Assessment of climate change impacts in Hungary with regional climate model simulations and development of a representative climate database

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KLIMADAT

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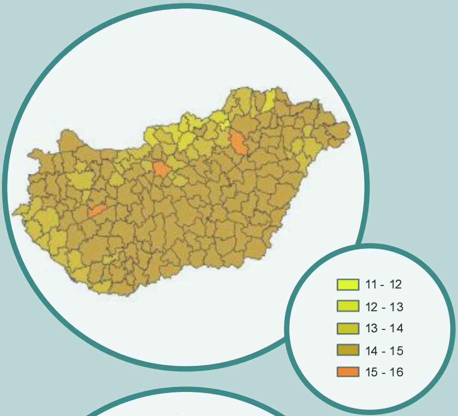
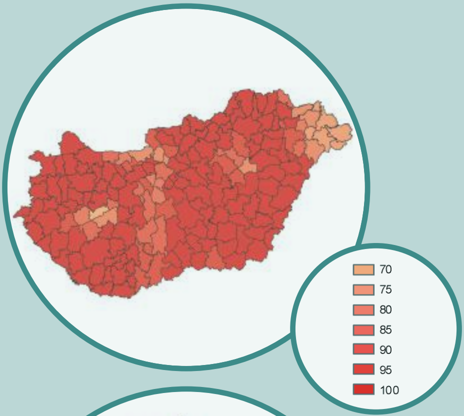
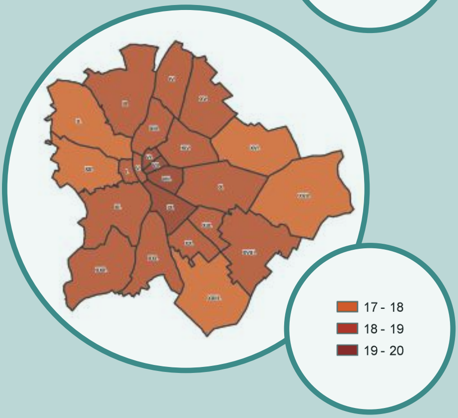
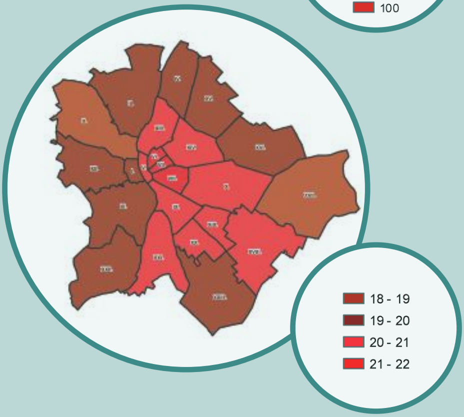
The figure on the front and inside cover:
Top left: July mean daily minimum temperature (°C) for LAU1 regions in Hungary in 1971–2000 based on measurements; top right: probability (%) of temperature increase from 1971–2000 to 2071–2100 greater than 2 °C based on results of 4 regional climate model simulations; bottom left/right: expected lowest/highest value of July mean daily minimum temperature (°C) in 2071–2100 for districts in Budapest based on results of 2 surface model simulations.









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Summary of the KlimAdat project

Executive summary

The adaptation to climate change requires information about the observed and projected meteorological changes. These data need to be collected in a common information system, which is accesible and easy to use by the members of the adaptation process. According to the World Meteorological Organization, the strong and continuous collaboration between the climate information producers and users is of key importance and the user needs should be taken into account already at the beginning of building the information system. In the KlimAdat project, a climate database and application has been developed based on detailed measurements and regional climate projections of the Hungarian Meteorological Service (OMSZ), following the abovementioned aspects.

The state of the climate in Hungary is assessed on the base of **gridded measurements**, that is also used for climate model validation. The former measurement dataset of OMSZ contained daily data of the most important meteorological variables on 10 km horizontal resolution for the period of 1961–2010. This dataset has been extended beyond 2010 using as many observations as it was available. Moreover, 6-hourly temperature and precipitation datasets have been elaborated as well.

New **regional climate projections** have been achieved with the ALADIN and REMO models for Central and Eastern Europe on 10 km horizontal resolution. The future anthropogenic activity was prescribed according to two scenarios supposing medium and high emission. Based on the ALADIN's projections, the climate change impacts in cities were investigated using the **SURFEX land surface model**.

