University of Szeged
Doctoral School of Geosciences

POSSIBILITIES OF FORECASTING THE THERMAL ENVIRONMENT OF SZEGED AT URBAN SCALE USING WRF MODEL

Summary of PhD thesis

Gergely Molnár

Supervisor:

Dr. Tamás Gál
deputy head of department, associate professor

Faculty of Science and Informatics, University of Szeged
Department of Climatology and Landscape Ecology

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1. Introduction

Climate change, as one of today's greatest environmental challenges, is exacerbated in urban areas. The synergy of the special urban (local) and regional climate contributes to the increase of heat load, air pollution and energy consumption, as well as to the decrease of biodiversity and drinking water quality in densely built-up areas. From the beginning of the 21st century, the urban way of life has become dominant on Earth, and various estimates agree that the population of settlements will show further growth in the forthcoming decades. All this means that a greater population has to cope with and adapt to the environmental problems affecting cities.

Recognizing the critical nature of the situation, the UN determined 17 global sustainability development goals in 2015, including the "Sustainable Cities and Communities". The sub-goals include, but are not limited to, the reduction of air pollution and the development of green-blue infrastructure. Achieving the targets is extremely crucial. As the more than 30 000 deaths during the 2003 European heatwave have shown, the vulnerability of urban areas to a growing number of extreme weather events is very significant.

Forecasting and responding to the climatological and ecological problems, therefore, requires increasingly urgent solutions from decision-makers. The responds are usually preceded by well-organized scientific analysis. This analysis can be carried out with dense measurement networks, remote sensing techniques or numerical meteorological models. The advantage of modeling over other methods is that it allows continuous conduction in space and time. Additionally, it is suitable for testing hypotheses, and not only for assessing the current situation, but also for estimating the future state of the environment. Owe to the continuous development of information technology, meteorological models are becoming a tool of increasing number of research.

One of the most common representatives of these models is the Weather Research and Forecasting (WRF), which is based on extensive development experience, is open source, very well documented, and can be flexibly applied to most environmental problems. The diversity of the WRF is indicated by the fact that, it is not only capable of simulating individual periods (i.e. case studies), but also estimating the future state of the atmosphere. The model also guarantees the analysis of the interactions between the urban surface and the atmosphere through its abundant parameterization options.

Szeged is an ideal study area for urban climate modeling, as its extent, built-up rate and anthropogenic activity are sufficient to modify meteorological variables. The geographical location and homogeneous topography of the settlement favour the evolution of the spatial differences of environmental parameters. Accurate observation of this contrast is supported by the urban climate measurement network established in 2014 by our Department. The measured variables can be applicable to the analysis of air temperature and relative humidity time series, and also ensures the verification of modeled outputs. A three-dimensional building database is also available for local research to provide more information on the relationship between surface morphology and air temperature/humidity.

Up to now, there has been only a little emphasis on the short-term numerical modeling of the thermal environment of Szeged on local scale. Therefore, my doctoral dissertation will concentrate on developing a WRF-based modeling system that is able to simulate and forecast (only for short-term) the local weather modification in Szeged. I intended to achieve my goals with the following steps:

I. revision of the WRF static database and, if necessary, modification of the related data according to the local conditions;
II. define the fixed and variable elements of the model configuration;
III. compile sensitivity studies to test the configurations over shorter simulation periods;
IV. evaluate the best settings of the model over a longer simulation period;
V. identify the future development directions of the outlined forecasting model system and formulate the possibility of its adaptation to other urban areas.

2. Databases and research methods

My doctoral research consist of two major steps: the preparation of basic modeling databases and the verification of simulations. The first, multi-step phase was based on the recognition that the soil distribution of Szeged and the surrounding areas appeared inaccurately and significantly simplified in the WRF default static databases. In addition to the soil texture, this problem also affected the data on the urban land cover and geometrical/thermodynamic canopy parameters. It was therefore necessary to update the static and dynamic databases of the model to be able to produce reliable modeling results.

The new soil classes were transferred to the model using the existing, domestically developed DKSIS data. The increased spatial heterogeneity of the default urban land use classes was achieved by two methods. In one of the procedures, I assigned training areas on Landsat-8 satellite images, and then performed maximum likelihood classification on the images. At the end of this process, I have created a database separating three different urban surface categories. I supplemented this procedure with an LCZ dataset being elaborated by my colleagues. Since the WRF was not initially able to handle ten urban categories of LCZ classification, I had to modify the specified physical parameterization modules in the model written in the Fortran programming language.

The specification of geometric surface parameters of Szeged was based on a three-dimensional building database. The shapefiles of the building stock were processed by QGIS software. The estimation of the relevant thermodynamic variables of local buildings and roads was preceded by the delimitation of the study areas representing the buildings in the given LCZ. The latter procedure required knowledge of the building materials of the artificial surface elements over the study areas, which I approached by processing Google Earth satellite images and fieldwork photos. As a result of the aforementioned methods, I modified approximately 90 default geometric and thermodynamic urban canopy parameters.

