FINAL REPORT (NKFI-120346)
***Modeling the urban and intra-urban scale thermal effect of climate change in the 21st century for cities in the Carpathian basin* (12.01.2016 – 08.31.2021)**

ORIGINAL PLAN GENERALLY: Objectives of the project

The overall aim of the research is the prediction of climate indices (e.g. summer days, tropical nights) describing the heat stress conditions in selected urban areas of the Carpathian Basin for the 21st century. For this climate prediction the combined effect of regional climate change and urban climate will be considered. The basis of the modelling process is the Local Climate Zones as an adequate surface parametrization for urban areas. The main modelling tool is the MUKLIMO urban climate model. This model firstly uses daily simulation of weather conditions (temperature, humidity, wind) on ideal days (when the heat stress situations are probable) and secondly it compares these daily simulations with climate or climate model data series in order to predict the spatial distribution of climate indices within urban areas.

For this complex modelling process the following distinct steps have to be accomplished.

THE STEPS OF THE ORIGINAL PLAN AND THEIR IMPLEMENTATIONS:

2.1. Adaptation of the model, simulation

PLAN:

For the adaptation of the MUKLIMO model we will use a study area in Szeged. In this area a detailed urban surface database is available (3D building database, satellite images, urban surface parameters, LCZ maps) and climate datasets (URBAN-PATH urban climate monitoring network, two measurement stations of the Hungarian Meteorological Service) are available. The key feature of this step is the optimization of the modeling process using all of the available surface parameters and meteorological data. First, we define land use classes for the applied MUKLIMO method based on LCZ classes and available databases. The next task is to find the optimal values for parameters of land use classes. In order to find the optimal values numerous model simulation are needed as the combination of land use parameter values are technically endless. This model optimizing process concentrates to one day simulation and applies all available meteorological data as a reference. After we achieved that the daily simulations of MUKLIMO are realistic we develop the technique for the application of the reference period simulations using stationary climate data and for the future scenarios the EURO-CORDEX regional climate model results.

DONE:

According to *Unger et al.* (2017) and *Skarbit et al.* (2017, 2018) the 24-element urban climate measurement network implementing in 2014 within the framework of URBAN-PATH project and its corresponding local climate zone (LCZ) classes put temperature studies in Szeged into a new spatial framework to assess local climate and urban heat island conditions. The stations were installed at locally representative sites using a GIS method based on the standard surface parameters of the LCZ classification. The network was purposely designed to monitor thermal differences among LCZ classes in Szeged and detailed site metadata for each of the monitoring stations were provided.

Studying modeling possibilities, *Gál et al.* (2017, 2018) discussed the first preliminary results about the expected changes of climate indices representing heat waves.

2.2. Validation of the model

PLAN:

We plan to test the performance of the modeling technique in case of Szeged and Novi Sad. The validation process has two stages. Firstly, we compare the daily simulations and 3-year mean climate indices with the measurements of the URBAN-PATH urban climate monitoring networks in both cities. The aim of this part of validation is the comparison of the measured and simulated intra-urban thermal patterns. Secondly, we compare the modeled climate indices for the reference period (1981-2010) at least in the HMS stations of Szeged. This validation process ensures that the predictions for the future scenarios represent properly the expected trends.

DONE:

Together with Szeged, *Bokwa et al.* (2018, 2019) studied five cities in Central Europe with the application of MUKLIMO model. Local Climate Zones concept was used to supply data for the model and for the interpretation of the the results obtained. Model outcomes were walidated with measurement data from urban climate monitoring networks (URBAN-PATH network in the case of Szeged) (see *Fig. 2* in *Bokwa et al.* (2019)).

