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# Preparation of climate scenarios for impact studies in the PERUN project: combining selected GCMs and the regional ALADIN model

## (Příprava klimatických scénářů pro impaktové studie v projektu PERUN: kombinace vybraných GCM a regionálního modelu ALADIN)

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***Abstract:*** The PERUN project requires consistent climate scenarios for impact modelling, vulnerability assessment and adaptation planning. Experience from previous projects showed that existing regional climate-model ensembles may provide valuable spatial detail but can also differ substantially from their driving global models in projected precipitation, radiation and surface-energy conditions over Central Europe. This motivated the preparation of a validated mini-ensemble of seven CMIP6 global climate models (GCMs) as the main representation of large-scale model and scenario uncertainty. The GCM component is complemented by ALADIN-CLIMATE/CZ, the central regional modelling output of PERUN. Its convection-permitting 2.3 km grid provides information tailored to the complex terrain of the Czech Republic and is particularly valuable for regional precipitation structure and heavy-precipitation risk. The two components are processed into consistent daily application-ready datasets. The applied approach does not rank the models according to their credibility but uses them as complementary sources of information on plausible future climate conditions. The resulting products support PERUN impact studies and provide a methodological basis for nationally consistent climate proofing applications.

***Keywords:*** climate scenarios – CMIP6 – model validation – ALADIN-CLIMATE/CZ – impact modelling – climate proofing

***Abstrakt:*** Projekt PERUN vyžaduje konzistentní klimatické scénáře pro impaktové modelování, hodnocení zranitelnosti a plánování adaptace. Zkušenosti z předchozích projektů ukázaly, že existující ansámbly regionálních klimatických modelů poskytují cenný prostorový detail, ale pro střední Evropu se mohou výrazně lišit od řídicích globálních modelů v projekcích srážek, radiace a povrchové energetické bilance. Proto byl jako hlavní reprezentace nejistoty velkoprostorového vývoje a emisních scénářů připraven validovaný mini-ansámbl sedmi globálních modelů CMIP6. Tuto složku doplňuje ALADIN-CLIMATE/CZ, klíčový regionální modelový výstup projektu PERUN. Konvekci rozlišující simulace s krokem sítě 2,3 km poskytuje informace přizpůsobené členitému reliéfu České republiky a je významná zejména pro regionální strukturu srážek a riziko intenzivních srážek. Obě složky jsou zpracovány do konzistentních denních dat využitelných v aplikacích. Tato studie modely neřadí podle jejich věrohodnosti, ale chápe je jako vzájemně se doplňující reprezentace možného budoucího vývoje klimatu. Výsledné produkty podporují impaktové studie projektu PERUN a tvoří metodický základ pro jednotné klimatické prověřování v České republice.

***Klíčová slova:*** klimatické scénáře – CMIP6 – validace modelů – ALADIN-CLIMATE/CZ – impaktové modelování – klimatické prověřování

## Introduction

Climate information for regional impact studies must satisfy two partly competing requirements. It should retain the large-scale response and uncertainty represented by global climate models, while also providing locally relevant daily data for complex terrain and for processes such as convective precipitation. No single model or model family can be assumed to meet all these requirements. The practical task is therefore to construct a transparent ensemble in which the strengths and limitations of its members are explicit.

In earlier Czech and European projects, regional climate-model (RCM) simulations from the ENSEMBLES and EURO-CORDEX initiatives were processed for applications in agriculture, hydrology and drought assessment. Their fine spatial resolution and improved representation of topography are valuable, and validation can show smaller mean biases and better spatial variability than in the driving GCMs. However, the projected climate-change signals of RCMs may differ markedly from those of the driving global models. For Central Europe, pronounced differences have been documented in precipitation, global irradiance, surface-energy fluxes and the partitioning between latent and sensible heat. Skalák et al. (2025) showed that EURO-CORDEX RCMs tend toward a wetter and less strongly warming growing-season pathway, whereas the GCM ensembles more often project stronger summer warming, increasing irradiance and conditions consistent with higher drought stress.

These discrepancies were important for the design of PERUN climate inputs. They do not allow a simple conclusion that one model family is correct and the other is wrong. Central Europe lies in a transition zone between the projected wetter conditions of northern Europe and drying in the Mediterranean, and precipitation changes remain less robust than temperature changes. A regional simulation that appears relatively wet compared with a GCM ensemble may therefore still represent a relevant branch of future uncertainty, especially for applications concerned with heavy precipitation and flood-generating conditions.

The adopted solution is therefore asymmetric but complementary. A validated mini-ensemble of seven CMIP6 GCMs forms the core of the scenario system because it samples a range of large-scale climate responses and four SSP pathways (Meinshausen et al. 2020). ALADIN-CLIMATE/CZ, developed within PERUN, is included as an essential high-resolution regional component. Its convection-permitting 2.3 km grid is specifically configured for simulations over Central Europe and the Czech Republic and adds spatial detail that cannot be represented directly by the coarse GCM grids. The combined framework is not intended as a model competition; it integrates different strengths and a broader range of physically plausible regional outcomes.

