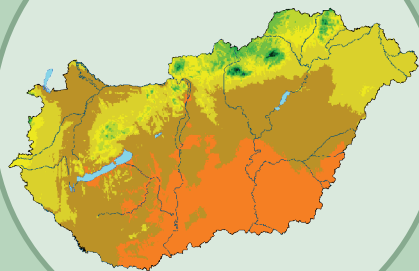
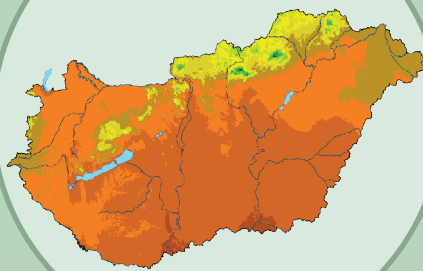


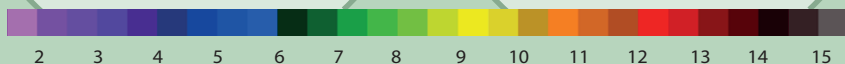
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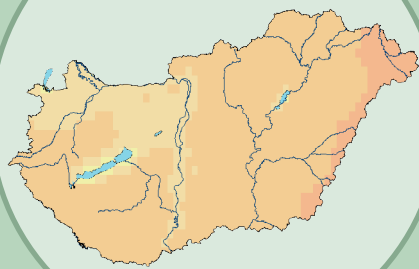
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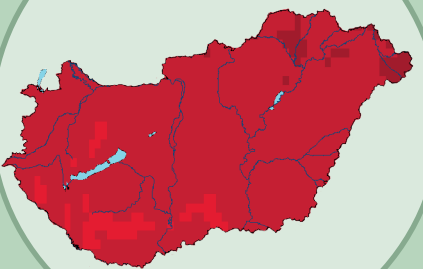
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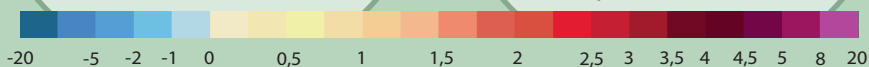
2041-2070 min



2041-2070 max



°C



# Climate Research

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*The top two maps on the cover page: Distribution of annual mean temperature in the normal periods of 1971–2000 and 1991–2020 (based on homogenized, interpolated data).*

*The bottom two maps on the cover page: The minimum and maximum expected change in annual mean temperature in the period of 2041–2070 with respect to 1971–2000 based on the results of four regional climate model simulations.*

## Introduction

Climate research is a scientific discipline concerned with the long-term investigation of the Earth's climate system. Its objective is to understand the natural and anthropogenic factors that shape our planet's climate, how it has changed in the past, and what changes can be expected in the future. The study of past and future climate conditions typically relies on surface meteorological measurements, satellite and other observational data, as well as the results of climate models.

At HungaroMet, climate research focuses on monitoring climate change in Hungary, assessing future changes, and analysing their impacts. The analysis of observed data using statistical climatological methods helps to identify and understand past and ongoing changes. The data stored in the HungaroMet archive - previously published in yearbooks and now organized in digital form - serve as the basis for this research in Hungary.

Future climate changes are projected using climate models that simulate the effects of anthropogenic forcing under different emission scenarios. These models provide projections that estimate the impacts of human activities on the climate system. At HungaroMet, simulations are conducted using several adapted regional climate models for the Central-Eastern European region. In addition, publicly available results from European regional climate modelling institutes are also utilized to ensure a comprehensive assessment of projected changes.

The results of climate research are fundamental to climate change adaptation, as they provide baseline information for impact and vulnerability assessments in climate-sensitive sectors, enable the quantification of risks, and support informed societal and economic decision making.

# Producing high quality climate data for the past and present

Meteorological observations have been conducted in Hungary for more than 150 years; however, measurement conditions have frequently changed over this period. At the same time, climate data processing and analysis require high-quality datasets with sufficient spatial and temporal resolution. Improving observational data and ensuring homogeneous spatial coverage necessitate the development of specialized mathematical methods. For the purposes of **homogenization** and **interpolation**, dedicated software tools have been developed at HungaroMet specifically for these tasks.

