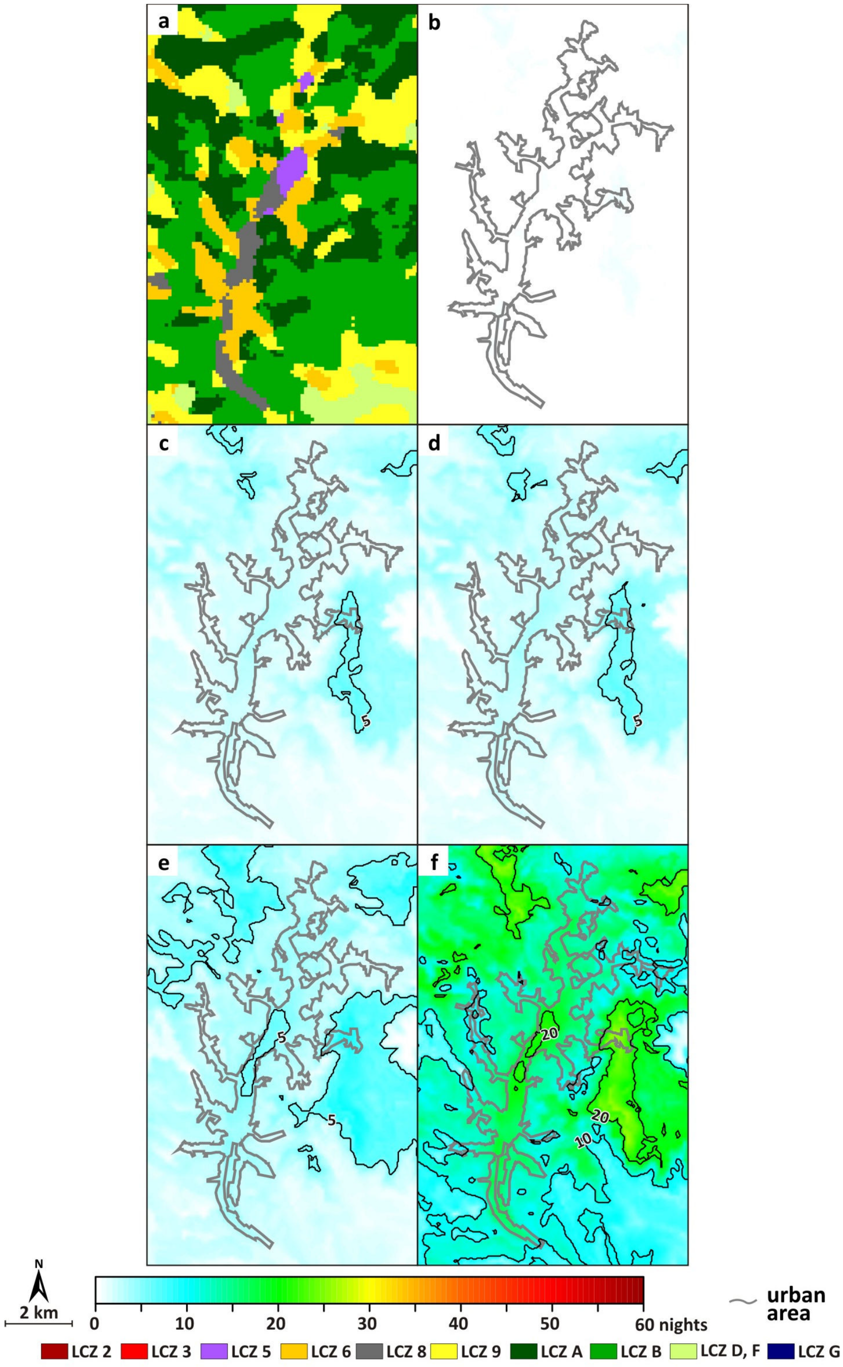

Fig. 18 LCZ map of Salgótarján (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are SW and S.

3.16. Salgótarján

In the 1981–2010 reference period, the number of TNs in the whole area of Salgótarján ranges between 0 and 3 (Fig. 18b).

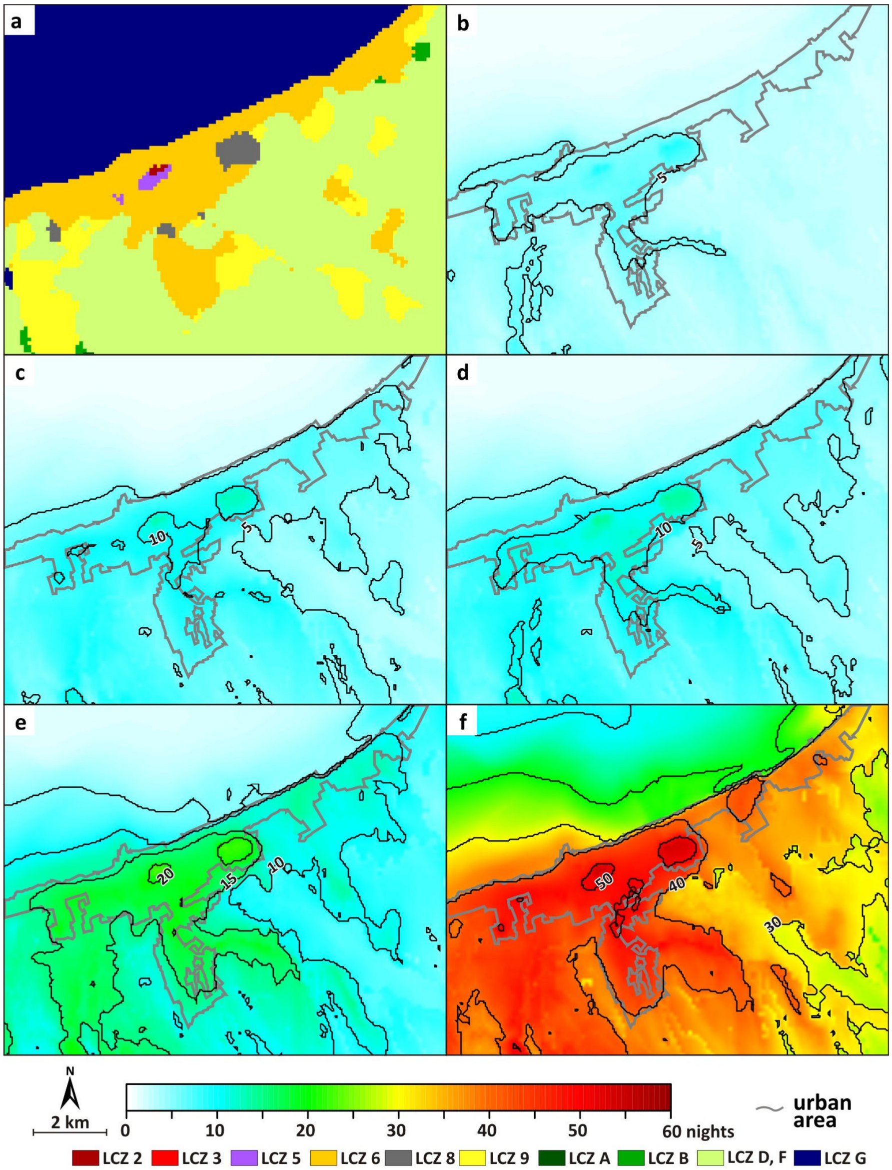

Fig. 19 LCZ map of Siófok (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and SW.