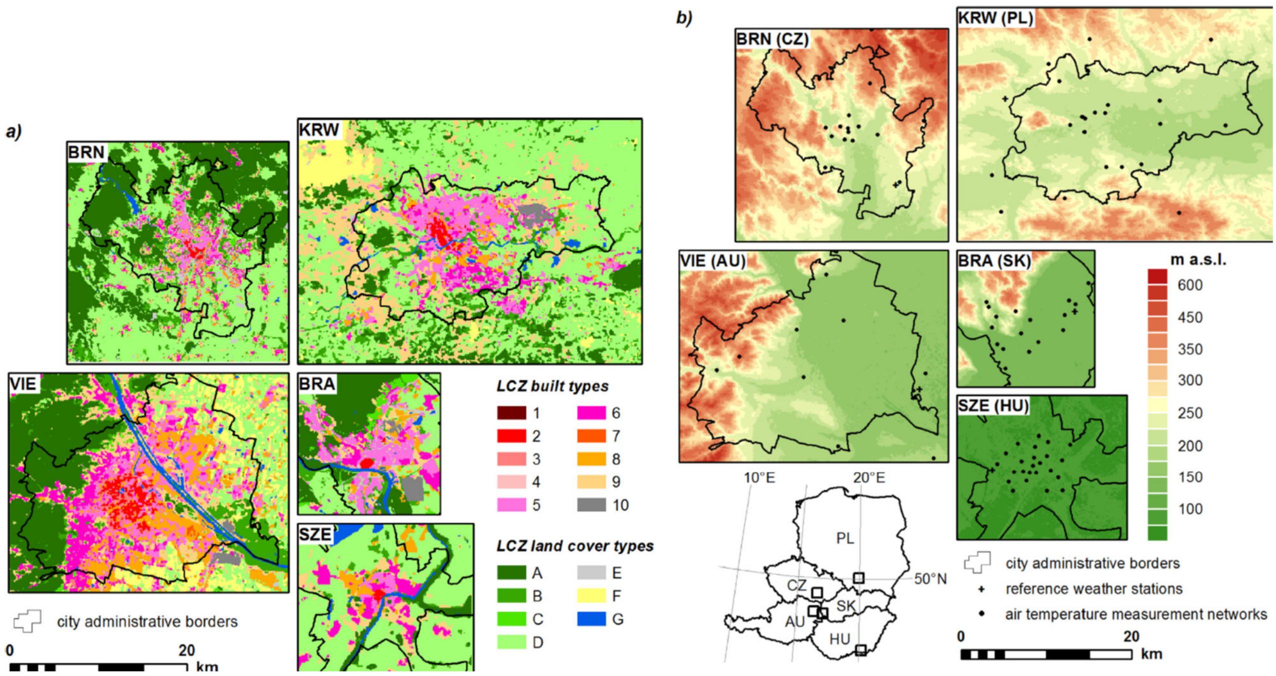

Fig. 2. LCZ classes (a) and relief features together with the location of measurement points (b) in the cities studied

The simulated temperature values generally agree well with the observations. They have high correlation and relative low RMS errors. The performance of the model varies between different measurement points within the city, and secondarily between the cities (see *Fig. 3a* in *Bokwa et al.* (2019)).

2.3. Mapping of Local Climate Zones for selected study areas in the Carpathian Basin

PLAN:

For the application of the model for other cities detailed LCZ maps are essential. Our aim is to obtain LCZ maps for different sized cities with different geographical background in the Carpathian Basin (e.g. Budapest, Debrecen, Győr, Pécs, Subotica, etc.). Based on these maps we can apply the climate model in these cities in order to estimate expected climate changes until the end of this century. Second goal of this step is the development a process for climate assessment of cities based on only LCZ maps. In theory if LCZ maps and climate simulations are available for cities in this region based on the experiences of these results, it is possible to make rough climate estimations for these cities where climate model results are not available. This new evaluation process could be excessively useful in the field of urban planning.

DONE:

Gál et al. (2021a), *Skarbit et al.* (2021) and *Unger et al.* (2021) produced LCZ maps for several different sized cities in the Carpathian Basin (see *Fig. 1* in *Gál et al.* (2021a)) using Bechtel-method (*Bechtel et al.* 2019, see *Fig. 1* in *Bechtel et al.* (2019)). For this study several Landsat images from different dates were used, in order to achieve more reliable LCZ classification. This approach is ensure 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. *Fricke et al.* (2020) produced LCZ maps for Szeged and Novi Sad, as well as a city outside of the Carpathian Basin.

