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PROJECTION OF PRESENT AND FUTURE DAILY AND EVENING URBAN HEAT LOAD PATTERNS

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

Key words: urban heat load, climate indices, present, future scenarios, Central Europe

1. INTRODUCTION

Research on urban climate is focused on different climate modifications caused by the built environments, in addition it also attempts to provide reliable projections for future climatic situations at local scale. Urban population follows a rapidly growing trend (UN 2019) which underlines the importance of the role of urban climate research. In order to reveal the effects of regional to local scale atmospheric phenomena, Regional Climate Models (RCM) are applied. This type of models is nested into General Circulation Models (GCM) whose output data serve as boundary conditions for the RCMs (McGregor 1997). To predict future climate patterns it is necessary to expect different possible future anthropogenic activity trends, therefore, the model runs are combined with future emission scenarios. In recent years there are four scenarios called them as Representative Concentration Pathways (RCP) distinguished by the enhanced radiative forcings resulting from different predicted levels of greenhouse gas concentrations (Stocker et al. 2014).

To simulate these modified climatological processes in urban areas via numerical models the spatial resolution of the models should be able to reflect the urban effects and the varied urban surfaces need to be differentiated from natural landscapes (Oke et al. 2017). MUKLIMO_3 (Sievers 1995), ENVI-met (Bruse and Fleer 1998) and Town Energy Balance models (Masson 2000) as specific urban climate models (UCM) are the most accurate approaches for urban climate modelling (Hidalgo et al. 2008).

To reveal the joint effects of climate change and urban areas, both the RCMs and UCMs are needed as they are able to deliver climate data on a regional scale and provide the climate modification by cities, respectively. One of the several approaches for surface parameterizations reflecting the effects of different surface units is the Local Climate Zone (LCZ) scheme. It is a climate-based classification system categorizing the different land-use areas by objectively quantified measures, that is, each zone is defined by its own geometric, surface cover, thermal and radiative properties (Stewart and Oke 2012). Therefore, this scheme can be used for surface input data for numerical modeling (Žuvela-Aloise 2017, Kwok et al. 2019).

As the settlements have an additional temperature-rising effect, the so-called urban heat island (UHI) phenomenon, the inhabitants of the strongly built-up and therefore less vegetated cities suffer from this excess heat load more than their counterparts living in the generally greener countryside, especially in heat wave periods (Hatvani-Kovacs et al. 2018, Hintz et al. 2018). As the UHI is mostly pronounced in the nocturnal hours, this thermal excess can be particularly dangerous at night causing, for example, higher mortality rate (McGregor et al. 2015).

The paper focuses on the recent and future daily and evening thermal climate of a Central-European city (Szeged, Hungary) by applying the MUKLIMO_3 microclimatic numerical model (Sievers 1995). In the region of Szeged a warming trend can be anticipated during the next decades (Skarbit and Gál 2016, Bokwa et al. 2018, 2019). The main purpose of this study is to analyze and compare the patterns of the annual numbers of daily and evening climate indices in the present (1981–2010) and in the periods of future climate change (2021–2050 and 2071–2100) based on a relatively optimistic future emission scenario (RCP4.5) and a much more pessimistic one (RCP8.5).

2. STUDY AREA, DATA AND METHODS

2.1. Study area and its land-use classes

Szeged (46.3°N, 20.1°E) is located in a flat terrain of south-eastern Hungary at about 80 m above sea level (Fig. 1). Its region belongs to the Köppen's climatic class of Cfa (temperate, no dry season, hot summer) (Köppen 1918, Unger et al. 2020). The city has 162,000 inhabitants and contains a densely and midlevel height built centre, openly arranged blocks of flats, large areas of family houses as well as shopping centers and warehouses. The rural areas around the city are mostly arable lands (e.g. maze) but in some places they are interrupted by groves (Skarbit et al. 2017). The presented climatic parameters of Szeged region (Table 1) are based on CRU TS v4.03 database (Harris et al. 2014).