I increased the number of the modified variables with the anthropogenic heat flux. I have compiled this dynamic database by adapting a global anthropogenic heat model and a regression method, and by considering the default values of the LCZ concept. The adaptation relied significantly on the distribution of population density in Szeged, which I have derived from the election data on constituencies from 2018. The methods also required knowledge of the dynamics of transport and residential energy consumption. For this, I applied data sources published by Hungarian utilities. The input data thus obtained were processed and the necessary calculations were performed with a Fortran program compiled for this purpose.

The dynamic database also includes the data tables of the local urban climate measurements and the upper atmospheric observations of the Hungarian Meteorological Service (HMS). I have used for an extensive data assimilation process. To do this, the measured variables found in text files were converted into the so-called LittleR format using a self-written bash script. Then, before starting the three-dimensional variational data assimilation procedure, I have developed a detailed assimilation strategy optimized for the characteristics of the study area.

The initialization of the simulations was preceded by the selection of model settings (e.g., horizontal grid spacing, number and position of model ranges) and parameterization packages (e.g., radiation, boundary layer, microphysics) that were later considered unchanged. I determined them partly on the basis of literature and partly after consulting international researchers.

By changing the non-fixed model settings, I compiled four sensitivity studies that consisted of additional modeling experiments. I have performed these simulations for two timeframes. The two modeling periods, which covered days with significant thermal modification of the urban surface, were defined by calculating the weather factor widely used in the literature. I have also tested the modeling system for a period with changing synoptic patterns. I selected this two-week period after analysing the data found in the "Napijelentés-kiadvány" of HMS. The modeling system compiled for forecasting purposed was optimized by detailed verification of the modeled near-surface air temperature. The verification metrics included in the study reflect the statistical measures most commonly used in the literature.

The modification of the static and dynamic databases was relied the QGIS, ERDAS IMAGINE, ArcGIS, and SAGA GIS softwares. The simulated variables were processed with scripts written in Fortran and Python programming languages. Additionally, GrAds, NCL, Python scripts, and the graphical toolkit of the Gnuplot package and CorelDRAW helped me to visualize the outputs of the WRF.

3. Results and conclusions

I. I recognized that the development of the WRF default static database is necessary before starting the simulations (*Molnár et al., 2017*; *Molnár et al., 2019b*).

1. After exporting and displaying the soil texture and land cover binaries found in the WRF WPS_GEOG directory, I came to the conclusion that the spatial distribution of soil classes and

urban surface categories in Szeged and in the narrower environment of the settlement does not correspond to the real conditions. Since the correct representation of static data is essential for modeling the thermal environment of an urban area with adequate accuracy, I considered the modification of these elements of the static database important to achieve my objectives.

2. Following the literature, I have also found necessary to review the static parameters related to the soil texture and artificial land cover categories. It was particularly important, because these default parameters were determined by international soil samples and urban surfaces, and therefore they did not reflect less the conditions characterizing Szeged.

II. Due to the specific properties of the study area, I have modified some elements of the WRF's static databases (*Molnár et al., 2017*; *Molnár et al., 2019a*; *Molnár et al., 2019b*).

1. By designating ROIs, I have performed a supervised surface classification on Landsat-8 satellite images. As a result, instead of one default, three different urban land cover categories were available to characterize the artificial surface elements in the study area. In the CORINE database, I have replaced the pixels of the artificial land use classes with this new categorization. By doing this, I have created a database that was already capable of replacing the default urban land cover data.
2. I have implemented an LCZ maps created by the staff of the Department into the model, which resulted in a more reliable surface coverage database distinguishing five urban classes within the city. During the implementation, I also modified the code snippets for each of the WRF physical packages, making the model compatible with the LCZ classification.
3. Using a three-dimensional building database from 2003 and remotely sensed data, I determined geometric parameters for the urban categories of the modified CORINE and LCZ-based land use databases. After making analysis with GIS tools, I have assigned a total of 18 (12) new values to the former (latter) database.

4. For the LCZ classes I defined not only geometric but also thermodynamic parameters. During the procedure based on images retrieved from satellite data and taken on field trips, I estimated the thermal capacity, thermal conductivity, and emissivity of walls, roofs, and roads. Using this method, I have derived a total of 54 new values.

III. I estimated the spatial and temporal variability of the anthropogenic heat flux of Szeged using three different methods (*Molnár et al., 2020*).

1. Based on the literature, I recognized that neglecting anthropogenic heat flux would damage the physical consistency of the model. In order to determine this parameter for Szeged, I applied the LCZ concept, the equations of the LUCY model and a regression method. The methods were based on knowledge of the local dynamics of transport and household energy consumption. I estimated this information with national-level data from energy utilities and point measurements of traffic.
2. The corresponding calculations were largely based on the areal distribution of the population of Szeged. In the absence of good quality, freely available population data, I predicted the spatiality of the population through political election data. The obtained pattern responded well to the large population of the housing estate area of Szeged and the decrease of the population towards the suburbs.
3. I found that there is a strong relationship between the population and the spatial distribution of the calculated heat flux in Szeged. With each estimate, I found that the anthropogenic heat output of the winter days is higher than that of the summer days. Regarding the daily course of the heat flux, I have shown that due to transport and energy use habits, an early morning and a late afternoon maximum emerges (i.e., bimodal distribution).