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

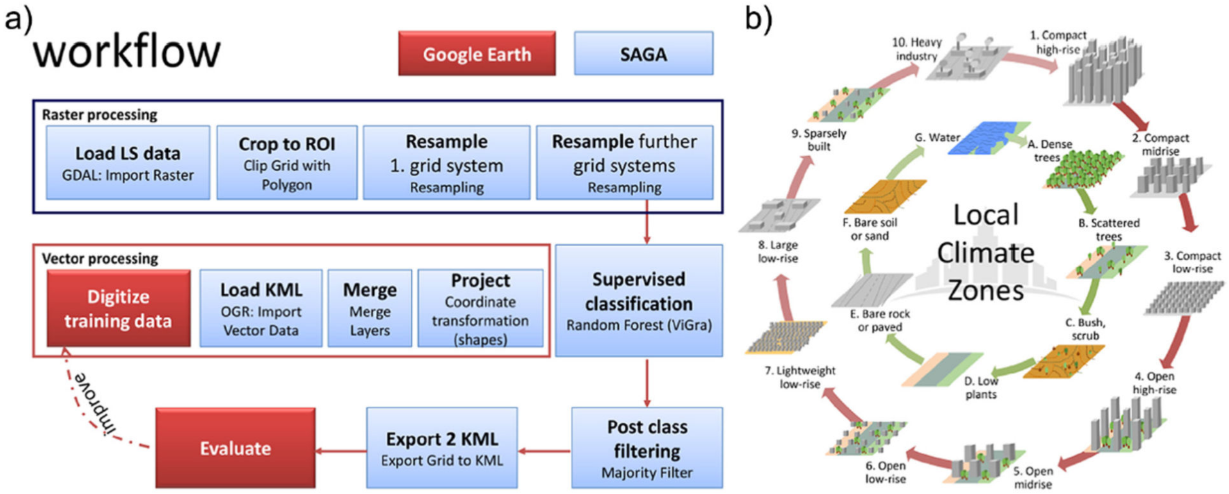

Fig. 1. a) The Local Climate Zone (LCZ) raster and vector data processing workflow (Bechtel et al., 2015). b) the LCZ types (Stewart and Oke, 2012;

2.4. Extension of model simulations

PLAN:

The main goal of the project is to simulate the effect of climate changes in urban scale for several cities in the Carpathian Basin. For the selected study areas we plan to simulate the climate indices for the reference period (1981-2010) and for two future cases of 2021-2050 and 2071-2100. For the future periods we apply fifteen different regional climate simulations (five global climate models and three regional climate models) in the case of different scenarios. The results may be useful for applied climate adaptation studies moreover for climate adaptation plans of these cities.

DONE:

Unger et al. (2020) discussed some partial results of the application of different scale models by analyzing the future development of daily and evening heat load patterns by climate indices for the urban areas of Szeged, stating that the values depend on the zone types and there are more index days towards to the densely built-up LCZs. Furthermore, 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 (see *Fig. 3* in *Unger et al.* (2020)), 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.