The LCZ map of Szeged has a spatial resolution of 100 m (Fig. 1). The city centre mainly consists of LCZs 2 and 3 (compact midrise and compact low-rise). Open midrise (LCZ 5) can be found north, northeast and south from the centre. LCZs 6 and 9 (open low-rise and sparsely built) occupies a large area south, north and northeast in the suburbs. LCZ 8 (large low-rise) covers a relatively large area in the northwest. Around the urbanized districts the prevailing land-use types are low plants (LCZ D).

These LCZ classes were used as input land-use data for the MUKLIMO_3 simulations (see Section 2.2).

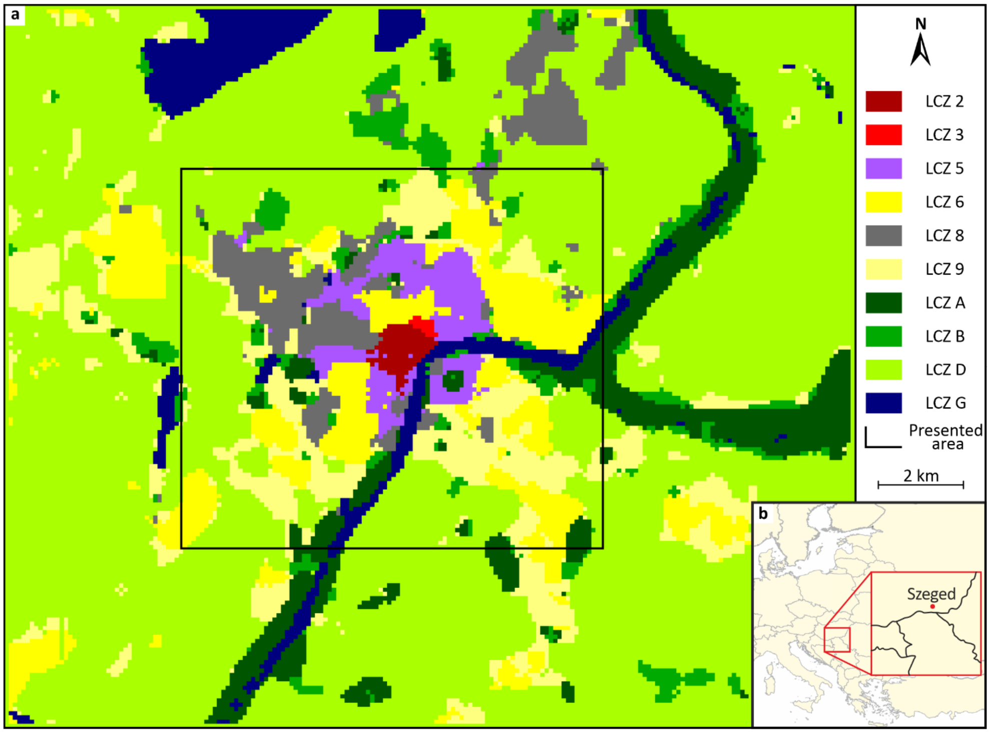

Fig. 1 Land-use class map in and around Szeged based on the LCZ classification system (the study area is indicated by black frame) (Skarbit and Gál 2016)

Table 1 Main climatic parameters (1986–2015) of Szeged region (Harris et al. 2014)

Mean annual temperature	11.9°C
Highest mean monthly temperature (July)	22.7°C
Lowest mean monthly temperature (January)	0.4°C
Mean annual amount of precipitation	508 mm

2.2. Urban climate modelling, climate indices

The model simulations at urban scale for this study were carried out with the non-hydrostatic microclimatic MUKLIMO_3 model (Sievers 1995). For more details about the model see Früh et al. (2011a), Skarbit and Gál (2016) and Žuvela-Aloise (2017).

For calculating climate indices the model needs climate input data. In this study results from global and regional climate projections were used as input data (air temperature, relative humidity, wind speed and direction) from the EURO-CORDEX projections (Jacob et al. 2014) with 0.11° spatial resolution (5 different GCMs and 3 different RCMs resulting 14 different simulations based on RCP4.5 and RCP8.5 scenarios). For the details about the applied models see Gál et al. (2021).

The cuboid method was applied which is a practical interpolation technique including meteorological data for a 30-year period without enormous computational efforts (Früh et al.

2011a). In the case of urban heat load, it is assumed that only the 2-m air temperature (T), the 2-m relative humidity and the 10-m wind velocity are the contributing factors.