In the near future, the number of TNs may still remain below 5 under both scenarios. Values above 5 can only occur in a small area in the very eastern part of the city due to the nearby dense tree cover (Figs. 18c and d).

In the 2071–2100 period, the more optimistic RCP4.5 scenario suggests that the number of TNs in the central part of Salgótarján may exceed 5, in addition to the eastern area mentioned in the previous period (Fig. 18e).

According to the RCP8.5 scenario, the number of TNs in the entire city may already be over 10 (Fig. 18f). These values can be as high as 20 in the more densely built-up central part (LCZs 5 and 8) and in the far eastern area.

3.17. Siófok

In the reference period 1981–2010, the number of TNs exceeds 5 in almost the entire area of Siófok (Fig. 19b). Values below 5 occur only in the southern and outer parts of the town and on the shore of Lake Balaton.

In the period 2021–2050, the number of TNs could be above 5 in the whole area of Siófok (Figs. 19c and d). Under the RCP4.5 scenario, values above 10 may appear in LCZ 8 in the eastern urban part, in LCZs 2 and 5 in the center, and in LCZ 6 slightly further south (Fig. 19c).

For the RCP8.5 scenario, values above 10 may already appear in a larger area (Fig. 19d). In this case, it already concerns a contiguous area covering most of the city, extending to the west, east and south.

In the period 2071–2100, the more optimistic RCP4.5 scenario predicts TNs could be over 10 in the whole area of Siófok, while in most of them it may be over 15 (Fig. 19e). Values above 20 may occur in the LCZ 8 in the eastern part of the city and in the LCZs 2 and 5 in the city center.

According to the RCP8.5 scenario, there could be a huge increase in the number of TNs in Siófok (Fig. 19f). Based on this scenario, it is possible that the whole city area can experience values above 40. Furthermore, in the densely built-up areas (LCZs 2, 5 and 8) and in LCZ 6 south of the center, the number of TNs can exceed 50.

3.18. Subotica

In the reference period 1981–2010, the number of TNs exceeds 5 in the LCZs 3 and 5 type built-ups in central Subotica, and in LCZ 8 the east and southwest (Fig. 20b). Higher values occur in the city center, where values above 10 also appear in LCZ 2.

In the period 2021–2050, minimal changes are expected under both scenarios (Figs. 20c and d). Values above 5 could occur in a large contiguous area, with propagation mainly in a westerly direction spread, to a greater extent according to the RCP8.5 scenario (Fig. 20d). In the northwestern part of the city, the number of TNs may also be above 5 in the LCZ 8 type built-up. In the city center, TNs above 10 are expected in a larger area compared to the reference period, with additional scattered smaller areas for RCP8.5.

In the period 2071–2100, the more optimistic RCP4.5 scenario suggests TNs above 5 in almost the entire area of Subotica, except for a few outlying areas (Fig. 20e). However, in the densely built-up central and eastern urban parts, the values may exceed 10, while in the compact zones they may exceed 15.

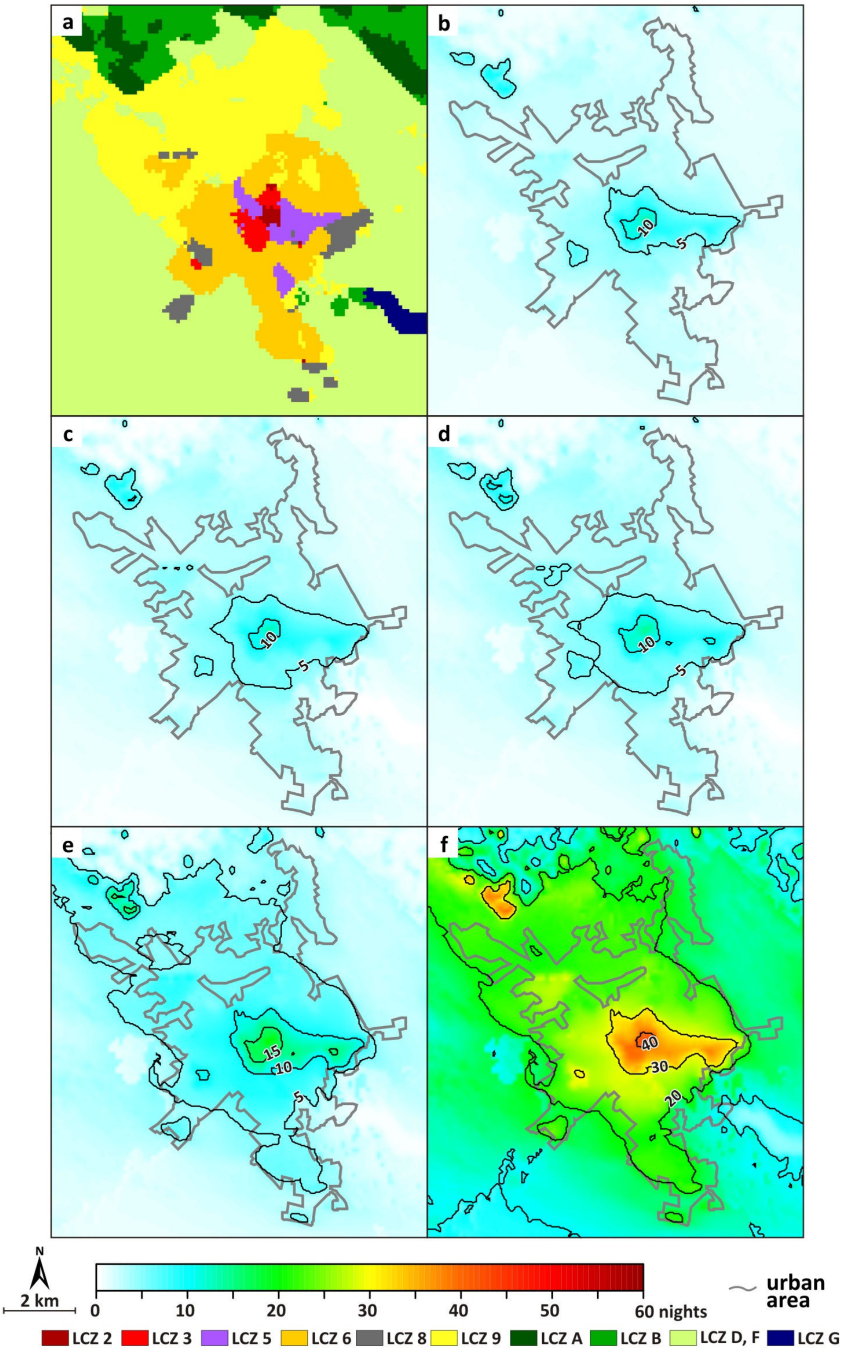

Fig. 20 LCZ map of Subotica (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and SE.

According to the RCP8.5 scenario, values over 20 are expected throughout the city and over 30 in the city center (Fig. 20f). Under this scenario, in the downtown compact zones the number of TNs could exceed 40.

3.19. Szeged

In the period 1981–2010, the number of TNs is over 5 most of Szeged (Fig. 21b). These include the inner, western, southern and southwestern parts of the city, where these values typically appear in the areas of LCZs 5, 6 and 8. In the city center, in the compact built-up areas (LCZs 2 and 3), the number of TNs exceeds 10 and 15, respectively.