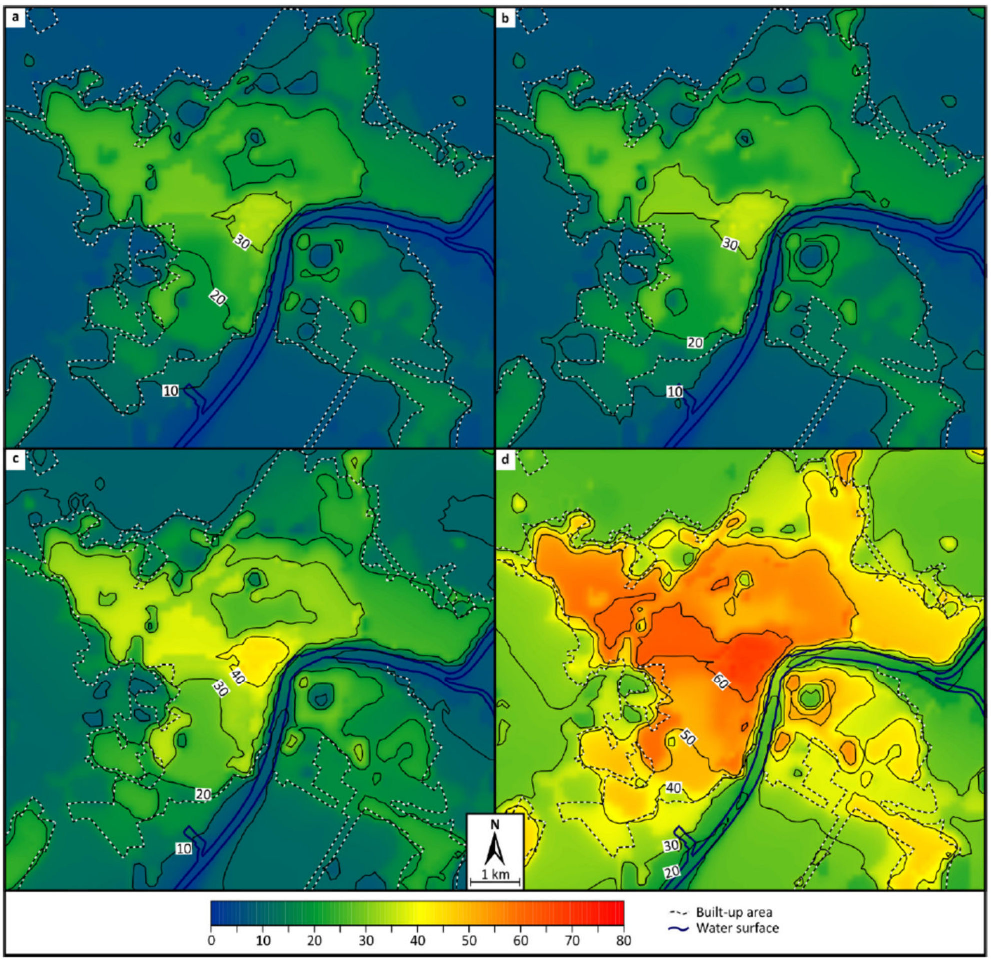

Fig. 3 Patterns of the annual number of hot days in the periods of 2021–2050 (a, b) and 2071–2100 (c, d) based on RCP4.5 (a, c) and RCP8.5 (b, d)

In *Gál et al.* (2021a) the climatic input of the applied MUKLIMO 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 two emission scenarios become distinct. In 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. To illustrate the results the authors selected five cities and analyze the thermal situations in these cities in detail (see *Fig. 3* in *Gál et al.* (2021a) as an example).