## Homogenization

From a mathematical statistical perspective, climate can be characterized by the probability distributions of meteorological variables at a given location. If these distributions are known, the climate of that location is effectively defined. Changes in these distributions are therefore interpreted as climate change. In this framework, past climate change can be estimated from meteorological observations, which provide the statistical samples for analysis.

Consequently, only those statistical models and methods can be applied that are capable of accounting for changes in the underlying probability distributions, i.e. changes in climate. Prior to conducting climate analyses, measurement time series must be carefully processed to remove erroneous data and non-climatic discontinuities, known as inhomogeneities. These may arise from changes in the measurement environment, observational practices, or instrumentation. This process is referred to **as homogenization**.

We apply the **MASH**<sup>1</sup> homogenization method developed at HungaroMet for data quality control, completion and homogenization. The mathematical basis of the software ensures that measurements are adjusted in a way that preserves the signal of climate change. Time series are always standardized to present-day conditions, meaning that past observations are corrected as if they had been measured at the same time, at the same location, and with the same instrumentation as in the present.

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<sup>1</sup> Szentimrey, T., 2023: Overview of mathematical background of homogenization, summary of method MASH and comments on benchmark validation. Int. J. Climatol.43, 6314–6329. <https://doi.org/10.1002/joc.8207>

## Characteristics of the MASH homogenization method

The method is suitable for homogenizing monthly and daily data series.

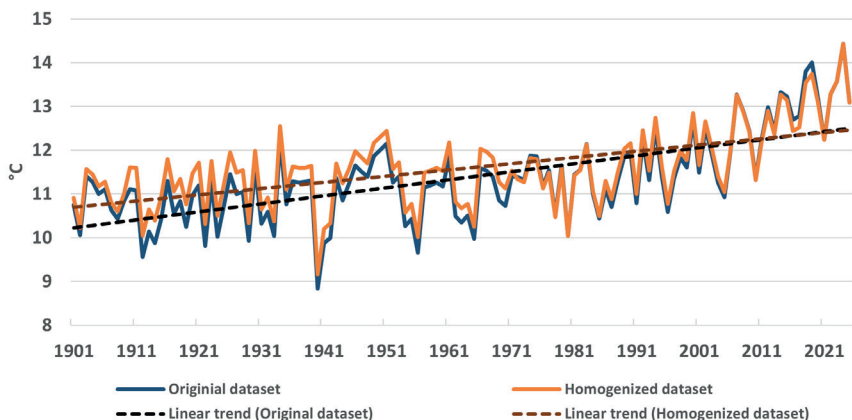
*Homogenization, quality control, and completion of **monthly** data series:*

- Based on relative homogeneity testing, comparing data series from different stations for the same period to detect inconsistencies;
- The aim is to detect and remove the breaks from non-climate change, so called inhomogeneities from the data series;
- It ensures the homogeneity of not only the monthly, but also the annual and seasonal data series;
- It uses two types of models depending on the probability distribution of climate elements;
- It can automatically use metadata indicating the time of change in measurement conditions.

*Homogenization, quality control, and completion of **daily** data series:*

- It uses estimated monthly inhomogeneities;
- It contains automatic data quality control and data completion process.

There may be significant differences between the original and homogenized data sets. As an example, we present the annual mean temperature in Budapest based on the original and homogenized data series (*Figure 1*). According to the linear trend estimation of the time series, the homogenized data series shows an increase of 1.77 °C, while the original series shows an increase of 2.27 °C over the past 125 years.



*Figure 1. The original and homogenized annual mean temperatures in Budapest between 1901 and 2025*

## Interpolation

Climate studies require not only high-quality and temporally consistent data series, but also reliable estimates for locations without direct meteorological observations. Surface meteorological measurements are inherently point-based; however, by interpolating data from observation stations, meteorological variables can be estimated at arbitrary locations or on regular grids. This enables the construction of spatially continuous fields, including country-wide maps (*Figure 2*). To ensure realistic results, geographical factors influencing the variable, such as topography and other location-dependent effects, must be considered. Interpolation can be further improved by incorporating, in addition to spatial characteristics, climate-related information from long-term data series, particularly the statistical properties (e.g., mean and standard deviation) of climate indicators.