In the near future, there may be slight changes in the number of TNs and there may be only minor differences between the two scenarios (Figs. 21c and d). In both cases, the size of areas with more than 5 and 10 tropical nights may increase. In the former, the spread can be observed in the northern and southeastern part of the city, while in the latter, west of the city center, along the LCZ 8 type built-up.

This trend is more pronounced under the RCP8.5 scenario, where values above 20 may already appear in the city center (Fig. 21d).

Larger changes are expected in the period 2071–2100, mostly under the RCP8.5 scenario. Based on the RCP4.5 scenario, the number of TNs could be above 10 in almost the entire city (Fig. 21e). Only the northern and eastern outer parts of the city can have values below this. However, in the inner areas of the city, values above 15 may be typical, while in the center, in the area of compact zones, the number of TNs may exceed 20 or even 25.

Based on the RCP8.5 scenario, the number of TNs in almost the entire city may be over 30, except for the northern and eastern areas (Fig. 21f). In the city center, as well as west of it, in LCZ 8, this value can exceed 40, and in a small area even 50.

3.20. Székesfehérvár

In the reference period 1981–2010, the number of TNs in most parts of Székesfehérvár is more than 5 (Fig. 22b). These include the downtown LCZs 2 and 5, as well as the LCZ 8 type built-up areas in the east, south and north of the city.

In the period 2021–2050, the number of TNs may be above 5 in almost the entire city, excluding the northwestern parts. Values above 10 may appear in the city center (LCZs 2 and 5) and in the eastern and southern districts (LCZ 8) (Figs. 22c and d). The only difference between the two scenarios is that, according to the more pessimistic RCP8.5, values above 5 and above 10 may appear in larger areas, respectively (Fig. 22d).

In the period 2071–2100, according to the more optimistic RCP4.5 scenario, the number of TNs may be over 10 in almost the entire area of Székesfehérvár, apart from the outskirts and green areas of the city (Fig. 22e). In the previously mentioned densely built-up areas of the city (LCZs 2, 5 and 8), the number of nights can exceed 15.

Under the RCP8.5 scenario, much larger changes are expected, as the number of TNs in almost the entire city can be over 30 (Fig. 22f). Within this, in this case, the values may already exceed 40 in the above-mentioned areas.

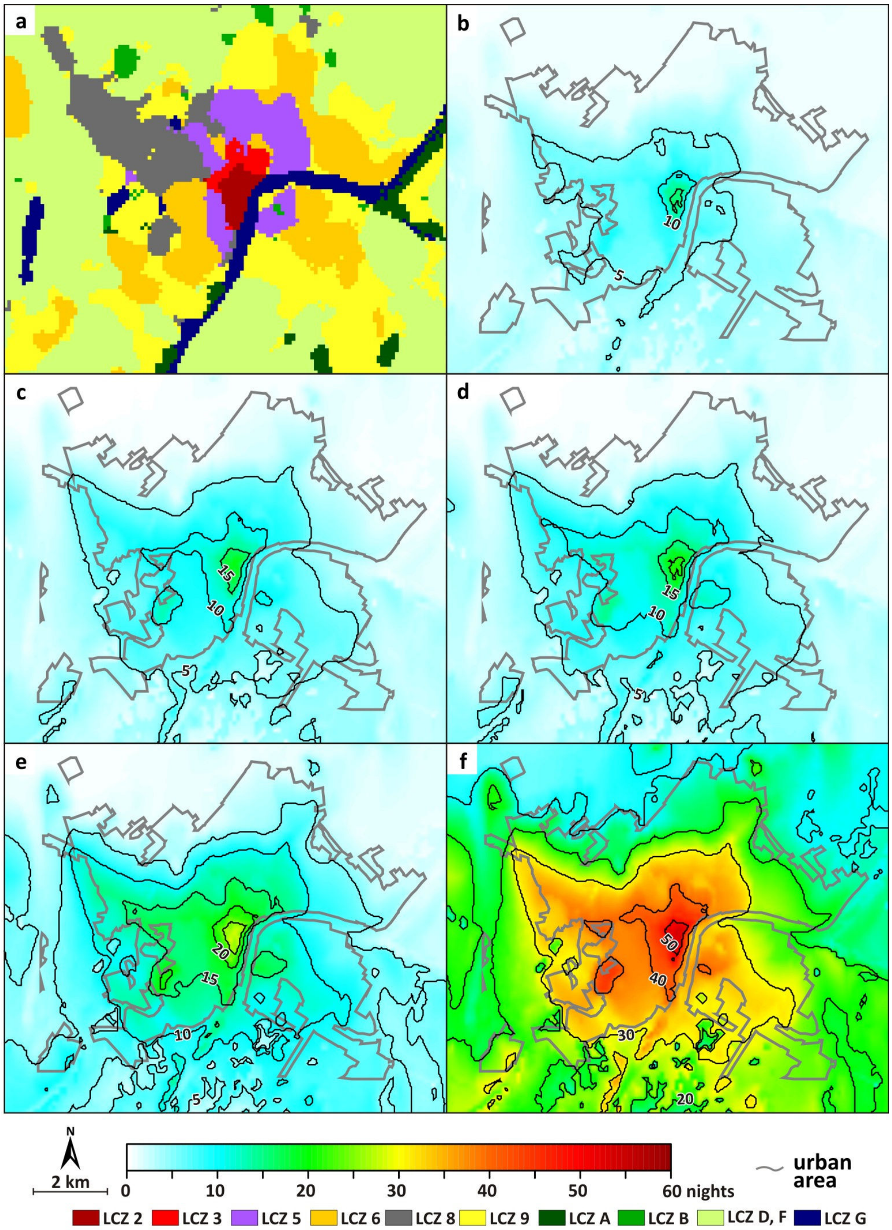

Fig. 21 LCZ map of Szeged (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and NE.