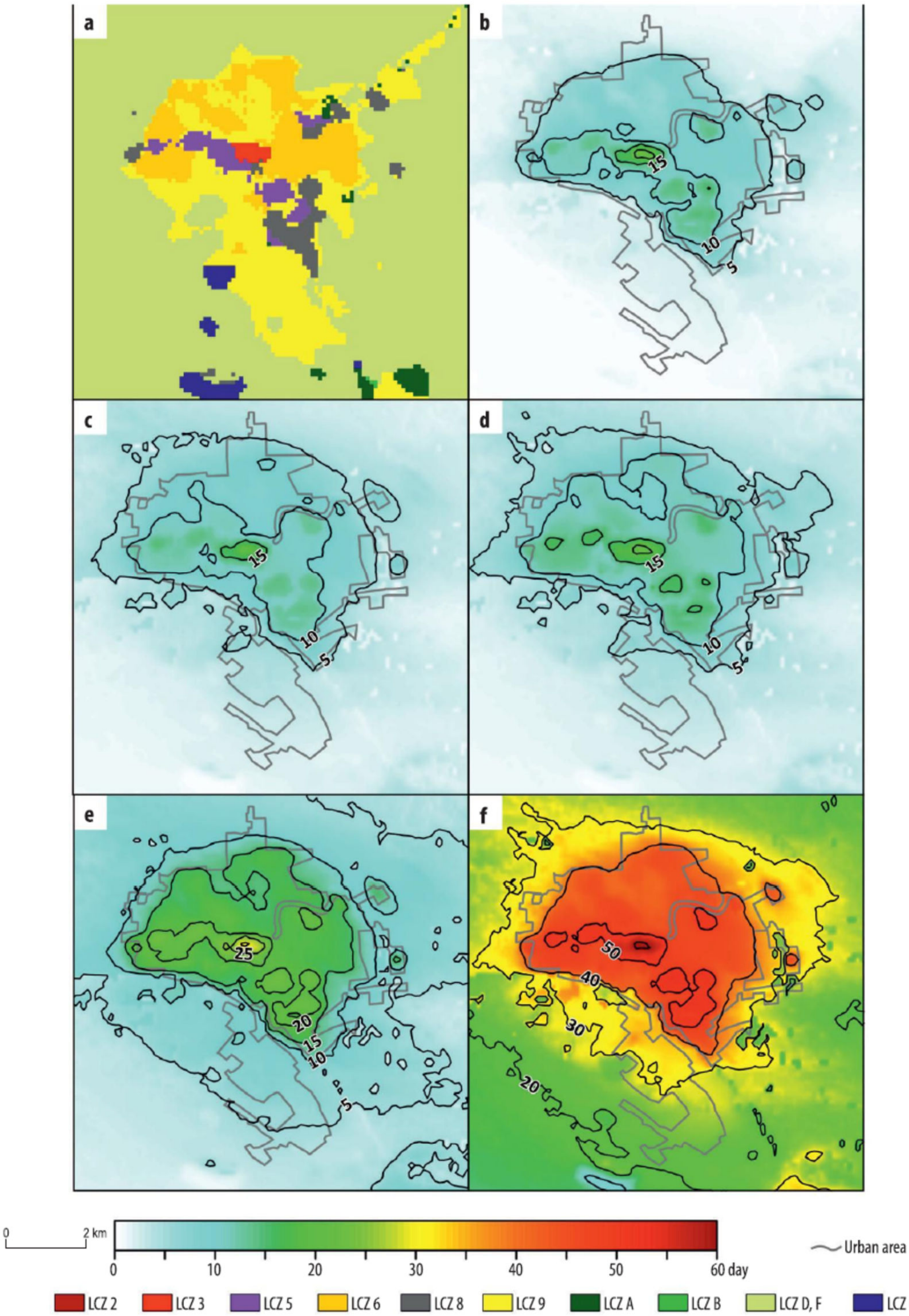

Fig. 5. LCZ map (a) and patterns of the tropical nights in Zrenjanin (Serbia) in 1981–2010 (b), in 2021–2050 by RCP4.5 (c), in 2021–2050 by RCP8.5 (d), in 2071–2100 by RCP4.5 (e) and in 2071–2100 by RCP8.5 (f). The prevailing wind directions are SE and NW.

Finally, as a fulfillment of the main objective of the project, *Unger et al.* (2021) and *Skarbit et al.* (2021) discussed the present and future urban and intra-urban scale thermal effects of climate change in the 21st century for all of the selected 26 cities in the Carpathian basin in detail.

These are 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. The results illustrate 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. *Unger et al.* (2021) and *Skarbit et al.* (2021) have made some recommendations to urban planners to reduce the expected adverse effects of climate change in urban areas.

2.5. Model experiments for the assessment of different layout of urban vegetation

PLAN:

The main goal of this step is to simulate the effect of different green area fraction, tree cover fractions and layout of urban parks on the intra-urban temperature and human comfort characteristics. The model experiment concentrates not only on the present climate (1981-2010) but the future cases of 2021-2050 and 2071-2100 as well. As an overall result of this step the optimal layout of urban green infrastructure structure can be determined, in order to help the mitigation of the effect of the urban climate and climate change.

DONE:

Gál et al. (2021b) discussed the present and future thermal effects of different types of green areas within the city on the example of Szeged. During the experiment, the thermal effects of dense trees, scattered trees, grasslands and mixed green infrastructure (see *Fig. 2* in *Gál et al.* (2021b)) has been investigated and assessed using different climate indices (number of hot days and tropical nights). The investigations encompassed 3 climatological time periods (1981-2010, 2021-2050 and 2071-2100) and two emission scenarios for future climate (RCP4.5 and RCP8.5).