Spatial interpolation is a mathematical procedure used to estimate the value of a meteorological variable at an arbitrary location based on observed data from neighboring sites. For this purpose, the MISH (Meteorological Interpolation based on Surface Homogenized Data Basis) software has been developed at HungaroMet. The method consists of two main components: a climate modelling system and an interpolation system built upon it. (The term “model” here refers to a statistical approach in **MISH**<sup>2</sup> and not to numerical climate models solving physical equations). During the modelling phase, statistical parameters that can be reliably estimated from long, homogenized, and gap-filled meteorological data series are taken into account, along with spatial trends, i.e. quasi-stationary effects (primarily related to topography) that influence the spatial variability of the given meteorological variable. Since the quality of the modelling strongly determines the accuracy of the interpolation, as many observational data series as possible are used in this phase, allowing fewer input data to be sufficient during the interpolation step.

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<sup>2</sup> Szentimrey, T. and Bihari, Z., 2014: Manual of interpolation software MISHv1.03, Hungarian Meteorological Service

## Characteristics of the MISH interpolation method

*Modeling program system for climate statistical parameters:*

- It works based on long homogenized data series and special model variables (e.g. topography);
- Modeling only needs to be done once, before interpolation applications.

*Interpolation program system:*

- Depending on the distribution of the meteorological element, we can choose between two types of interpolation formulas;
- Interpolation of daily, monthly and multi-year averages is also possible;
- Provides an estimate of interpolation errors;
- It is possible to use background information (e.g. satellite data, radar data, forecasts, etc.).

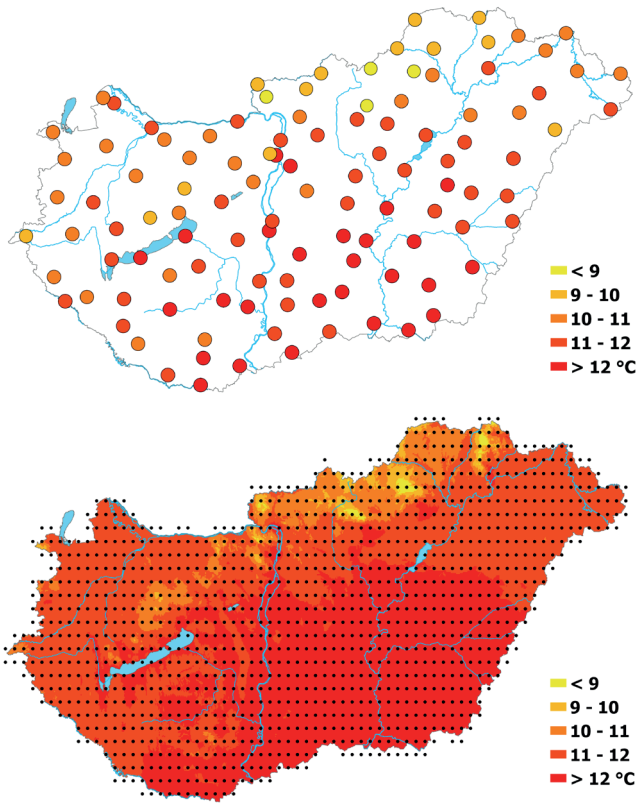


Figure 2. Interpolation of station data to grid points ensures uniform spatial coverage

# Assessment of future climate change

## Background of climate modelling and uncertainties

The question of how the climate system may change due to the future human activity can be studied by climate models. These models are based on numerical approximation of equation systems that describe the atmospheric, surface and other physical processes. Global climate models represent the behaviour of the whole Earth system at a 150–200 km horizontal resolution and they serve information about the large-scale aspects of climate change. Their results can be further refined over a selected domain with **regional climate models** (RCM) usually at a 10 km resolution.

Uncertainties in future climate model simulations may be derived from the following sources:

- **Natural variability** of the climate system, which causes continuous changes without any external forcing;
- **Model uncertainty** due to differences among climate models in description of small-scale physical processes (e.g., cloud formation and precipitation);
- The future evolution of human activity is represented by different scenarios for anthropogenic emissions of greenhouse gases and aerosols. Due to the **scenario uncertainty**, future climate simulations are considered as **projections**.

To properly take these uncertainties into account, it is essential to analyse several climate projections produced by different climate models and different scenarios. It is strongly advised to present the future results with adding its uncertainty (*Figure 3*).