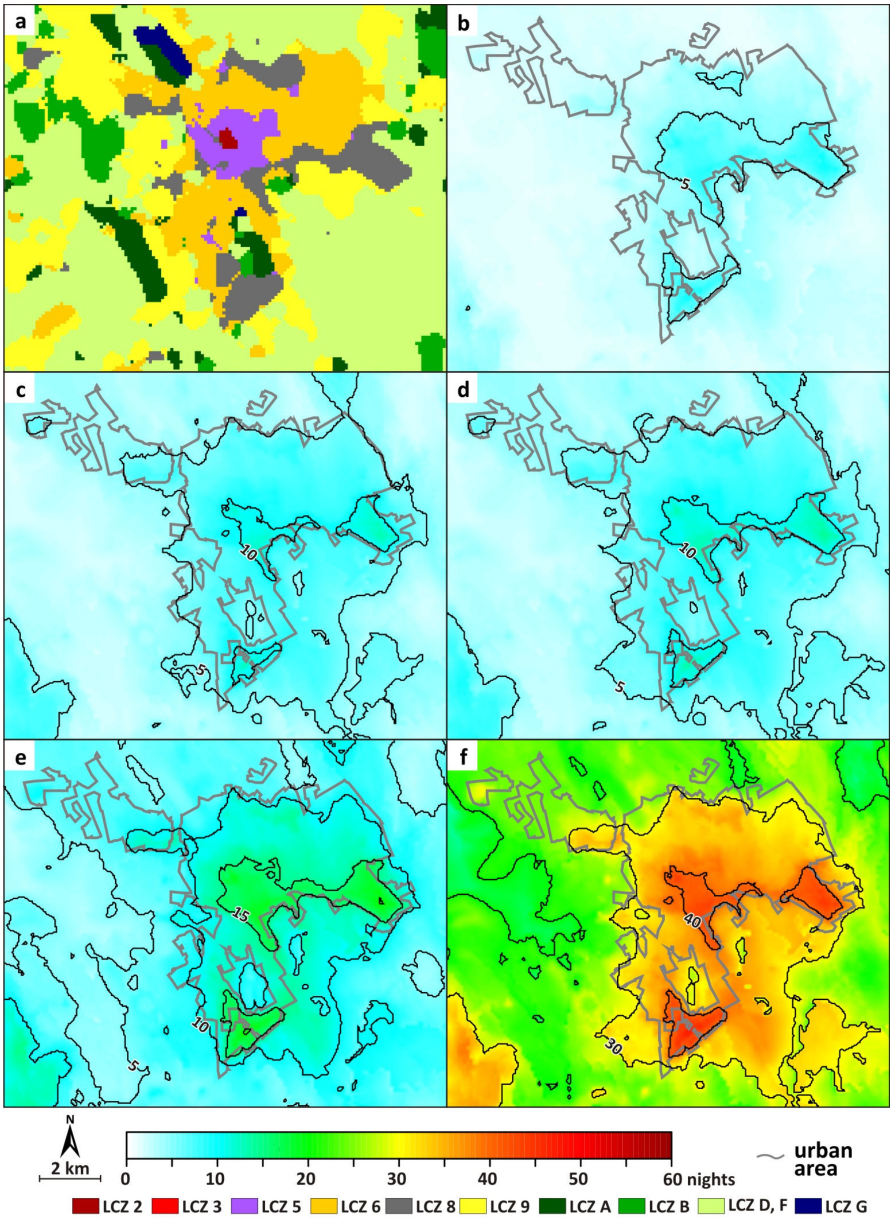

Fig. 22 LCZ map of Székesfehérvár (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and W.

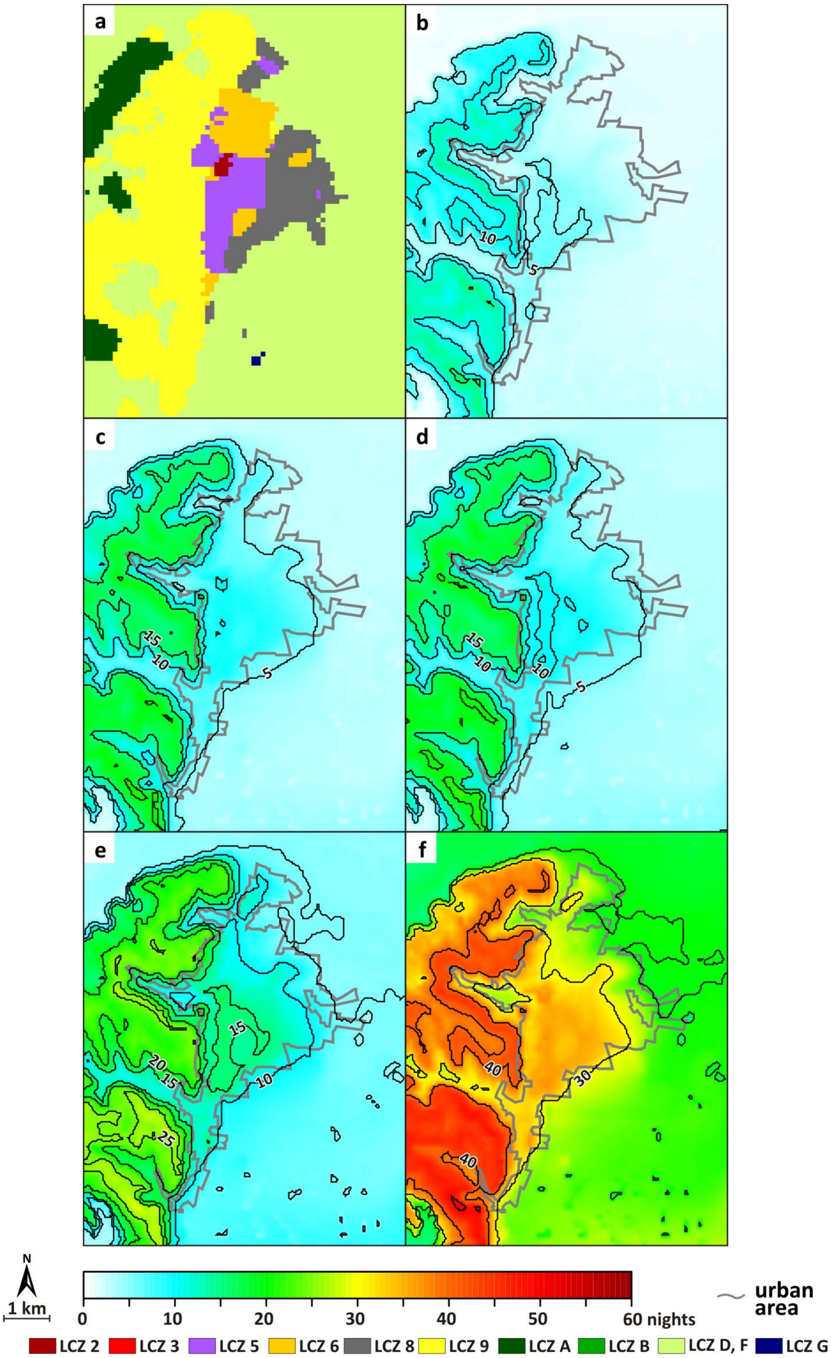

Fig. 23 LCZ map of Szekszárd (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and W.

3.21. Szekszárd

In the reference period 1981–2010, the number of TNs exceeds 5 only in some parts of LCZs 2, 5 and 8 in the central area of Szekszárd (Fig. 23b). The values that appear in the city are strongly influenced by the dense tree cover and the topography west of the city limits. As a result, sparsely built-up areas of the higher areas to the west of the city show higher values than in the Szekszárd area. In some parts of this area, the number of TNs is already over 10 during this period.

In the period 2021–2050, the number of TNs may be above 5 in almost the entire city, excluding the northeastern parts (Figs. 23c and d). In some parts of the city center, in the case of RCP8.5 scenario, in a larger area, the values may already exceed 10 in LCZs 2 and 5 (Fig. 23d). To the west of the city, the number TNs can exceed 15 in most areas.

In the period 2071–2100, the more optimistic RCP4.5 scenario predicts the number of TNs over 10 in most of Szekszárd (Fig. 23e). Lower values can only be along the eastern border of the city. In the city center, in a larger contiguous area in LCZs 2, 5 and 8, bounded around the LCZ 6 type built-up, the number of TNs could be above 15. To the west of the city, the values can reach 20, and in a smaller area even 25.

Under the RCP8.5 scenario, the number of TNs in most of Szekszárd may be over 30 (Fig. 23f). Values below 30 can occur only in the outskirts of the city, most notably in the northeastern part of the city while west of the city they may already exceed 40.

3.22. Szolnok

In the 1981–2010 reference period, the number of TNs is above 5 in the more densely built-up areas of the city center (LCZs 2, 3 and 5) and in the more southern LCZs 6 and 8 (Fig. 24b). Values above 5 also appear in other parts of the city, typically in LCZ 8 type built-up. The number of TNs is above 10 in a small area within LCZ 2 in the city center.