These scientific developments were supported by **technological investments**. Acquisition of a new high performance computer and the expansion of the data storage system needed to perform the climate simulations in time. The **KLIMADAT geo-information system** (GIS) has been developed on the base of GIS software supported by an external contractor.

The meteorological data prepared in the project serve climate impact studies, adaptation planning and decision making. In order to fulfill the user needs at its best, several **workshops** were organized to ensure the continuous dialogue between the data providers and users. A **guidance** was also prepared about the interpretation and usage of climate model data.

1. Project goals

In order to assess the present climate of Hungary and validate the climate models, **gridded observational data** are needed. In the previous years, the Hungarian Meteorological Service developed a detailed gridded dataset in the frame of the CARPATCLIM[1] and NAGiS[2] projects. This dataset contains daily data of the most important meteorological variables on 10 km (0.1°) horizontal resolution for the period of 1961–2010. The upgrade of the database was necessary: on the one hand, its extension to the present day in order to continuously monitor the climate change; on the other hand, its refinements with sub-daily temperature and precipitation data in order to use them for detailed intra-day climate model validation.

To investigate the future climate change in Hungary, two **regional climate models** (RCMs), ALADIN-Climate and REMO are applied at OMSZ. The projections of these models supported several climate impact studies in the frame of national and international collaborations in the past 15 years. In the beginning, the models were applied on 10-25 km horizontal resolution covering the Carpathian Basin.

The future anthropogenic activity was described according to the medium emission scenario of the SRES family considered in the 3rd and 4th Assessment Report of the IPCC. This projection set consisting of two simulations needed to be further developed from several aspects. On the one hand, the model results covering only the Carpathian Basin could not support impact studies targeting the Danube Catchment Area. On the other hand, long-term adaptation strategies cannot build upon only one anthropogenic scenario.

In the KlimAdat project the following goals were envisaged (Fig. 1):

- Extending the **gridded observational dataset** beyond 2010 and refining its temporal frequency from daily to 6-hourly.

- Running **climate projections** with the new versions of the ALADIN-Climate and REMO RCMs over the Danube Catchment Area on 10 km horizontal resolution considering two anthropogenic scenarios.

[1] Climate of the Carpathian Region; 2010–2012, www.carpatclim-eu.org
[2] The National Adaptation Geo-Information System, EEA-C11-1 project; 2013–2016, https://nater.mbfsz.gov.hu/en

- Executing **simulations using the SURFEX land surface model** on 1 km horizontal resolution to assess the climate change impacts in cities.

- Thorough **assessment of the model results** and development of **post-processing methods**: defining indices that support adaptation planning and decision making, taking into account the climate projection uncertainties in the impact studies.

- Elaboration of a web-based **geo-information system**.

- Assessment of the **user needs**; **user education** on the usage of climate model outputs.

- **IT developments** to support the above-mentioned goals.

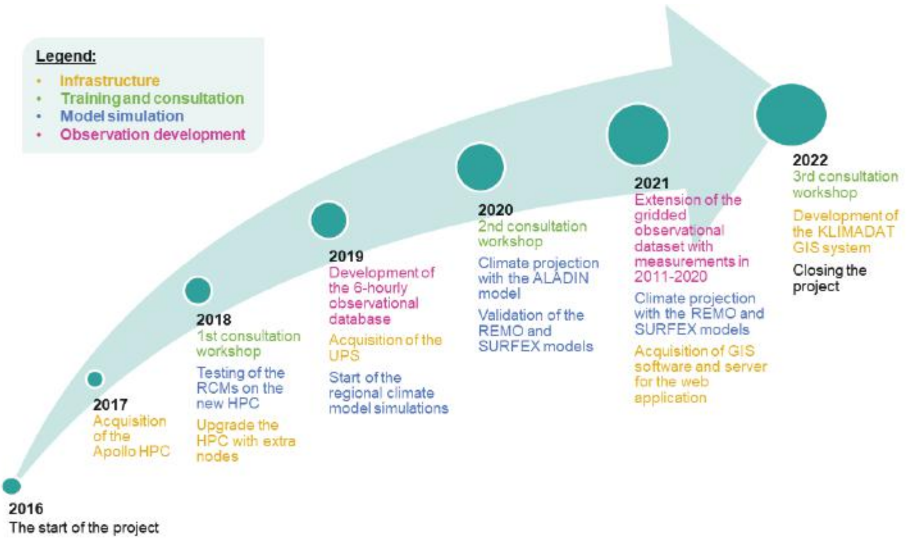

Fig. 1. Milestones in the KlimAdat project.