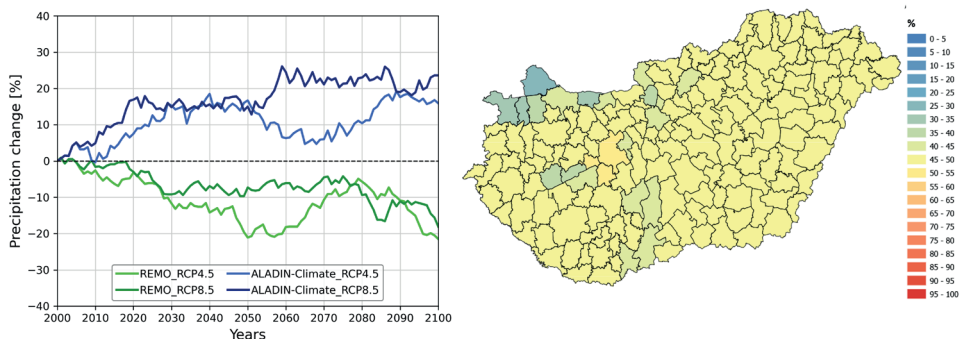
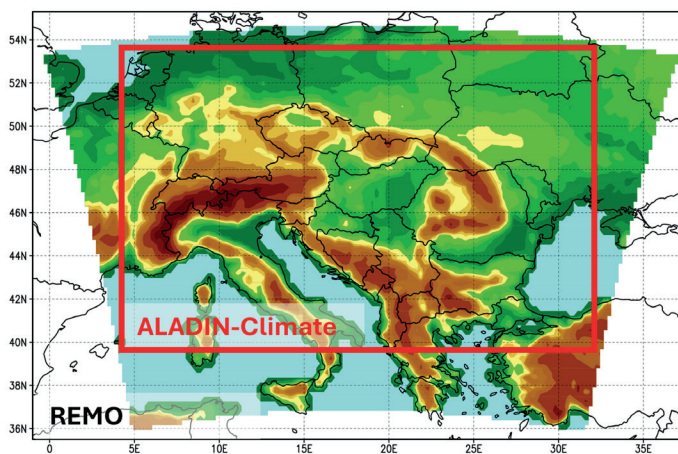


Figure 3. Left: summer precipitation change [%] in the 21st century with respect to 1971–2000 based on results of 4 regional projections of HungaroMet; Right: the probability of the summer precipitation decrease [%] in 2071–2100 based on the same results

## Regional climate model simulations at HungaroMet

At the Hungarian meteorological service, climate dynamics studies have been conducted since 2004, primarily based on two regional climate models (**ALADIN-Climate** and **REMO**).

ALADIN-Climate is developed at the French meteorological service (CNRM) and it was adapted in Hungary in 2005<sup>3</sup>. The REMO model was adapted in 2004<sup>4</sup>, and it is currently developed at the Climate Service Center Germany. Physical processes driving outside the domain of these RCMs are prescribed by global climate models: the CNRM-CM5 and MPI-ESM-LR Earth system models for ALADIN and REMO, respectively. The RCMs were run over a domain covering Central and Eastern Europe at a 10 km resolution (*Figure 4*). Simulations span the period of 1950–2100 and consider two scenarios with medium (RCP4.5) and high (RCP8.5) anthropogenic emission pathways. Key results from the four simulations are presented in *Figures 3, 7, 8 and the bottom two maps on the cover page*.



*Figure 4. Model domains for ALADIN-Climate and REMO simulations conducted at HungaroMet*

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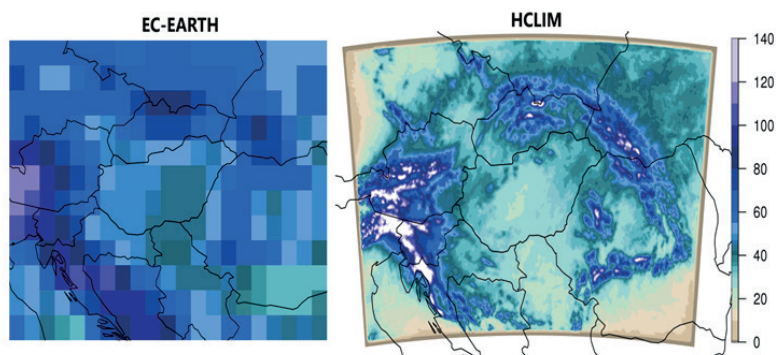
<sup>3</sup> Bán, B., Szépszó, G., Allaga-Zsebeházi, G., Somot, S., 2021: ALADIN-Climate at the Hungarian Meteorological Service: from the beginnings to the present day's results. *Időjárás* 125, 4, 647–673