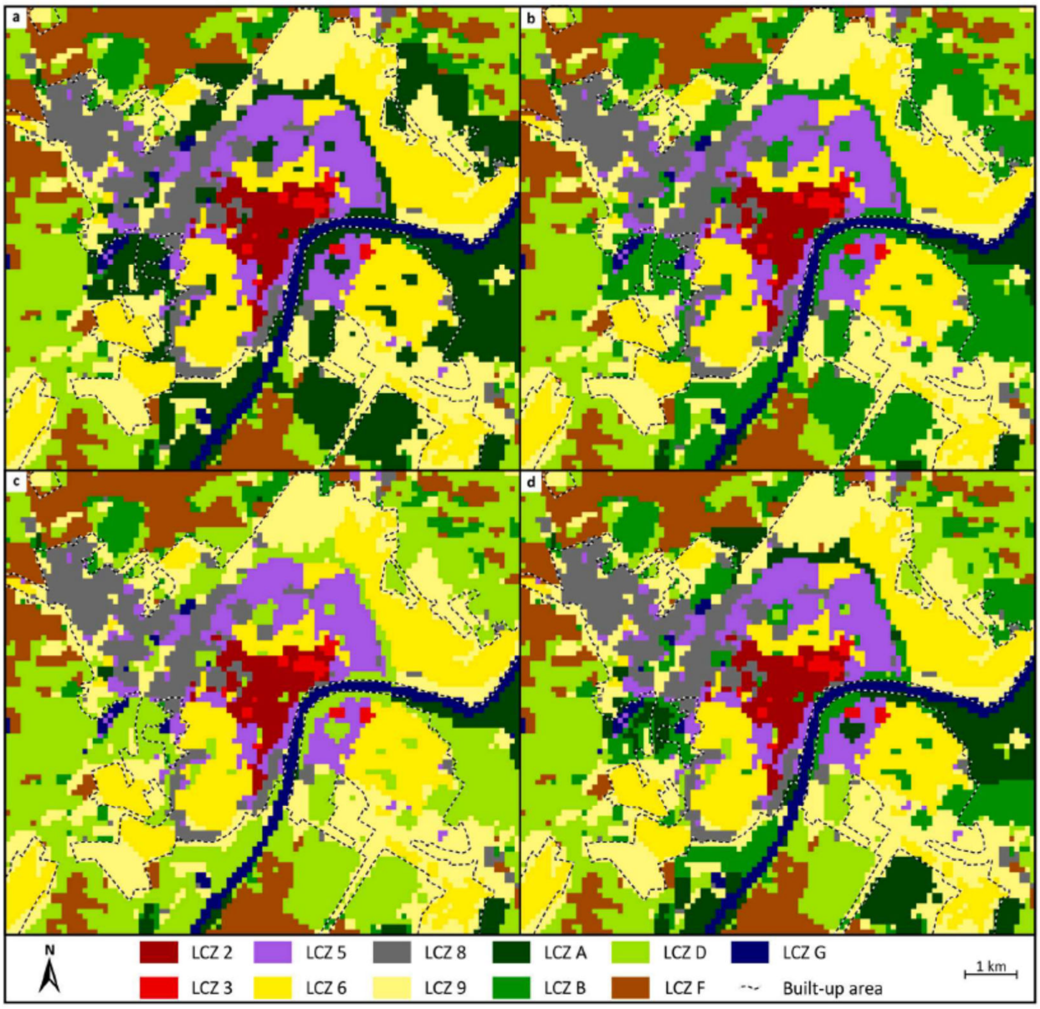

Fig. 2. Cases of modified land-use classes of Szeged using the *LCZ* classification (a – case A = dense trees, b – case B = scattered trees, c – case C = grasslands, d – case D = mixture of green spaces). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

It was found that urban green spaces (e.g. parks) generally cool the environment, although, the cooling potential of the different green types differs. The highest reduction of heat load was found in the case of large urban parks comprising of dense trees near the downtown. The spatial extension of detected cooling was found small. However, it would increase during the future, especially in the case of grasslands (see *Fig. 5* in *Gál et al.* (2021b)). For urban planners, it is highly recommended to introduce new green sites within a city and to increase the spatial extension of the existing ones to mitigate and adapt to the impacts of climate change in the urban environment.