In the period 2021–2050, the two scenarios show similar results (Figs. 24c and d). In most parts of Szolnok, the number of TNs may be above 5, only in the less densely built-up southern and northern parts of the city may this value be lower. Values above 10 may occur in the central parts as well as further south in LCZ 8. In addition, there may be more than 15 TNs in LCZ 2 in the city center.

In the period 2071–2100, the more optimistic RCP4.5 scenario projects that almost the entire area of Szolnok, except some outlying areas, could experience TNs above 5 (Fig. 24e). The values can be more than 10 in most parts of the city for the LCZ 6 type built-up and can exceed 15 in the city center and further south in LCZ 8. Values above 20 may appear in the compact zones (LCZs 2 and 3) in the city center.

Under the RCP8.5 scenario, the number of TNs could be over 20 in almost the entire city (Fig. 24f). Values above 30 may occur in large areas of the city in LCZs 6 and 8 and in the southern urban part in LCZ 9. They can be above 40 in the compact zones and in LCZ 8, while in a small area in the city center, they can even exceed 50.

3.23. Tatabánya

In the reference period 1981–2010, the number of TNs in the entire area of Tatabánya is less than 5, such nights occur only in the northwestern part of the city, on average once or twice a year (Fig. 25b).

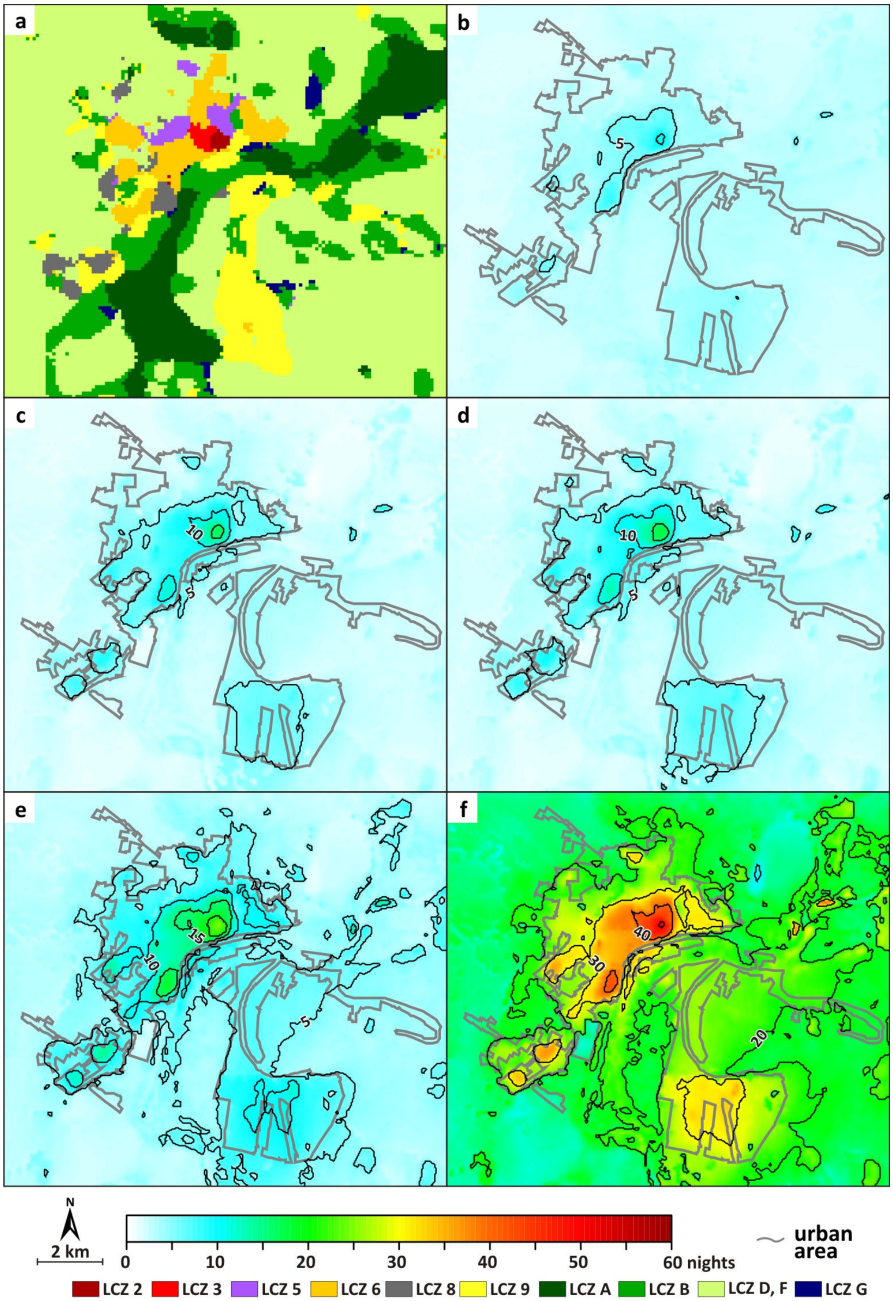

Fig. 24 LCZ map of Szolnok (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NE and W.