<sup>4</sup> Szépszó, G., 2014: Climate dynamics investigations for the Carpathian Basin with the REMO regional climate model. Theses of the PhD dissertation, Eötvös Loránd University, Faculty of Science, PhD School for Earth Sciences, Geography–Meteorology Program

## High-resolution climate modelling

Local precipitation events that produce large amounts of rainfall within a short period cannot be represented in sufficient detail at the 8–10 km horizontal resolution of the currently used regional climate models. Since climate change affects both the frequency and intensity of extreme weather events, it is essential to obtain a detailed and accurate modelled representation of these phenomena in order to prepare for their potentially hazardous impacts, such as flash floods.

To achieve this, we use a high-resolution model – already widely applied in weather forecasting – that directly describes convection processes related to thunderstorm formation, rather than relying on empirical-statistical approximations. At HungaroMet, we have adapted the **HARMONIE-Climate** (HCLIM<sup>5</sup>) model for this purpose. This RCM is the climate version of the HARMONIE numerical weather prediction model developed in the international ACCORD (A Consortium for CONvection-scale modelling Research and Development) consortium. Currently, the model is being tested over a multi-year period at a horizontal resolution of 2–4 km, including evaluations of its capability to represent heavy precipitation events in the Carpathian Basin (*Figure 5*).



*Figure 5. Annual precipitation amount [mm/month] in the Carpathian Basin region based on the EC-EARTH global climate model at 80 km resolution and the HCLIM regional climate model at 2.5 km resolution, driven by the global model, for the period of 1996–2000*

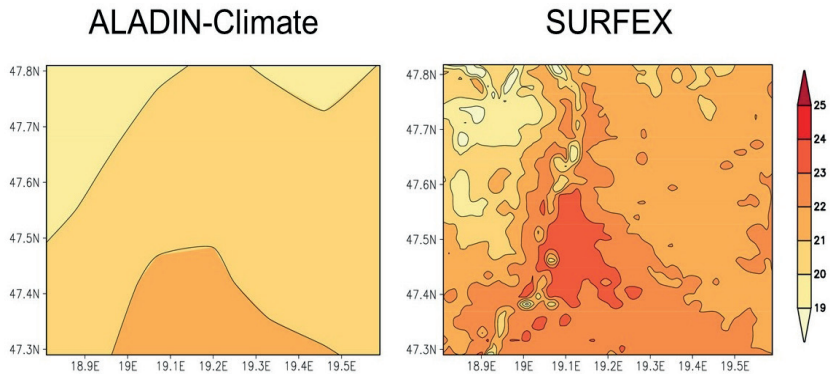
<sup>5</sup> Belušić, D. et al., 2020: HCLIM38: a flexible regional climate model applicable for different climate zones from coarse to convection-permitting scales. *Geosci. Model Dev.* 13, 1311–1333, <https://doi.org/10.5194/gmd-13-1311-2020>

## Studying urban changes

The urban atmosphere is warmer, drier and more turbulent on average than its natural environment, which can amplify certain characteristics of climate change, thereby increasing the vulnerability of cities. The characteristics of urban climate are not well represented in today's RCMs, since their resolution is not fine enough, and they describe urban processes with strong approximations. Therefore, their results are complemented with a **surface model** at HungaroMet, which specifically focuses on simulating the interactions between the urban surface and the atmosphere.

Using the **SURFEX** surface model we currently have simulations for Budapest and Szeged between 1970 and 2100. The model provides a more detailed description of near-surface meteorological variables, but not of local precipitation and cloud processes. *Figure 6* shows that its application allows for a more detailed representation of orographic effects and urban characteristics, such as the **urban heat island**.

Using SURFEX, we can quantify the reduction in the urban heat island effect that a chosen adaptation action can reach, thereby it directly supports strategy and related decision making. For example, we examined the impact of surface changes to roads, roofs, modifications to green areas, or the timing of watering during the day in Budapest.



