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# Uncertainty estimates for climate change scenarios: basic overview and examples from PERUN

## (Tvorba scénářů změny klimatu a hodnocení nejistot: různé přístupy a příklady z projektu PERUN)

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***Abstract:*** Climate change scenarios represent plausible alternative future climate states that may occur under certain assumptions about the development of anthropogenic forcings, especially emissions and concentrations of greenhouse gases and aerosols, as well as land use changes. In the past, possible development trajectories of these factors were mainly described using emission scenarios, whereas today more complex socio-economic scenarios are used; the current generation is referred to as "socio-economic pathways." The aim of developing climate change scenarios is to define the range of possible future outcomes and to provide a basis for estimating future climate conditions. Various approaches are used to derive projections. The main sources of data are the outputs of global climate models, sometimes supplemented by various downscaling methods. The model outputs must then be adjusted using post-processing techniques to reduce the impact of known systematic errors, and it is also necessary to assess the level of uncertainty associated with the resulting data. Within the PERUN project, the main source of information about possible climate development in the territory of the Czech Republic is a set of simulations from the ALADIN-CLIMATE/CZ model, driven by the global model CNRM-ESM2-1. To estimate the uncertainties that accompany each climate scenario, additional model simulations are also used – particularly the CMIP5 and CMIP6 ensembles, regional simulations from EURO-CORDEX initiative, and other available high-resolution simulations. This contribution summarizes the basic procedures for developing scenarios, processing model outputs, and assessing uncertainties. It also presents some results of uncertainty analysis obtained within the PERUN project.

***Keywords:*** climate change scenario – global climate model – regional climate model – uncertainties in climate model outputs

***Abstrakt:*** Scénáře změny klimatu představují přijatelné alternativní stavy klimatu v budoucnosti, které mohou nastat za určitých předpokladů o vývoji antropogenních vlivů na klima, zejména emisí a koncentrací skleníkových plynů a aerosolů, ale také změn ve využívání krajiny. Dříve byly možné trajektorie vývoje těchto faktorů popisovány převážně emisními scénáři, zatímco dnes se pracuje s komplexnějšími socio-ekonomickými scénáři; současná generace je označována anglickým termínem "socio-economic pathways". Cílem tvorby scénářů změny klimatu je vymezit prostor možného vývoje a poskytnout podklad pro odhady budoucího klimatu. K odvozování projekcí se využívají různé přístupy. Základ spočívá v analýze výsledků globálních klimatických modelů, případně doplněných metodami downscalingu. Modelové výstupy je následně nutné upravit pomocí postupů post-processingu, aby se omezil vliv známých systematických chyb, a rovněž je nutné posoudit míru nejistoty spojenou s výslednými daty. Hlavním zdrojem informací o možném klimatickém vývoji na území Česka je v projektu PERUN sada simulací modelu ALADIN-CLIMATE/CZ, s řídícím globálním modelem

CNRM-ESM2-1. Pro odhad nejistot, které provázejí každý klimatický scénář, se využívají také další modelové simulace – zejména soubory experimentů CMIP5 a CMIP6, regionální simulace EURO-CORDEX a další dostupné simulace s vysokým horizontálním rozlišením. Příspěvek shrne základní postupy tvorby scénářů, zpracování modelových výstupů a hodnocení nejistot. Uvedeme také některé výsledky analýzy nejistot získané v rámci řešení projektu PERUN.

***Klíčová slova:*** scénář změny klimatu – globální klimatický model – regionální klimatický model – nejistoty modelových výstupů

## Introduction

Climate change scenarios represent plausible alternative future climates that may occur under specific assumptions about the evolution of anthropogenic influences, particularly greenhouse gas and aerosol emissions, and land-use changes. The primary purpose of these scenarios is to provide a basis for impact assessments on ecosystems and society. Importantly, they are not deterministic forecasts but rather potential climate trajectories, describing the range and limits of potential climate development. Most contemporary climate change scenarios are based on outputs from numerical climate models. While other methods exist – such as the use of analogues from Earth's geological past – recent progress in model development and increasing computational capacity have led to a strong emphasis on climate model–based projections. Global climate models (GCMs), also referred to as Earth System Models (ESMs), operate on the whole globe and include all climate system components. Regional climate models (RCMs) have a limited integration domain, with driving boundary conditions usually taken from a GCM. In any case, raw model outputs cannot be used directly due to systematic biases, and they must be adjusted to account for known biases of historical simulations (see Section 3).