In this study, the annual numbers of hot days and beergarden days were considered as climate indices measuring the urban heat load in the daytime and evening, respectively (Früh et al. 2011b, Skarbit and Gál 2016). The definition of the hot day is when the daily T_{max} equals or exceeds 30°C. A beergarden day is a day when the T is at least 20°C at 20h (LST), that is evenings people can sit in the open (in beergardens, restaurants, caffes, open-air theatres etc.) at that time without feeling cold. These evenings are important from the point of view of leisure-time quality in climatic zones characterized by a longer cold season. The patterns of the index numbers were calculated both for the present and for the future for all scenarios. The northwest and northeast directions were selected as prevailing wind directions for the Szeged region (based on the data of nearby WMO station 12982).

3. RESULTS AND DISCUSSION

3.1. Present heat load patterns

Simulated patterns for the present (1981−2010) can be followed on Fig. 2. In this period the number of hot days exceeds 30 in the city centre (Fig. 2a). Close to the centre (LCZs 2 and 3) and both in the northern (LCZ 5) and in the northwestern parts of the city (LCZ 8) there are 20-25 hot days per a year, while in the suburbs (LCZs 6 and 9) there are only 10 to 20. In the large urban parks and green areas the values are below 10.

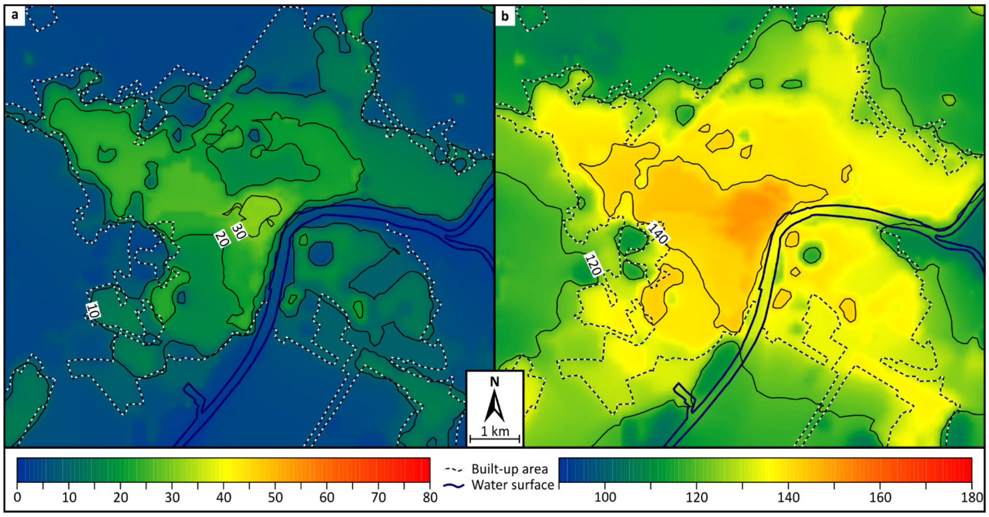

Fig. 2 Patterns of the annual number of hot days (a) and beergarden days (b) in the present (1981–2010) (the boundary of the built-up area is indicated by white-black dashed line)

The spatial distribution of the evening index in the present shows a bit similar pattern (Fig. 2b). In the central areas (LCZs 2 and 3) the number of the beergarden days exceeds 150, and the area of more than 140 extends NW following the industrial and warehouse zones

(LCZ 8), as well as southwards (LCZ 5). In the suburbs (LCZs 6 and 9) this index is still over 120 while in the surrounding rural areas (mainly LCZ D) its number is between 100 and 120.