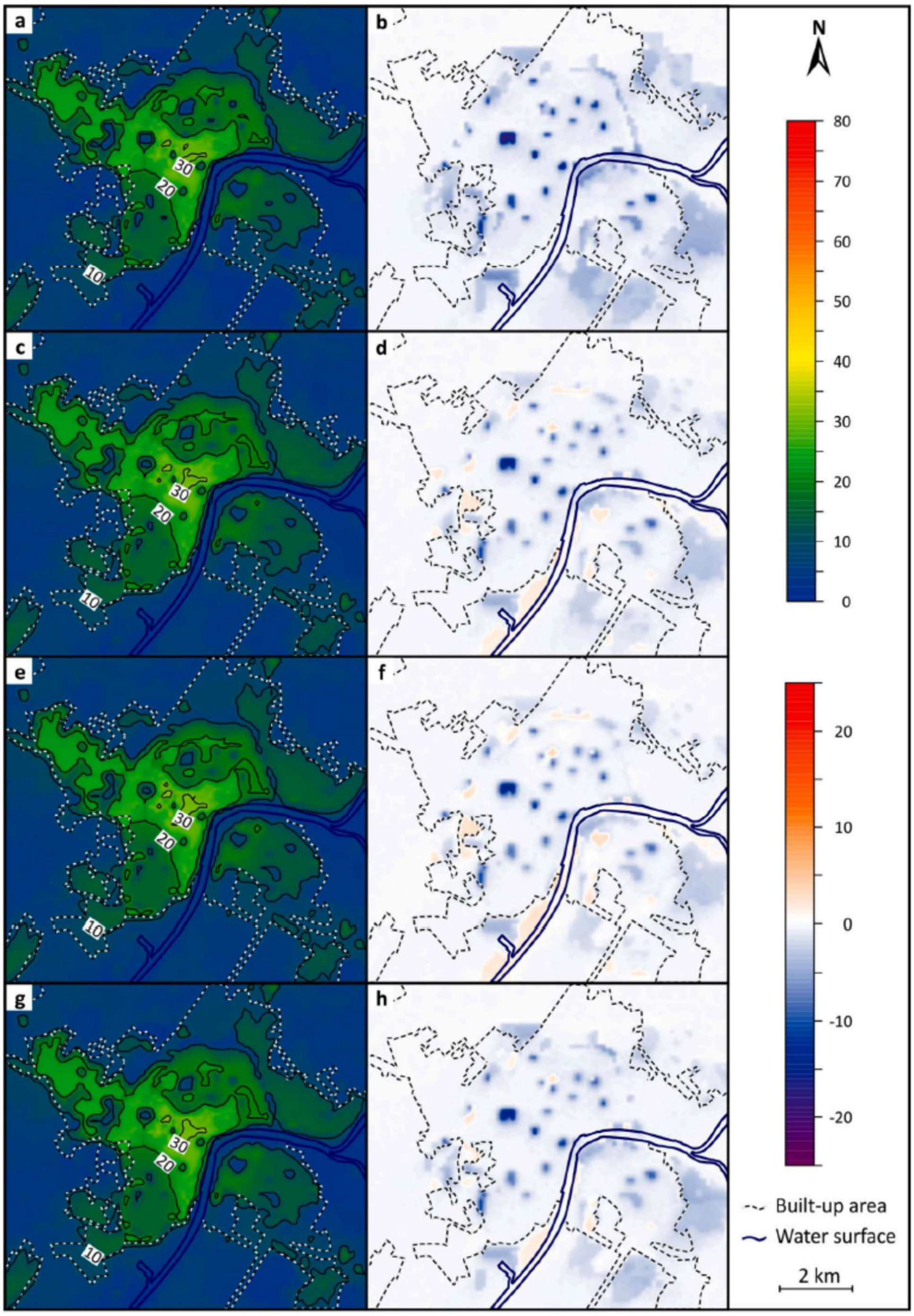

Fig. 5. Patterns of annual number of hot days in case of different scenarios (left) and the difference between the scenarios and the original case (1981–2010) (right).

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