The growing availability of simulations, particularly through coordinated international projects such as CMIP6 (Eyring et al. 2016) and CORDEX (https://cordex.org/), has significantly enhanced the ability to analyze future climate projections. The large number of simulations enables the evaluation and communication of uncertainties in projections. A robust understanding of these uncertainties is essential for interpreting projected changes. Nevertheless, focusing on regional scales, such as producing projections for the Czech Republic, still represents quite a challenging task. Within the project PERUN, the main data source for the projections are several simulations of the convection-permitting regional climate model ALADIN-CLIMATE/CZ (Termonia et al. 2018; Mašek 2023). However, to account for numerous uncertainties (see Section 2), it is necessary to also use data from available multi-model ensembles (e.g., Abramowitz et al. 2019; Holtanová et al. 2022; Holtanová and Kalvová 2015).

## Sources of uncertainty in climate model outputs

Uncertainty in climate model outputs arises from multiple sources, which are often categorized into four main groups: initial conditions, boundary conditions, parameterizations, and model structure (e.g., Tebaldi and Knutti 2007). These sources affect both global climate models (GCMs) and regional climate models (RCMs), although additional complexities arise in regional modeling due to the limited integration domain (e.g., Denis et al. 2002; Laprise et al. 2008).

Initial conditions represent a fundamental source of uncertainty linked to the chaotic nature of the climate system and its internal variability. Even small perturbations in the initial state can lead to different model trajectories. This uncertainty can be quantified using ensembles of simulations with slightly perturbed initial conditions (e.g., Maher et al. 2025).

Boundary conditions introduce another important uncertainty, especially in regional modeling. In GCMs, some processes are prescribed rather than dynamically simulated, such as atmospheric composition derived from emission scenarios. In RCMs, lateral boundary conditions are provided by driving data from GCMs, and any errors in these inputs can propagate into the regional simulation. Additional uncertainty arises from the coupling between the driving model and the nested RCM, including inconsistencies in spatial and temporal resolution and physical parameterizations. The

influence of boundary conditions is often assessed using ensembles of RCM simulations driven by different GCMs (Holtanová et al. 2014; Vautard et al. 2021).

Parameterizations arise from the need to represent subgrid-scale processes that cannot be explicitly resolved, even at relatively high spatial resolution. These include, for example, radiative energy transfer, convection, cloud processes, and interactions of atmospheric flow with complex terrain. Parameterization schemes combine physical theory with empirical relationships, introducing uncertainty that can be explored using perturbed physics ensembles (Tebaldi and Knutti 2007).

Model structure encompasses uncertainties related to the overall design of the model, including spatial and temporal resolution, numerical methods, and grid configuration. This type of uncertainty is typically assessed using multimodel ensembles, which include simulations from different climate models with different structural choices. However, the resulting uncertainty estimates probably underestimates the real uncertainty range (Abramowitz et al. 2019).

Besides the uncertainties connected directly to the climate model outputs, it is necessary to evaluate the range of possible future development of anthropogenic forcings. This is done using a set of socio-economic scenarios (Nakićenović et al. 2000; Moss et al. 2010; Meinshausen et al. 2020).

### Examples of methods of climate model outputs pre-processing

Climate change scenarios based on the outputs from global (GCM) or regional climate models (RCMs) can be developed using a range of methodological approaches. The choice of method depends on the intended application of the scenario, including the target region, time horizon, and the required meteorological variables. A fundamental prerequisite for all scenario development methods is the availability of high-quality observational data. Without such data, it would not be possible to validate climate models or apply any post-processing techniques. Evaluating the ability of a model to reproduce observed climate characteristics over a historical reference period is always the first essential step.