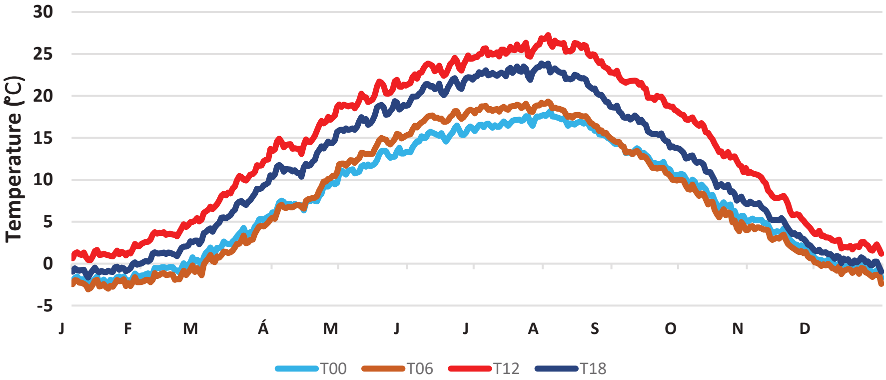

Fig. 2. Hourly temperature averages by day for the period of 1971–2000 and for Hungary.

2. Results

2.1. Methodological improvements to the observation dataset

Methodological improvements have been made to continuously monitor climate change and to study the intraday patterns of temperature and precipitation. **To study intraday characteristics**, the daily grid point observation database had to be refined in time. We have four daily measurements for 58 stations since 1970 and for 89 stations since 1997 for temperature and precipitation, respectively. Using these, and by **further development of the MASH and MISH software**, we have produced a 6-hourly (0, 6, 12, 18 UTC) grid point observation database for the area covering Hungary with 1233 grid points, for temperature (*Fig. 2*) over the period 1971–2020 and for precipitation over the period 1997–2020.

The **six-hourly temperature** series are highly inhomogeneous, and their inhomogeneities are not the same as the daily series, i.e., we cannot neglect the daily trend for inhomogeneities. To develop the interpolation methodology, we modified the spatial trend values for the daily values using regression coefficients between daily and hourly values (*Szentimrey*, 2019).

The **six-hourly precipitation** sum data series are less inhomogeneous due to the shorter period, so we performed a slight homogenization for the hourly data series and applied the procedure for the daily sum in the absence of a daily run to interpolate the hourly data series.

These improvements resulted in the **HuClim observational database** (*Izsák et al.*, 2022) by the end of the project. The HuClim was built using the largest and most detailed station dataset possible, making it the most accurate database on the climate of Hungary for both model validation and monitoring of past climate change.

2.2. Regional climate modelling

To investigate future climate change in Hungary, simulations were carried out with the **ALADIN-Climate and REMO regional climate models** for a domain covering Central and Eastern Europe with a horizontal grid resolution of 10 km.

REMO was upgraded to the 2015 version and a **sensitivity study** was performed to define its integration domain for further experiments (*Suga et al.*, 2020). The results of the following evaluation and control simulations were **validated** with the homogenized and interpolated CarpatClim-HU observation database for the period of 1981–2000 to assess the accuracy of the model in terms of reproducing the past climate. The validation results of REMO were compared with the results of ALADIN-Climate version 5.2 (*Bán et al.*, 2021).

In climate simulations for the future, the influence of human activity must be taken into account in addition to natural climate forcings. Different scenarios are used for this purpose to describe the possible future path of greenhouse gas and aerosol concentrations. Three **climate projections** have been prepared in the framework of the project with two RCMs and two RCP scenarios based on radiative forcing changes: two simulations were achieved with REMO considering the medium (RCP4.5) and high (RCP8.5) emission scenarios, and the preceding

Table 1. Simulation set-up of the ALADIN and REMO models.