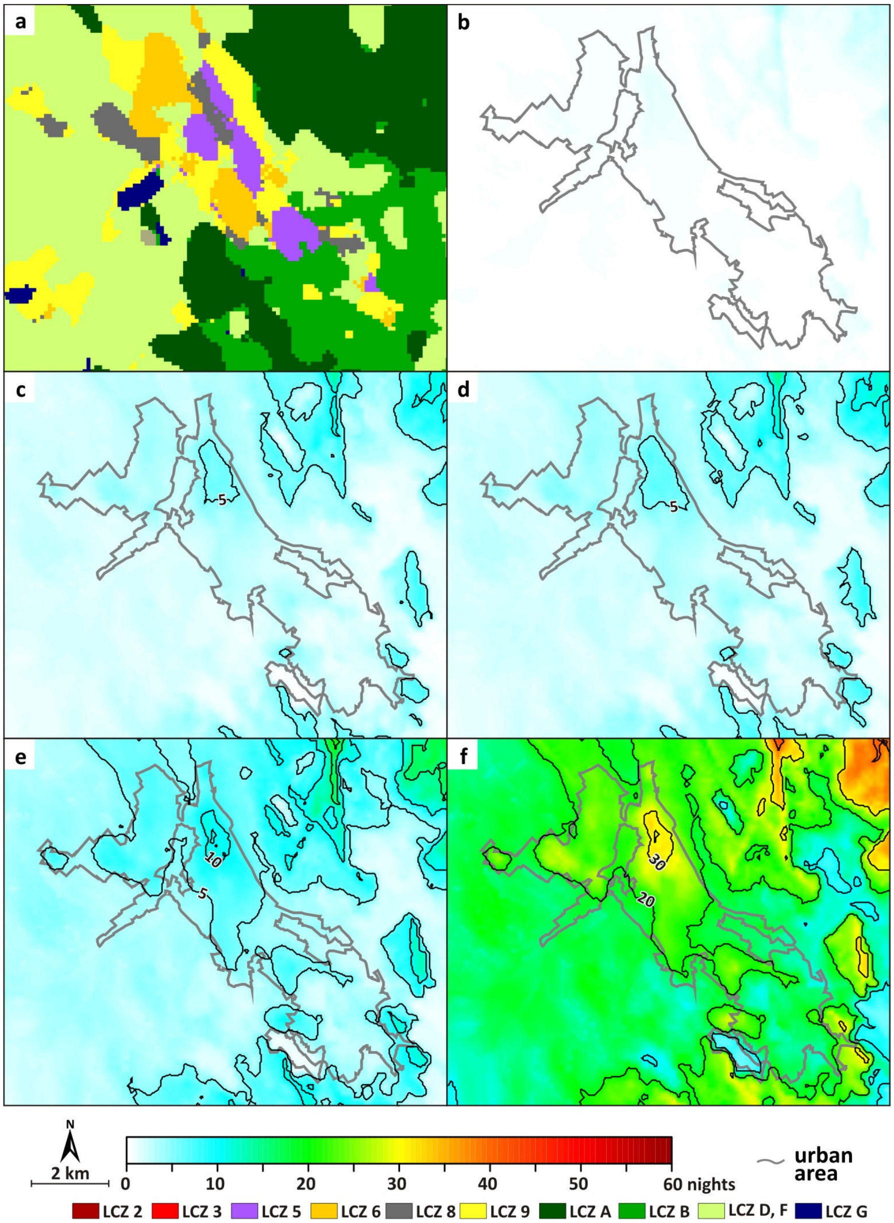

Fig. 25 LCZ map of Tatabánya (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are NW and W.

In the period 2021–2050, the two scenarios show almost the same results (Figs. 25c and d). Only in the northwestern part of Tatabánya, in some parts of LCZs 5 and 8 type built ups the number of TNs may exceed 5. The difference between the two scenarios is that RCP8.5 shows values above 5 in a slightly larger area (Fig. 25d).

In the period 2071–2100, the more optimistic RCP4.5 scenario predicts that the number of TNs in most of Tatabánya may be above 5 (Fig. 25e). Values below this can only occur in some parts of the LCZs 9 and 6. In the northwestern part of the city, in LCZs 5 and 8, the values can already be above 10.

According to the RCP8.5 scenario, the number of TNs in most areas of Tatabánya may be over 20 (Fig. 25f). Only in some areas of the less built-up districts (LCZs 6 and 9), mainly to the south, can values be lower. However, in the northwest, in LCZs 5 and 8, the number of tropical TNs can already be over 30.

3.24. Timisoara

In the reference period 1981–2010, the number of TNs in almost the entire area of Timisoara exceeds 5 (Fig. 26b). These values also appear to the northwest of the city, due to the prevailing south and southeast wind direction. Values above 10 are typical in the central areas of the city, which appear mainly in the LCZ 6 type built-up. Even in this period, there are areas in Timisoara, where the number of TNs can be above 15, typically in LCZs 2, 5 and 8.

There will be no remarkable changes in the period 2021–2050 compared to the reference one (Figs. 26c and d). The model results for this period give slightly less TNs for the area than the measurement results for the reference period. The difference is reflected in the smaller extent of the areas mentioned in the reference period, which is particularly noticeable for the RCP4.5 scenario values (Fig. 26c).

The RCP8.5 scenario gives almost the same results as the reference period (Fig. 26d).

In the period 2071–2100, the more optimistic RCP4.5 scenario projects the number of TNs above 5 over almost the entire area of Timisoara, excluding the southern and southeastern parts (Fig. 26e). In a large part of the city, values can exceed 10, even in the less developed LCZ 9. Values above 15 may occur for the most part of the inner city in LCZs 5, 6 and 8, while in most of the city center, they may be above 20 (in LCZs 2, 5, 6 and 8).

Under the RCP8.5 scenario, apart for the eastern urban parts, the number of TNs can be over 30 in almost the whole area of Timisoara (Fig. 26f). In addition, in most parts of the city, values above 40 can be more characteristic, while in a larger central area they may even exceed 50.

3.25. Veszprém

In the reference period 1981–2010, the number of TNs in Veszprém is below 5, and in most of the city it is only between 1 and 2 (Fig. 27b).

In the period 2021–2050, the number of TNs may exceed 5 in several areas (Figs. 27c and d). Under the RCP4.5 scenario, these values may appear in the northwest in the LCZ 8 type built-up as well as in several smaller areas of the city (Fig. 27c).

Under the RCP8.5 scenario, several areas are affected by this change (Fig. 27d). In this case, in the eastern urban parts, in a large area of LCZ 5, the number of TNs may already exceed 5.

In the period 2071–2100, the RCP4.5 scenario predicts that the number of TNs may be over 5 in almost the entire area of Veszprém (Fig. 27e). The values may exceed 10 in the LCZ 8 in the northwest, as well as in several small areas in other parts of the city.