In the scenario development, it is necessary to remove systematic model errors by adjusting simulated time series for the future period based on biases identified in the historical period. One of the simplest approaches to this post-processing of raw model outputs is the delta method. In this approach, the difference between the mean values of the characteristic of interest (e.g., monthly mean temperature) derived from historical and scenario simulations for selected time periods is applied to observed data from the reference period to construct future climate scenarios. This way, the projection accounts for simulated change in the mean state, but the variability is inherited from observations. A similar approach is often referred to as “unbiasing”, where the bias of historical model simulations from observations is used to adjust the model outputs for the scenario time period. Thus, the scenario preserves the temporal variability of the scenario model simulation.

More advanced, but recently widely used techniques aim not only at the mean, but also higher moments, or the whole statistical distribution. A widely used method is quantile mapping (Déqué 2007). All bias correction methods rely on the important assumption that model biases remain constant over time, meaning that corrections derived for the reference period remain valid in the future.

A limitation of many bias correction approaches is that they are typically applied independently to individual variables, which may disrupt physical consistency of the results. More recent developments seek to address this issue by accounting for the multivariate nature of meteorological data (Cannon 2018).

### Internal climate variability as a benchmark for model simulations

Internal climate variability (ICV) arises from the inherently chaotic nature of the climate system and exists even in the absence of changes in external forcings. Estimating ICV is crucial for both model evaluation and the interpretation of projected climate change. If the model bias in a reference period (evaluated against observations) is lower than the ICV estimate, it can be considered negligible.

Similarly, if the projected change in the characteristic of interest is smaller than the ICV estimate, it can be considered lower than the "climate noise". Evaluating the time of emergence of simulated changes (the period in which the projected changes become higher than ICV) is important within the framework of climate change detection and attribution (Stott et al. 2010). Within the project PERUN, the study of Randriatsara et al. (2026) aims to compare different estimates of ICV of seasonal mean temperature over Europe. A follow-up study will then apply these estimates as benchmarks for projected temperature changes.

## Hybrid method to include more global climate models

Regional climate models (RCMs), particularly high-resolution simulations such as convective-permitting models, provide detailed spatial information about regional climate and its changes, but are typically driven by only a limited number of global climate models (GCMs). Within the project PERUN, simulations of ALADIN-CLIMATE/CZ are driven by only one GCM (CNRM-ESM2-1, Séférian et al. 2019). To address this limitation, we are going to incorporate the hybrid method, introduced by Ruosteenoja and Räisänen (2024). This approach allows combining the spatial pattern of change from the RCM with the magnitude of the climate change signal from a different GCM (not the one used for the boundary conditions of the RCM). The procedure is computationally cheap, therefore, we will be able to incorporate a wider range of global model responses without requiring computationally expensive simulations for each GCM. We already successfully applied the hybrid method for combining projections of changes in the spatial distribution of Köppen-Trewartha climate types over Europe simulated by EURO-CORDEX RCMs with a subset of CMIP6 GCMs (Holtanová et al. 2025). In Randriatsara et al. (2026) we are combining the outputs of ALADIN-CLIMATE/CZ with simulations of selected CMIP6 GCMs with a wide range of equilibrium climate sensitivity and simulations from a large ensemble of MPI-ESM (Maher et al. 2019). This way we are able to enhance the uncertainty estimate while preserving spatial details provided by the PERUN regional simulations.

## Conclusion

Assessing future climate change over the Czech Republic requires careful consideration of multiple sources of uncertainty. In the near future, a new generation of the EURO-CORDEX simulations (Sobolowski et al. 2025) will become available. Using the simulations from this multi-model ensemble will enable further improvement of the uncertainty within future climate change scenarios for the Czech Republic.

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## Statement on use of AI

Generative AI was used to assist with English grammar and text clarity, but all conceptualization, design, and conclusions are original to the authors, who take full responsibility for the content's accuracy and academic integrity.

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