3.2. Future heat load patterns

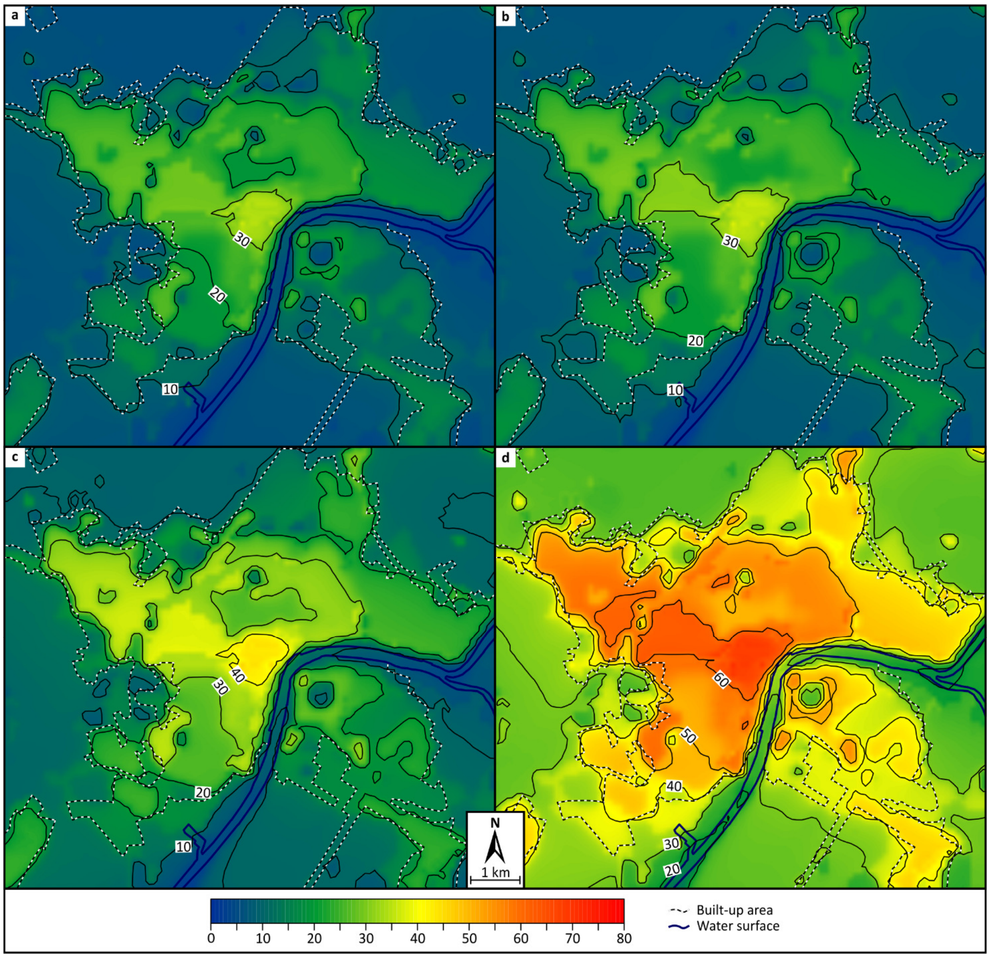

Fig. 3 Patterns of the annual number of hot days in the periods of 2021–2050 (a, b) and 2071–2100 (c, d) based on RCP4.5 (a, c) and RCP8.5 (b, d)

Fig. 3 shows the patterns of the number of hot days for two future periods (2021–2050 and 2071–2100) based on RCP4.5 and RCP8.5 scenarios. In the period of 2021–2050 (Figs. 3a-b), the difference in the patterns between the two scenarios is not very significant: in the city centre (LCZs 2 and 3) the number is around 30-35 although this area is larger in the case of RCP8.5 as it covers some parts of LCZ 8 towards NW. The area of 20-30 is much more extensive as stretches towards NW (LCZ 8), northwards and southwards (LCZ 5). In the case of RCP8.5 the 20-day isoline extends a bit towards the SW (LCZ 6). It can also be seen that in the urban parks this index value remains below 10. In the surrounding rural areas (mainly LCZ D) the annual number of hot days is also smaller than 10.

Based on the results of 2071–2100, the emission scenarios deliver two distinct outcomes (Figs. 3c and 3d). When the emissions decline at the end of the century (RCP4.5) (Fig. 3c), the further warming is slight comparing to the period of 2021–2050 (Fig. 3a). The city centre (LCZs 2 and 3) has an additional number of about 10 (40-45 hot days a year). Close to the centre there are 30-40 hot days with a larger area of 20-30 stretching towards NW, while in the suburbs (LCZs 6 and 9) their numbers are still over 20 days. Urban green spaces and rural areas remain cool in this case (hot days less than 10).