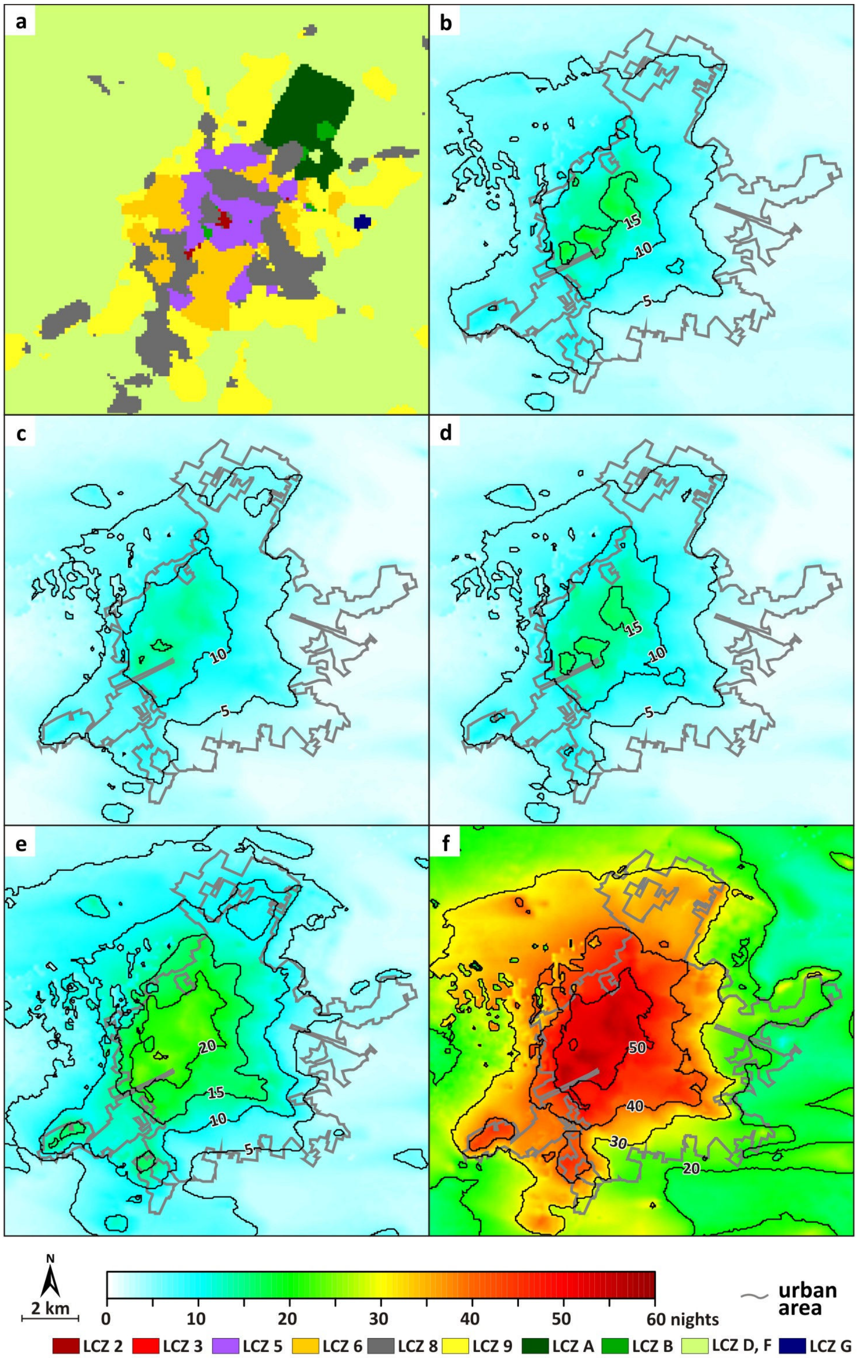

Fig. 26 LCZ map of Timisoara (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are S and SE.

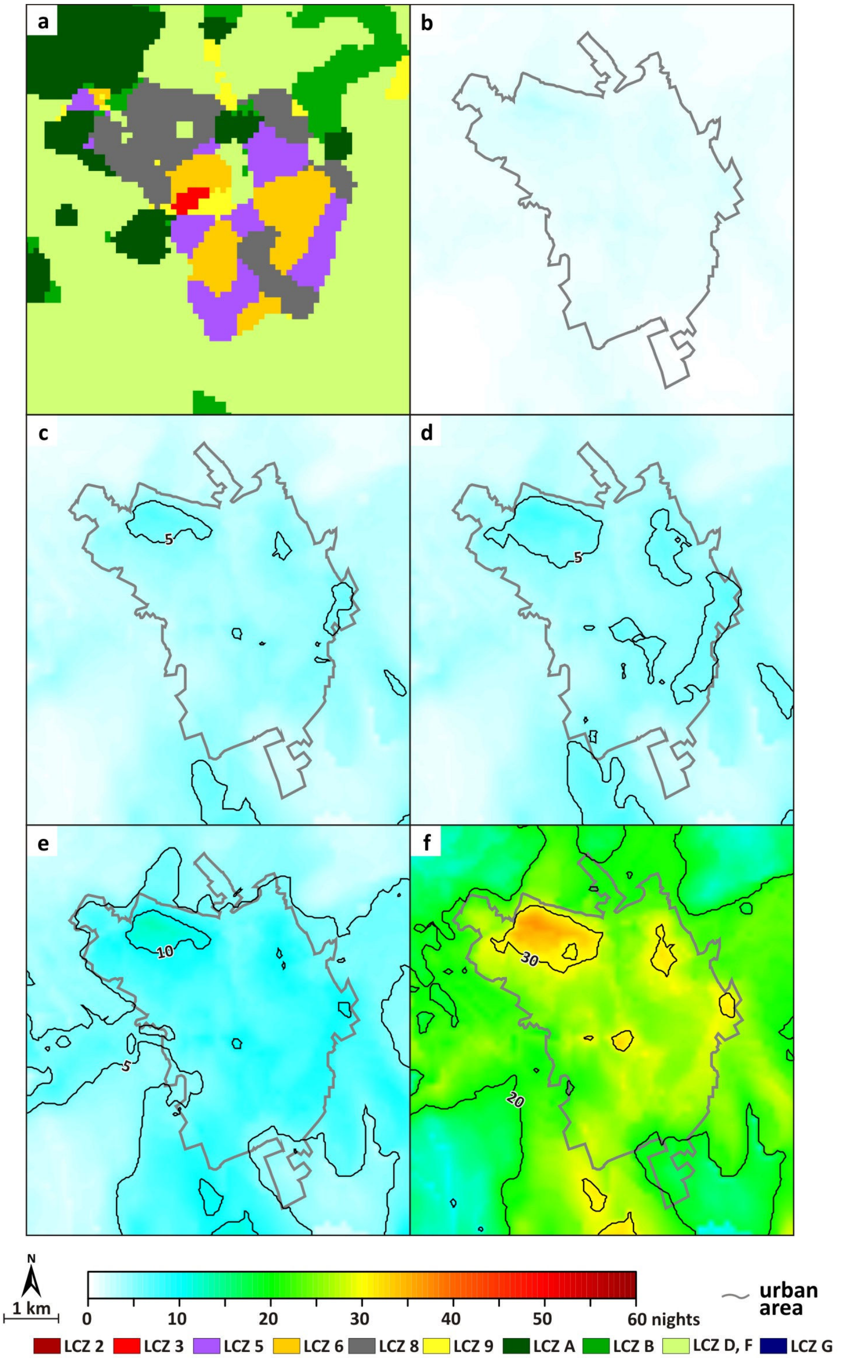

Fig. 27 LCZ map of Veszprém (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are SW and S.