This contribution describes the selection of the GCM mini-ensemble, the processing of model signals into application-ready daily datasets, the rationale for including ALADIN-CLIMATE/CZ, and the way the combined information is used in the PERUN and climate proofing context. Detailed development of the transformation method is outside the scope of this paper and is referenced only briefly to preserve a clear distinction from a separate methodological publication.

## Data and validation framework

The initial set of candidate models included CMIP6 simulations from both ScenarioMIP and HighResMIP simulations with nominal horizontal resolutions from approximately 50 to 250 km. Seven daily meteorological variables required by common impact models were considered: mean, maximum and minimum 2 m air temperature, precipitation, global solar radiation, 10 m wind speed and relative humidity. Historical simulations for 1980–2014 were evaluated against station-based technical series derived from measurements provided by the Czech Hydrometeorological Institute. The technical series were quality controlled, homogenized and completed using neighbouring stations and spatial information (Štěpánek et al. 2011, 2013).

Model eligibility was first constrained by practical data requirements. A candidate had to provide the meteorological variables needed for downstream calculations, sufficiently long historical and scenario simulations, and usable SSP coverage. Most models with a nominal resolution near 250 km were not retained for the final mini-ensemble because of the limited number of grid cells over the Czech Republic. HighResMIP simulations were also unsuitable as the main operational basis because they generally provided only SSP5-8.5 and often ended near 2050. Nevertheless, the 50 km ScenarioMIP version of CNRM-CM6-1-HR could be retained for the available long-term scenarios.

The validation followed the framework previously applied to EURO-CORDEX model combinations (Meitner et al. 2023). Performance was assessed for all seven variables using: (i) correlation of the annual cycle, describing the reproduction of seasonal timing; (ii) spatial correlation of long-term climatologies, with emphasis on summer and winter; and (iii) spatial variability evaluated using normalized standard deviation and centred root-mean-square difference in Taylor diagrams. Data completeness was treated as an additional criterion because impact models typically require a consistent multivariable input set.

The assessment was relative within the available ensemble. Models with clearly poor annual-cycle correlation for precipitation, notably INM-CM5-0 and NorESM2-MM, were excluded. CESM2 could not be fully validated because daily maximum and minimum temperature were missing from the historical run. Models with some weaker spatial correlations were not automatically removed when they contributed useful spatial resolution or helped preserve the ensemble spread. Unlike the earlier RCM selection, no unambiguous central GCM could be identified across all variables; a model near the ensemble centre for temperature could be close to an edge for precipitation or radiation. The final selection was therefore based on removing weak or incomplete candidates while preserving the range of plausible responses. The seven selected GCMs are summarized in Tab. 1.

*Table 1. Selected CMIP6 GCMs forming the core mini-ensemble.*

| Model | Nominal resolution | Scenario coverage | Selection note |
|---|---|---|---|
| CNRM-CM6-1-HR | 50 km | SSP1-2.6, SSP5-8.5 | Highest spatial resolution among the long-term ScenarioMIP simulations |
| CMCC-ESM2 | 100 km | All four SSPs | Complete multivariable set |
| EC-Earth3 | 100 km | All four SSPs | Complete multivariable set |
| GFDL-ESM4 | 100 km | All four SSPs | Complete multivariable set |
| MPI-ESM1-2-HR | 100 km | All four SSPs | Retained despite weaker spatial correlation for some variables |
| MRI-ESM2-0 | 100 km | All four SSPs | Retained despite weaker spatial correlation for some variables |

| Model | Nominal resolution | Scenario coverage | Selection note |
|---|---|---|---|
| TaiESM1 | 100 km | All four SSPs | Complete multivariable set |

## Processing into application-ready scenarios

The selected GCMs were processed for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Climate-change signals were evaluated for four overlapping 30-year periods centred approximately on 2030 (2015–2044), 2050 (2035–2064), 2070 (2055–2084) and 2085 (2070–2099). The overlap provides a consistent sequence of assessment periods across the century. For both climatological and hydrological applications, changes should be interpreted over sufficiently long periods, such as 30 years, rather than from individual simulated years, which are strongly affected by natural variability.

The coarse GCM grid cannot be used directly for local impact modelling. In earlier processing, distribution-based bias correction was applied to climate-model outputs. For the present combined framework, however, methodological consistency between the GCM component and ALADIN-CLIMATE/CZ was essential. Therefore, after the initial model-specific preparation, climate-change signals from both model branches were transferred to the observational reference dataset using the same advanced delta-change procedure. This approach modifies high-quality observed daily series rather than forcing raw model values to reproduce station conditions, and it captures changes in means, variability and precipitation tails (van Pelt et al. 2012).

The final Czech-domain products have a daily time step and a 500×500 m grid for all seven meteorological variables. The fine spatial structure is inherited from quality-controlled and homogenized station technical series and their spatial interpolation (Štěpánek et al. 2011), while the climate-change signal is supplied by each individual model and SSP. This common processing framework provides methodologically consistent inputs for impact studies across the full set of GCM and regional climate model projections.