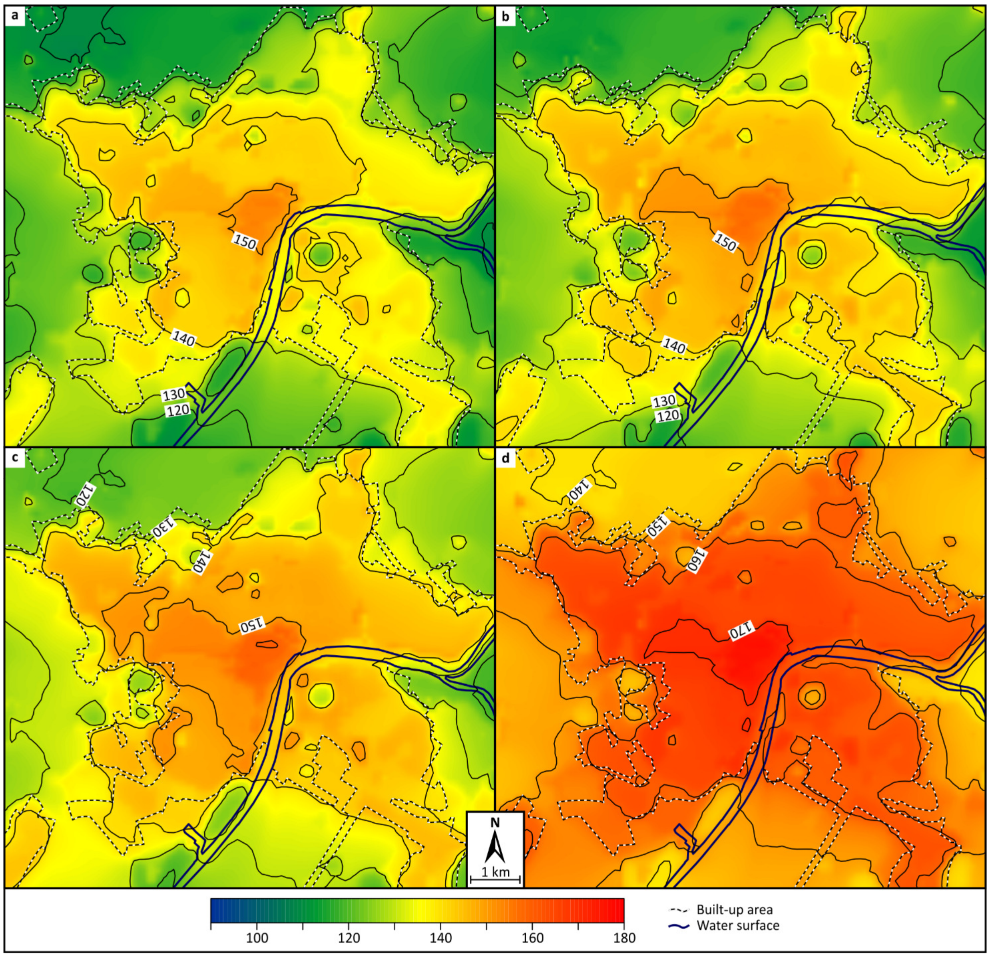

Fig. 4 Annual number of beergarden days in the periods of 2021–2050 (a, b) and 2071–2100 (c, d) based on RCP4.5 (a, c) and RCP8.5 (b, d)

In the case of the pessimistic scenario (RCP 8.5) the daily heat load drastically increases in the whole domain (Fig. 3d). In the city centre and NW to it (LCZs 2, 3 and 8) the number of hot days exceeds 60 a year which is a 30-day rise compared to the earlier periods (Figs. 2b and 3b). In addition, almost the entire built-up area experiences more than 40 hot days. Even the surrounding rural areas (mainly LCZ D) has the index number of about 20. Like cool islands, the larger city parks experience a relatively smaller levels of heat load (20-30 hot days).