*Figure 6. Summer mean 2-meter air temperature [°C] for the period of 1991–2000, based on the 10 km resolution ALADIN-Climate and 1 km SURFEX simulations for Budapest*

## Data processing

Data processing is generally carried out in a similar way for both historical data and future projections.

### Mean values

The state of the climate is typically described using 30-year averages, known as **climate normals**, in accordance with the recommendations of the World Meteorological Organization (WMO). By analyzing the normal values of consecutive 30-year periods, a comprehensive picture of climate variability and change can also be obtained. The *upper pair of figures on the cover* illustrates the spatial distribution of mean annual temperature for the 1971–2000 and 1991–2020 normal periods.

Results for future periods are often expressed in terms of changes relative to a selected **reference period**. For this purpose, a baseline period is defined against which projected changes are evaluated. For example, the *lower pair of figures on the cover* shows the minimum and maximum projected changes for 2041–2070 relative to the 1971–2000 reference period.

### Time series and trend analysis

We use climate time series to examine how a given meteorological variable changes over long periods. To quantify these changes, we apply **trend fitting**. The sign and magnitude of the trend coefficient allow us to estimate the direction and rate of change on annual, decadal, or full-period timescales.

To estimate changes in temperature values, a linear trend fitting is applied. The slope of the trend line represents the rate of change per year. Multiplying this slope by the length of the period provides the total change over the given time interval. Since this is an estimate, its statistical reliability is also assessed. Specifically, a 0.9 confidence interval is calculated for the change, meaning that the true value of the change lies within this interval with a probability of 0.9. The change is considered not statistically significant if the confidence interval includes zero; in this case, the time series does not show a clear increasing or decreasing trend.

The lower bound of the confidence interval can be interpreted as the “at least” estimate of the change, while the upper bound represents the “at most” estimate. For precipitation we often apply exponential trends and express the changes in percentage terms.

Figure 7 shows the evolution of annual mean temperature in Hungary between 1901 and 2100 relative to the 1971–2000 climatological mean (10 °C). We also include a linear trend fitted to the observed data, which indicates that the annual mean temperature in Hungary has increased by approximately 1.7 °C (lower bound of confidence interval: 1.3 °C, upper bound: 2.1 °C) over the past 125 years, which can be considered significant at a 90% confidence level. For future projections, we usually present model simulation results as 30-year **moving averages**, since year-to-year variability would otherwise cover the climate change signal. The range for future values shown for a given year represents the average change over the preceding 30-year period (e.g., the values for 2100 correspond to the period of 2071–2100).