IV. I have developed a WRF-based data assimilation method for Szeged based on the surface and upper atmospheric measurements of HMS and the local urban climate monitoring system (*Molnár et al., 2018*).

1. As part of the 3DVAR data assimilation procedure, I recognized that due to the coverage of the measurement stations, I needed to use a hybrid method consisting of GFS model outputs and the assimilated observations. I have compiled a bash script that harmonizes the measured data with the temporal resolution of the default GFS data and converts the measured variables from surface stations and radiosonde to LittleR format required in WRDA only for the predefined time frame.

V. I tested the sensitivity of the model to land cover data, urban canopy schemes, anthropogenic heat, and meteorological input data through four experiment groups *(Molnár et al., 2019a*; *Molnár et al., 2019b*; *Molnár et al., 2020*).

1. In the first sensitivity study for land cover databases, I found that the best performance of the model can be achieved with LCZ-based urban classes and their associated canopy parameters. At the same time, I have also shown that increasing the complexity of the artificial surfaces in the model has a positive effect on the verification results during the selected simulation periods.
2. In the second sensitivity test for roof level schemes, I found that the best performance of the model was carried out with the $SLUCM_{WRF}$ parameterization during the selected simulation periods. Additionally, I concluded that increasing the complexity of the schemes did not result in a proportional improvement in the verification metrics due to the applied 1.5 km horizontal resolution.
3. In the third sensitivity study on anthropogenic heat release, I found that the anthropogenic activity in Szeged is high enough to alter the modeled variables (e.g. temperature, flow rate, turbulent kinetic energy) near the surface and within the urban boundary layer. I have also shown that this change can be greatest during the winter days. Based on the results, I also found that the relationship between the intensity of anthropogenic heat release and the generated heat surplus is non-linear.
4. In the fourth sensitivity study for the meteorological input data, I found that there was no improvement in the verification results of the simulated near-surface temperature on the winter days as a result of the applied data assimilation. In the data assimilation

run, biases increased mostly at the assimilation steps of three-hour frequency. From this, I concluded that modeling errors can be mitigated by increasing the assimilation steps and refining the hybrid assimilation procedure.

VI. **I selected and tested the model configurations with which the thermal environment of Szeged can be optimally forecasted** (*Molnár et al., 2019a; Molnár et al., 2020*).

1. After the experience of the sensitivity studies, I was able to select the non-fixed settings for land cover, urban canopy layer parameterization schemes, anthropogenic heat flux and meteorological input data that can form the framework of an operational meteorological model designed for urban-scale forecasting.
2. I tested the model settings for a two-week long, contiguous period with dynamically varying synoptic pattern. During the verification of the near-sufrace temperature and other relevant meteorological variables, I found that the modeling system captures well the changes of weather condition, however, the simulation of precipitation and cloud cover needs to be improved. I also made it clear that additional testing periods are necessary to be examined to identify further shortcomings of the compiled modeling system.

VII. **I made a proposal on how to transfer the modeling system adapted to Szeged to another urban area.**

1. I determined the degrees of freedom of the model settings that can be considered when the modeling system is intended to apply in other urban area with similar accuracy. With a decision tree flowchart, I also determined the steps by which re-adaptation can be performed. Additionally, I highlighted those stages that can be eliminated or added to present ones, depending on the data availability.
2. I highlighted the potential applications of the modeling system and pointed out the areas that could benefit from the urban-scale forecasting of temperature and other modelled outputs.

Publications related to the thesis points

1. **Molnár G**, Kovács A, Gál T (2020): How does anthropogenic heating affect the thermal environment in a medium-sized Central European city. A case study in Szeged, Hungary. *Urban Clim 34*, 100673. (Q1; IF_{2020}: 3,834)

2. **Molnár G**, Gyöngyösi AZ, Gál T (2019a): Integration of an LCZ-based classification into WRF to assess the intra-urban temperature pattern under a heatwave period in Szeged, Hungary. *Theor Appl Climatol 138*, 1139–1158. (Q2; IF_{2019}: 2,882)

3. **Molnár G**, Gyöngyösi AZ, Gál T (2019b): Modeling of urban heat island using adjusted static database. *Időjárás 123*, 371–390. (Q4; IF_{2019}: 0,277)

4. **Molnár G**, Gyöngyösi AZ, Gál T (2018): Evaluation of a WRF-LCZ system in simulating urban effects under non-ideal synoptic patterns. *Acta Clim Chorol Univ Szegediensis 51–52*, 57–73.

5. **Molnár G**, Gyöngyösi AZ, Gál T (2017): A városi hősziget vizsgálata meteorológiai modell segítségével Szeged. *Légkör 62*, 130–135.