The number of pleasant evenings (beergarden days) in the future periods can be followed by Fig. 4. In the period of 2021–2050 (Figs. 4a and 4b), the difference in the patterns between the two scenarios is minor: in the city centre (LCZs 2 and 3) the number is over 150 although this area is larger in the case of RCP8.5 as it covers some parts of LCZ 8 towards NW. The area of over 140 is much more extensive stretching towards NW (LCZ 8), northwards and southwards (LCZ 5), moreover, in the case of RCP8.5, also to the east (LCZ 6) and the SE (LCZs 6 and 9) (Fig. 4b). In the urban parks this evening index value remains below 120 and in the rural areas the values are between 120 and 130.

In the period at the end of the century, according to the favorable scenario, the number of beergarden days in the wider central areas (LCZs 2, 3 and 8) is over 150, moreover, even in a limited downtown area, it even exceeds 160. The isoline of 140 surrounding the interiors in the present period (Fig. 2b) now practically frames the entire urban area (Fig. 4c). By this time, the city parks and the rural areas near the suburbs can be characterized by index values of 130-140, and they fall below 130 only further away from the built-up parts.

In the case of RCP 8.5 the evening measure drastically increases both in the urbanized and rural areas (Fig. 4d). In the city centre and NW of it (LCZs 2, 3 and 8) its values exceeds 170 rising 20-30 days compared to the earlier periods (Figs. 2b and 4b). In most parts of the city the index value is above 160, but it is above 150 even in the suburbs. The urban green spaces and the rural areas can also be characterized by the pleasant evenings of at least 140.

4. CONCLUSIONS

In this paper a modelling study was presented by applying the MUKLIMO_3 urban model (Sievers 1995) in order to project the recent and future daily and evening thermal climate of a Central-European city (Szeged, Hungary). The model is able to reveal the microscale climatic effects of different of land-use types, namely the thermal effect of the elements of the LCZ scheme (Stewart and Oke 2012). This study intended to highlight the joint thermal effects of urban climate and global climate change. Our main purpose was to analyze and compare the annual patterns of the daily and evening climate index values in the present (1981–2010) and in the periods of future climate change (2021–2050 and 2071–2100) based on optimistic (RCP4.5) and pessimistic (RCP8.5) future emission scenarios.

According to the obtained patterns the areas with the largest index values appear in the city centre extended NW to it (LCZs 2, 3 and 8) as well as the values decrease towards to the vegetated rural surfaces (LCZ D). That is, the values depend on the zone types and there are more days towards to the densely built-up LCZs. Additionally, a general temporal change can be detected as the index patterns show the substantial increasing tendency for both indices towards the end of this century. Table 2 helps to summarize the main trends in the change that are expected in the future. It contains the change in the numbers (rounded to ten) of the hot and beergarden days in the city centre between the recent (1981–2010) and future simulated cases (2021–2050 and 2071–2100), as well as the differences between the rural and central areas.

Table 2 Increase of the hot and beergarden days in the city centre (LCZ 2) between the recent (1981–2010) and future simulated cases (2021–2050 and 2071–2100) based on the RCP4.5 and RCP8.5 scenarios, as well as the differences (in paranthesis) between the rural (LCZ D) and centre (LCZ 2) areas (the numbers are rounded to ten)

Climate index	**Present period 1981–2010**	**Scenario**	**Future periods 2021–2050**	**2071–2100**
hot days	0 (30)	RCP4.5	0 (30)	10 (40)
		RCP8.5	0 (40)	30 (50)
beergarden days	0 (30)	RCP4.5	10 (40)	10 (40)
		RCP8.5	20 (50)	30 (40)

As Table 2 shows, the change in the period of 2021–2050 compared to the reference period and the difference between the two scenarios is slight, although in the case of the evening index the increase is twice as large for scenario RCP8.5 (20 days) as for the optimist one. In contrary, in the distant future the increase is more significant and the two scenarios project different patterns in terms of the index value magnitudes.

However, drawing conclusions from these temporal changes in the index values in an urban environment points in two directions:

(i) On the one hand, the increasing number of hot days expresses a strongly deteriorating change in unfavourable and stressful thermal conditions until the end of the century.

(ii) On the other hand, the change in the number of the evening index can actually be considered a positive development, as it provides more opportunities for regeneration and leisure-time activities outdoors in the already thermally less stressful evening hours for the urban inhabitants.