Model	Boundary condition	Resolution	Period	Scenario
ALADIN	CNRM-CM5	10 km	1951–2100	RCP4.5
ALADIN	CNRM-CM5	10 km	1951–2100	RCP8.5
REMO	MPI-ESM_LR	10 km	1951–2100	RCP4.5
REMO	MPI-ESM_LR	10 km	1951–2100	RCP8.5

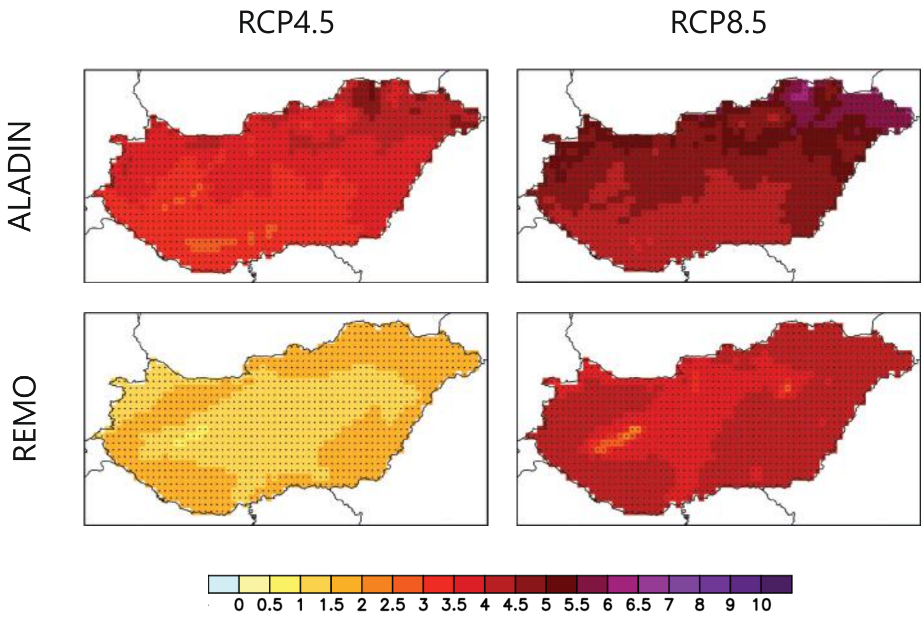

Fig. 3. Winter mean temperature change (°C) in Hungary for 2071–2100 based on the four RCM simulations. Reference period: 1971–2000.

ALADIN-Climate projection forced by RCP8.5 was completed with the RCP4.5 scenario. The four simulations (*Table 1*) show the uncertainty arising from both scenario and model selections. The results were evaluated for 2021–2050 and 2071–2100, and the future changes were compared with the characteristics of the 1971–2000 period (*Megyeri-Korotaj et al.*, 2022).

Based on the results, **mean temperature increase** of less than 2 °C is expected in Hungary in 2021–2050, which is significant (i.e. the change exceeds the natural variability) for the whole country. By the end of the century, the increase averaged over Hungary is expected between 1.6 and 4 °C, and the impact of different scenarios is clearly visible: the highest warming is obtained in the experiments with RCP8.5. **The largest changes are projected in summer and winter**, with a considerable spatial variation in winter: two model simulations show stronger warming over northern Hungary (4-5 °C by the end of the century), while two simulations project larger changes in the western and eastern parts of the country (*Fig. 3*). The number of frost days (when daily minimum temperature is below 0 °C) may decrease substantially by the end of the century, with a spatial average up to 78%, while the number of hot days (when daily maximum temperature reaches 30 °C) may increase by 6-27 days.

The projections show **precipitation** increase over Hungary in spring, autumn and winter, but in summer, two model simulations project an increase from the beginning of the century and two ones show a decrease, with a degree around 20% by the end of the century (*Fig. 4*). In 2021–2050, the number of wet days (when daily precipitation reaches 1 mm) increases in all seasons except summer, while the direction of