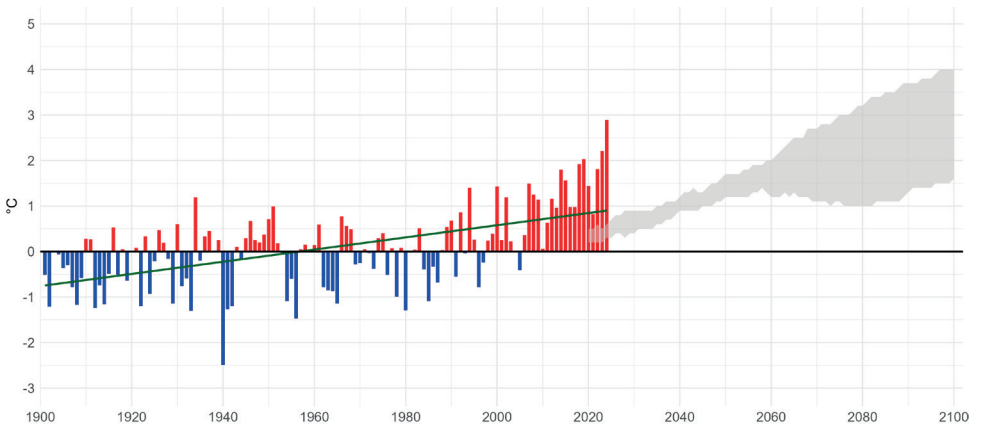


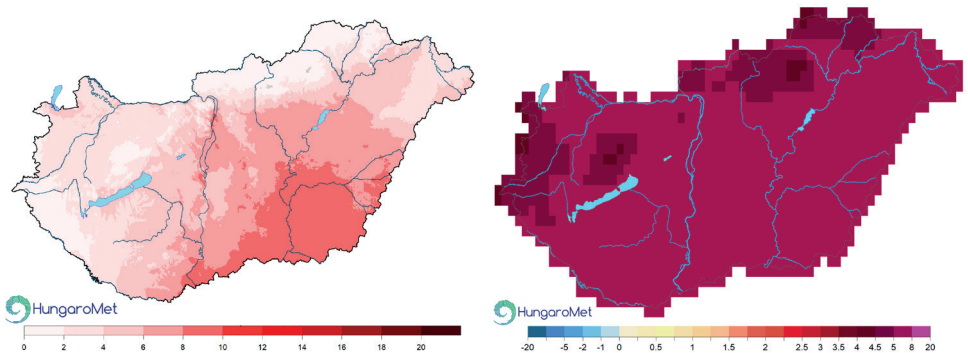
Figure 7. The anomaly of the annual mean temperatures in Hungary between 1901 and 2100. Reference period: 1971–2000; green line: linear trend; grey range: range of expected change covered by regional climate model simulations, interannual variability smoothed with a 30-year moving average from 1991.

## Climate extremes

The characterization of climate change includes the analysis of indicators derived from **daily** meteorological variables, as these often have stronger impacts in sectors such as human health and agriculture than changes in monthly or seasonal means. These indicators, known as **climate indices**, are calculated from daily minimum, mean, and maximum values, or from accumulated variables.

Climate indices may describe both extreme (e.g., hot days occurring only a few times per year in Hungary) and non-extreme conditions (e.g., frost days occurring in average about one quarter of the year). Most commonly, they quantify either the frequency of threshold exceedance or the duration of conditions above or below a given threshold. An example is the annual number of heatwave days, defined as days with a daily mean temperature of at least 25 °C (*Figure 8*). Extreme precipitation indices characterize the frequency of unusually wet periods and prolonged dry spells.

We compute climate indices from homogenized historical daily temperature and precipitation data and assess national-scale changes using trends fitted to area-averaged gridded values. For future projections, we apply bias correction to the underlying meteorological variable, then calculate the indices and quantify their changes based on the corrected data.



*Figure 8. Annual number of heatwaves in Hungary between 1971 and 2000, and the maximum of the expected change in the period of 2071–2100 with respect to 1971–2000*

## Climate services

HungaroMet serves user needs from various sectors by providing targeted products. Publicly available monthly, annual, seasonal, and yearly climate assessments present current conditions and their extremes in the context of climate change. Climate impact studies are primarily based on the 1991–2020 climatological normal period, which best represents present-day climate conditions.

Using tools of statistical climatology, estimates can be derived for return periods and design values of variables such as high and low temperatures, strong wind gusts, and short-duration precipitation totals. In addition, more complex, sector-specific indicators can be developed according to user requirements.

Targeted, case-specific impact studies are supported with climate information based on both observational data and climate model simulations. A wide range of observational datasets is available from the HungaroMet Meteorological Open Data Portal. The KLIMADAT application provides a spatially structured database of climate indicators. In addition, the thematic layers of the NAGiS database, which are also based on climate data, support climate change adaptation and related decision-making processes.

## Further information

### Climate portal



### Open Data Portal



### KLIMADAT portal



### NAGiS portal



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**Danube-ADAPT – Developing an evidence-based, regionally integrated policy decision-support system by establishing a climatological database for the Danube region and creating a unified vulnerability assessment framework with policy integration:**

A project led by HungaroMet, supported by the Interreg Danube Region Programme, implemented with domestic co-financing, which aims to build a factual, territorially integrated policy decision support system by developing a climatological database for the Danube region and creating a unified vulnerability assessment background and policy integration.



**LIFE COOL ZONE – Innovative Municipal Cooperation and Integrated Solutions for Managing Heatwaves in Functional Urban Areas:**

The project will improve the understanding of heat risks in major cities and urban regions with a special focus on Debrecen and Oradea, support cooperation between neighbouring municipalities, including across borders, and demonstrate how nature-based solutions can effectively cool urban areas. In the long term, the project is expected to reduce health risks related to heatwaves, improve living conditions in the most affected neighbourhoods, strengthen local capacities for climate adaptation and provide practical models that other cities can easily replicate.