The obtained results are very illustrative examples for the demonstration of the expected changes of the climate during this century and these examples show that there are several sides to these changes in urban environments. Furthermore, they clearly prove that global or regional scale climate predictions without urban climate interactions do not have enough detailed information for urban planners or local authorities.

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REFERENCES

Bokwa A, Dobrovolný P, Gál T, Geletič J, Gulyás Á, Hajto MJ, Holec J, Hollósi B, Kielar R, Lehnert M, Skarbit N, Šťastný P, Švec M, Unger J, Walawender JP, Žuvela-Aloise M (2018) Urban climate in Central European cities and global climate change. Acta Climatol 51-52:7-35

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

Bruse M, Fleer H (1998) Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ Mod Softw 13:373-384

Früh B, Becker P, Deutschländer T, Hessel JD, Kossmann M, Mieskes I, Namyslo J, Roos M, Sievers U, Steigerwald T, Turau H, Wienert U (2011a) Estimation of climate-change impacts on the urban heat load using an urban climate model and regional climate projections. J Appl Meteorol Clim 50:167-184

Früh B, Kossmann M, Roos M (2011b) Frankfurt am Main im Klimawandel – Eine Untersuchung zur stadtischen Warmebelastung. Berichte des Deutschen Wetterdienstes 237. Offenbach am Main, Selbstverlag des Deutschen Wetterdienstes, Offenbach am Main, 68 p.

Gál T, Mahó SI, Skarbit N, Unger J (2021) Analysis of the effect of different urban green spaces on urban heat load patterns in the present and in the future. Comput Environ Urban (accepted)

Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int J Climatol 34:623-642

Hatvani-Kovacs G, Bush J, Sharifi E, Boland J (2018) Policy recommendations to increase urban heat stress resilience. Urban Clim 25:51-63

Hidalgo J, Masson V, Baklanov A, Pigeon G, Gimeno L (2008) Advances in urban climate modelling. Ann NY Acad Sci 1146:354-374

Hintz MJ, Luederitz C, Lang DJ, von Wehrden H (2018) Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. Urban Clim 24:714-727

Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, Georgopoulou E (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Change 14:563-578

Köppen W (1918) Klassifikation der Klimate nach Temperatur, Niedershlag und Jahreslauf. Pettersman Geogr Mitteilungen September/Oktoberheft:194-203

Kwok YT, Schoetter R, Lau KK-L, Hidalgo J, Ren C, Pigeon G, Masson V (2019) How well does the local climate zone scheme discern the thermal environment of Toulouse (France)? An analysis using numerical simulation data. Int J Climatol 39:5292-5315

Masson V (2000) A physically-based scheme for the urban energy budget in atmospheric models. Bound-Lay Meteorol 94:357-397

McGregor JL (1997) Regional climate modelling. Meteorol Atmos Physics 63:105-117

McGregor GR, Bessemoulin P, Ebi K, Menne B (eds) (2015) Heatwaves and Health: Guidance on Warning-System Development. WMO-No. 1142, World Meteorological Organization – World Health Organization, ISBN 978-92-63-11142-5, 96 p.

Oke TR, Mills G, Christen A, Voogt JA (2017) Urban Climates. Cambridge University Press, Cambridge, 523 p.

Sievers U (1995) Verallgemeinerung der Stromfunktionsmethode auf drei Dimensionen. Meteorol Zeitschrift 4:3-15

Skarbit N, Gál T (2016) Projection of intra-urban modification of night-time climate indices during the 21st century. Hung Geogr Bull 65:181-193

Skarbit N, Stewart ID, Unger J, Gál T (2017) Employing an urban meteorological network to monitor air temperature conditions in the 'local climate zones' of Szeged (Hungary). Int J Climatol 37/S1:582-596

Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. Bull Am Meteorol Soc 93:1879-1900

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

United Nations, Department of Economic and Social Affairs, Population Division (2019) World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York, United Nations

Unger J, Skarbit N, Kovács A, Gál T (2020) Comparison of regional and urban outdoor thermal stress conditions in heatwave and normal summer periods: A case study. Urban Clim 32:100619

Žuvela-Aloise M (2017) Enhancement of urban heat load through social inequalities on an example of a fictional city King's Landing. Int J Biometeorol 61:527-539