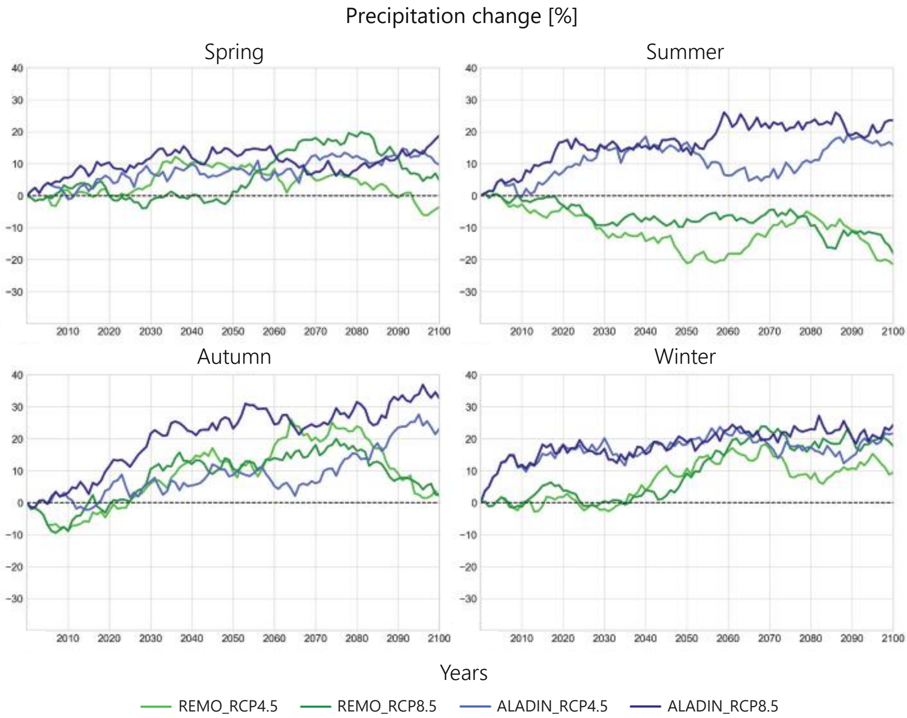

Fig. 4. The 30-year moving average of the seasonal mean precipitation change (%) in Hungary based on the four RCM simulations. Reference period: 1971–2000.

change is uncertain in summer. Despite the uncertainty in summer, the longest dry periods (when daily precipitation is below 1 mm) tend to become 3-4 days longer, and more events with daily precipitation sum above 10 mm will occur by the end of the century. This implies a **more uneven distribution of precipitation within a year**.

2.3. Urban climate modelling

The results of the ALADIN regional climate model have been refined with the **SURFEX land surface model over Budapest** on 1 km horizontal resolution, to investigate the impact of climate change on the cities (*Table 2*). Similarly to the regional climate modelling steps, the future urban climate projections were preceded by the **model validation**, where the interaction of the RCM and the land surface model was assessed (*Zsebeházi*, 2020; *Zsebeházi and Szépszó*, 2020; *Zsebeházi and Mahó*, 2021). Afterwards, using the ALADIN projections as input, two simulations were achieved for Budapest based on the RCP4.5 and RCP8.5 scenarios (*Allaga-Zsebeházi*, 2021a,b). Therefore, these urban climate projections provide information about the **scenario uncertainties**. They cover the period of 1961–2100 and the results were evaluated considering the 1971–2000 period as reference.

Over the city, **winter may warm the most** (the magnitude of the change is 1.6-1.9 °C in 2021–2050 and 3.2-4.3 °C in 2071–2100), while the transient seasons (spring and autumn) may be subjected to moderate temperature increase. Differences in warming between the urban and rural areas are seen only at the end of the century in spring and summer: extreme high temperature values may increase in the future independently of the land cover, and the built-in areas will be warmer than the surrounding natural areas in the future as well. However, the rural areas may warm to a greater extent (with 0.5 °C) compared to the city.

As a result, especially in spring and summer **the nocturnal urban heat island**

Table 2. Simulation set-up of the SURFEX land surface model.

Urban model	Atmospheric forcings	Horizontal resolution	Period	Scenario
SURFEX/TEB	ALADIN	1 km	1971–2100	RCP4.5
SURFEX/TEB	ALADIN	1 km	1971–2100	RCP8.5

(the temperature difference between the urban and rural areas) **may be weaker**.

The number of heatwave days (when the daily average temperature reaches 25 °C) in 2021–2050 may increase with 39-43% in Budapest (*Fig*. *5*), while the frequency of frost days (when the daily minimum temperature is below 0 °C) may lessen, and its relative decrease is higher in the urban areas. Those days when the minimum temperature is lower than -10 °C may cease at the end of the century in Budapest.