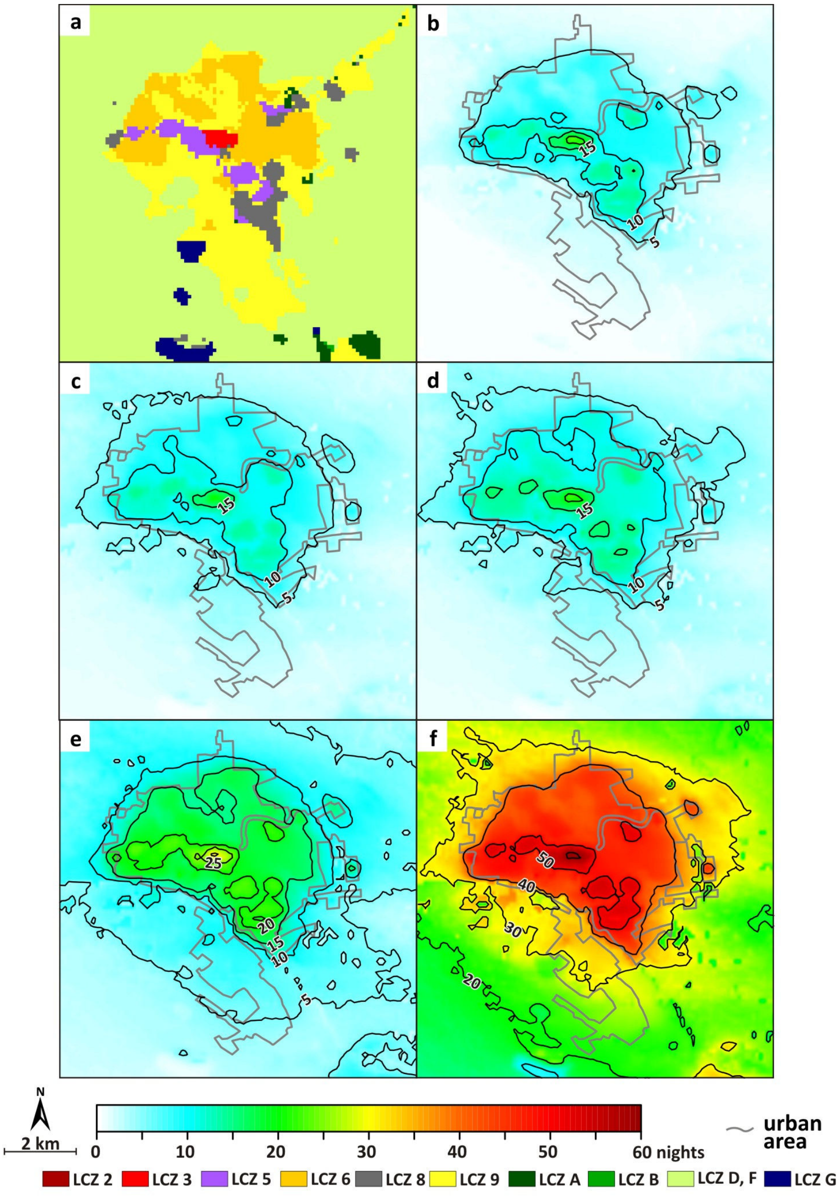

Fig. 28 LCZ map of Zrenjanin (a) and the number of tropical nights in the study area in 1981–2010 (b), in 2021–2050 based on scenarios RCP4.5 (c) and RCP8.5 (d), as well as in 2071–2100 based on scenarios RCP4.5 (e) and RCP8.5 (f). Prevailing wind directions are SE and NW (Gál et al. 2021a).

According to the RCP8.5 scenario, the number of TNs could be over 20 in almost the entire city (Fig. 27f). Higher values, above 30, may occur in LCZ 3 and in parts of LCZs 5 and 8 type built-up areas.

3.26. Zrenjanin

As Zrenjanin is located at a slightly lower latitude compared to the other cities, the number of TNs is already higher in the 1981–2010 reference period (Fig. 28b). The values are above 5 in almost the whole city, except to the southern areas, above 10 in the LCZs 5 and 8, as well as already above 15 in the case of LCZ 3 (Gál et al. 2021a).

In the near future, the extent of urban areas with TNs above 5 or 10, respectively, may increase, especially in the case of the RCP8.5 scenario (Fig. 28d). Furthermore, values above 15 may appear in more and more areas in LCZs 5 and 8 type built-ups. There may be values above in the LCZ 3 area. For the RCP4.5 scenario (Fig. 28c), the maximum of TNs is lower than in the reference period, which can be attributed to the usage of different data sources (Carpatclim and EURO-CORDEX) (Gál et al. 2021a).

In the period 2071–2100, the RCP4.5 scenario projects TNs above 15 in almost the entire city. Values above 20 can appear in several areas of the city, especially in the LCZs 5 and 8 type built-ups (Fig. 28e). In the city center (LCZ 3), the typical value may be above 25, but in a small area it may even exceed 30.

Under the RCP8.5 scenario, the values could be twice as high, as the number of TNs in almost the entire city could exceed 40 (Fig. 28f). In more densely built-up areas (LCZs 5 and 8), the values can be over 50, while in the city center, they can even be over 60 (Gál et al. 2021a).

4. DISCUSSION: SOME OPTIONS FOR MITIGATING CLIMATE CHANGE IN URBAN AREAS

Based on the results obtained, it can be stated that:

(i) The number of TNs within cities is strongly influenced by the nature of the built-up type of that part of the city. It can be seen that higher values occur in compact zones (LCZs 2 and 3) than in more open built-ups. Thus, it is advisable to avoid denser development and rather to increase the height of buildings, leaving more open built-up. Consequently, if the goal is to redevelop an area characterized by LCZ 6 (open lowrise), it is recommended to prefer LCZ 5 (open midrise) type built-up over LCZ 3 (compact lowrise).

(ii) Secondly, the number of TNs is also high in LCZ 8 (large lowrise) neighborhoods, due to the high percentage of impervious surfaces in this zone (typically above 80%). This is the built-up type in the area of warehouses as well as large shopping centers, so in these cases it is especially worthwhile to replace the pavement between the buildings with natural, permeable surfaces.

(iii) Thirdly, in urban planning, it is worth considering the relationship between the location of densely built-up neighborhoods within the city and the prevailing wind directions. Namely, in this case, the shifting effect of the wind can transport the warmer air characteristic above the denser built-up areas to other, sparsely built-up urban areas as well. Thus, higher heat load also appears in areas where the nature of the built-up type would not justify this. Therefore, in those suburban parts of the settlement that are located in the direction of the prevailing wind, it is particularly important to avoid dense development, as this can add an extra amount of heat to an already heavily loaded, typically compact built-up urban center. In addition, in cities and districts located in the valleys of areas with steep relief, it is especially important to avoid dense development, as it can block the refreshing and cooling effect of a nocturnal down-slope breeze.

(iv) Fourthly, in order to mitigate the effects of climate change, it is worthwhile to increase the proportion of green spaces in cities in addition to changing of the built-up types. There is a general consensus that urban green spaces have favorable climatic effects, especially during the summer. At the same time, dense tree vegetation (LCZ A), which is best suited to alleviate the heat stress during the day, has the opposite effect at night, and increasing the heat load. Thus, it is worth considering the different diurnal effects together, as other plant formations (e.g. scattered trees – LCZ B) may be a more favorable solution (Gál et al. 2021b).

(v) Furthermore, fifthly, it is still important to consider the impact of vegetation on urban wind patterns. This is because, especially dense tree vegetation results in less efficient nocturnal air mixing, which can cause an increase in heat load in its surroundings. Consequently, when creating urban green spaces, attention must also be paid to the type of the vegetation and the location of the green space in relation to the prevailing wind direction (Gál et al. 2021b).

5. CONCLUSIONS

In this study, the changes in the number of tropical nights were examined during the 21st century in Carpathian Basin cities compared to the 1981–2010 reference period. In this period, the number of tropical nights is usually between 0 and 10, but in some larger and southern cities it can exceeds even 15. The determining factors, apart from location and size, are the prevailing wind directions and the built-up types in the city. The highest number of TNs is usually in the compact zones (LCZs 2 and 3) in the city center, in the more densely built LCZ 5 and in LCZ 8, where the rate of impervious surfaces is high.

In the near future, the change could not be remarkable and the difference between the two scenarios are minimal. In general, the sizes of the areas, where the number of TNs exceed 5 or 10 could increase in the suburbs of the cities. The average number of TNs in the urban area may increase 0–9 nights depending on the city and scenario. The difference between the scenarios in the average urban value can be 0–2 nights.

At the end of the 21st century, the scenarios give different number of TNs in the cities and the difference is large between them. Under the RCP4.5 scenario, in most cities the average number of TNs could be approximately between 10 and 25. There are a few examples where the values can be much lower: Eger, Kaposvár, Tatabánya and Salgótarján, due to their location. Furthermore, in Budapest the values could be over 30 in a large area in the center. However, the changes under the RCP8.5 scenario could be much larger since in most of the cities the number of TNs can exceed 30 or 40. In this scenario, there are also different values from the average: the lowest urban values are between 15 and 30 nights in the above-mentioned cities, while in Budapest the highest values are above 60.

Our results show that urban heat loads are expected to increase strongly in the Carpathian Basin cities, especially under the more pessimistic scenario. Heatwaves, which are not yet very common today, could be more common in the future and could become a permanent feature of summers in the studied area. This phenomenon is gradually becoming more of a challenge in city life and increasing health risks as dwellers could be exposed to extreme heat stress. Therefore, there is an increasing urgency to develop and implement various adaptation and mitigation strategies as soon as possible so that our future remains livable in cities.

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