2.4. The KLIMADAT application

The **regional and urban information** produced from measurements and simulation data can be visualized in **maps and graphs** using the KLIMADAT application. It is accessible at **https://klimadat.met.hu**. Currently, 22 regional and 11 urban climate variables are calculated for temperature and precipitation. In addition to annual means, seasonal means are derived for precipitation indicators and monthly means are also computed for

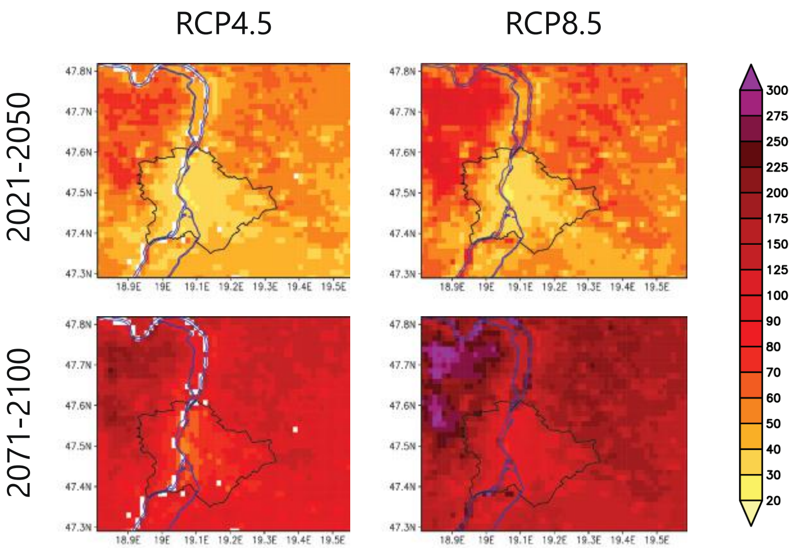

Fig. 5. Relative change (%) of the heatwave days (when daily average temperature reaches 25 °C) in 2021–2050 and 2071–2100 based on SURFEX simulations considering the RCP4.5 and RCP8.5 scenarios. Reference period: 1971–2000.

some parameters. In climate studies, characteristics and changes are investigated along multiple decades, thus 30-year periods with 10-year shift can be selected from the time range covering 1971–2100.

Source of the information varies by the selected time interval. The **measurements** are available for periods of 1971–2000, 1981–2010 and 1991–2020. The data in the maps for Hungary are calculated with interpolation of the homogenized station series to a 0.1-degree resolution grid. The city maps are prepared combining the 0.1-degree resolution measurements and the urban heat island values provided by the 0.01-degree resolution surface simulations. Information from 2001–2030 to 2071–2100 are based on the results of 4 regional and 2 surface climate model simulations (*Tables 1* and *2*). **Assessment of projection uncertainties** is crucial to interpret the model results and it is supported by special visualization techniques. The **quantile-based maps and graphs** show the expected minimum, maximum or median values of the given indicator based on the available simulation results. The **regional probability maps** estimate the likelihood that the future change exceeds a certain threshold. (The cover figure shows some results for the daily minimum temperature in July.)

The climate indicators can be displayed for several **pre-defined regions**. In addition to the grid point values over Hungary, averages for NUT3 and LAU1 regions can be visualized. In city maps, data are available currently for Budapest, either as grid point values or averages for districts. The maps and the graphs can be saved in PDF and georeferenced TIFF formats.

3. Communication with the users

In the previous years, we have established a solid partner network that we intended to expand in the project. To inform our users about the project milestones and results, three consultation workshops were organized. In these events we trained our users about the usage and limitations of the model results and assessed their requirements on the KLIMADAT database and visualization system.

The **first workshop** was organized on 7 December 2018 at the headquarters of OMSZ. After presenting the scientific goals of the project, some partners shared their experiences on working with regional climate model results in their impact studies, the challenges they face and the synergies they see.

Photos taken at the first consultation workshop.

The participants had opportunity also to phrase their desires for the climate database.

In the **second workshop** held on 14 February 2020, we informed the participants about the progress, and two guest presenters introduced the Copernicus Climate Change Service (C3S) and the impact of using bias corrected regional climate model results in an ecosystem model. In an interactive session the attendants formed small teams based on their 'role' in climate adaptation and explored some existing climate databases (e.g., the C3S Climate Data Store and NAGiS) whether the available data and information may fulfill their needs. They examined also the content, completeness and usability of these data portals.

The **third consultation workshop** held on 28 February 2022 was online due to the COVID restrictions. The main aim of this workshop was to introduce the actual version of the KLIMADAT climate data portal. The users could test its different (download, visualization etc.) functions through some typical examples, and share their experiences right at the workshop and in the following weeks as well.

The methodology that we follow in climate services is demonstrated also in a **brochure**. Climate simulations are tending to become more and more freely accessible, although their proper interpretation and usage is not straightforward and requires some background knowledge on climate modelling. The booklet shows the most important questions that are usually raised by impact researchers and adaptation planners when they request climate model data to implement them in their impact study and adaptation plan.

Photos taken at the second consultation workshop.

Link to the brochure:
https://tinyurl.com/2xessby7

4. IT infrastructure developments

In order to execute the regional climate model simulations in due time, the **high performance computer and data storage system** dedicated to climate modelling as well as the related infrastructure needed to be upgraded. Previously the climate models were run on a Lenovo Flex System x240 M5 server, which capacity was 2.5 TFLOPS (Tera FLoating-point Operation Per Second). In the frame of the project this server was updated to an HPE Apollo 6000 high performance computer, which is almost 6 times faster than its predecessor. Using the new HPC, a 150-year climate simulation with the REMO model required approximately 3 months of computing time. Note that due to the continuous post-processing and saving the results, the simulation was actually prepared approximately within 9 months.

To develop the KLIMADAT database, **GIS software and server** (dedicated to host the database and web application) were purchased. The application is based on ArcGIS software, i.e. ArcGIS Enterprise Workgroup Standard and ArcGIS Image Server Workgroup. To visualize the data, two ArcGIS Desktop licenses were acquired. The development of the application was supported by the GDi Hungary Ltd.

The Apollo HPC used for climate model simulations and its main features:

- **Capacity: 14.1 TFLOPS**
- **Number of nodes: 10**
- **Number of processors per node: 40**
- **Memory per node: 128 GB RAM**

5. Presenting the project results at national and international events

The aim of the project and its outcomes were presented at the following events:

- In 2018 at the General Assembly of the European Meteorological Society (EMS) in Budapest (Hungary).
- In 2018 at the 44th Meteorological Scientific Days entitled 'Climate change and adaptation' in Budapest (Hungary).
- In 2020 at the annual meeting of the Euro-CORDEX in Hamburg (Germany).
- In 2020 at the General Assembly of the European Geoscience Union (online).
- In 2021 at the 47th Meteorological Scientific Day entitled 'Global climate trends, national research challenges' in Budapest (Hungary).

6. Publications and project reports

Publications

Allaga-Zsebeházi, G., 2021a: Future temperature and urban heat island changes in Budapest: a comparative study based on the HMS-ALADIN and SURFEX models. *Időjárás*, 125 (4), 675–692. doi: 10.28974/idojaras.2021.4.7.

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Izsák, B., Szentimrey, T., Lakatos, M., Pongrácz, R., Szentes, O., 2022: Creation of a representative climatological database for Hungary from 1870 to 2020. *Időjárás*, 126 (1), 1–26. doi: 10.28974/idojaras.2022.1.1.

Suga, R., Megyeri-Korotaj, O. A., Allaga-Zsebeházi, G., 2021: Sensitivity study of the REMO regional climate model to domain size. *Advances in Sciences and Research*, 18, 157–167. doi: 10.5194/asr-18-157-2021.

Zsebeházi, G., Mahó, S. I., 2021: Assessment of the urban impact on surface and screen-level temperature in the ALADIN-Climate driven SURFEX land surface model for Budapest. *Atmosphere*, 12, 709. doi: 10.3390/atmos12060709.

Zsebeházi, G., Szépszó, G., 2020: Modeling the urban climate of Budapest using the SURFEX land surface model driven by the ALADIN-Climate regional climate model results. *Időjárás*, 124 (2), 191–207. doi: 10.28974/idojaras.2020.2.3.

Project reports

Allaga-Zsebeházi G., 2021b: Joint evaluation of the urban climate projections achieved with the SURFEX based on the RCP4.5 és RCP8.5 scenarios.
(in Hungarian)

Bán B., Suga R., Megyeri-Korotaj O. A., 2021: Validation of the ALADIN5.2 and REMO2015 regional climate model results.
(in Hungarian)

Megyeri-Korotaj O. A., Bán B., Suga R., 2022: Joint evaluation of the REMO2015 and ALADIN5.2 regional climate models' projection results.
(in Hungarian)

Suga R., Megyeri O. A., Zsebeházi G., 2020: Sensitivity study of the REMO regional climate model to domain size.
(in Hungarian)

Szentimrey T., 2019: Gridded observational dataset of 6-hourly station measurements.
(in Hungarian)

Zsebeházi G., 2020: Validation of the SURFEX simulations driven by the ALADIN-Climate regional climate model.
(in Hungarian)

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