ALADIN-CLIMATE/CZ was included as the dedicated regional component of the PERUN scenario framework. The convection-permitting simulation has a horizontal grid spacing of 2.3 km, is driven by a CMIP6 GCM, and provides additional information relevant to the complex terrain of the Czech Republic and to local and regional precipitation processes. For the main scenario dataset, it was processed using the same Advanced Delta Change Method as the selected GCMs and delivered on the common 0.5 km application grid. In addition, a separate bias-adjusted version was prepared using distribution adjustment by percentiles (Štěpánek et al. 2016). This complementary product preserves a continuous model time series and may therefore be useful for applications that require continuous temporal evolution rather than projections represented by individual 30-year periods. The overall processing workflow is summarized in Tab. 2.

*Table 2. Main processing steps used to prepare climate data for impact studies within the PERUN project.*

| Input data | Model assessment | Ensemble selection | Scenario processing | Final products |
|---|---|---|---|---|
| CMIP6 candidate models | Multivariable validation | Seven-GCM core ensemble supplemented by ALADIN-CLIMATE/CZ | Advanced Delta Change transformation | Daily climate data on a 500 × 500 m grid |

## Role of ALADIN-CLIMATE/CZ in the combined ensemble

ALADIN-CLIMATE/CZ is not included merely as a wetter member of the ensemble. It is one of the principal modelling outputs of PERUN and provides high-resolution regional climate information that complements the selected GCM projections. The GCM mini-ensemble samples uncertainty in large-scale climate response and socioeconomic pathways, whereas ALADIN-CLIMATE/CZ resolves

convection at a 2.3 km grid and represents the influence of the Czech Republic's complex terrain in substantially greater detail. Its role is therefore both scientific and practical: it complements the GCM component in regional impact applications and strengthens the representation of precipitation-related hazards. The combined role of both components within the PERUN scenario framework is illustrated in Fig. 1.

Differences between ALADIN-CLIMATE/CZ and the GCM component are treated as complementary information rather than as evidence that one projection should be discarded. Future precipitation in Central Europe remains uncertain, and higher seasonal totals or stronger precipitation intensities cannot be excluded. The regional simulation consequently broadens the range considered in risk assessment, particularly for pluvial and fluvial flooding, erosion, drainage design, water retention and other applications in which underestimating the upper precipitation branch could lead to maladaptation.

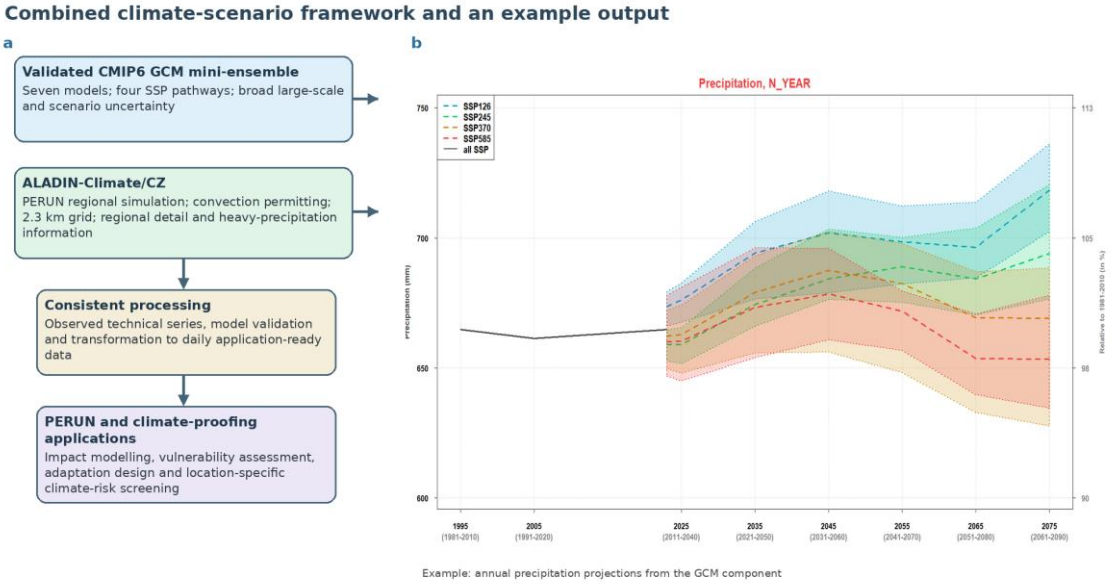



*Fig. 1. Combined climate-scenario framework. (a) The validated CMIP6 GCM mini-ensemble and the high-resolution ALADIN-CLIMATE/CZ simulation provide complementary inputs for consistent processing and subsequent PERUN and climateproofing applications. (b) Example of annual precipitation projections from the GCM component, illustrating the spread across SSP pathways and models; ALADIN-CLIMATE/CZ is retained as a separate high-resolution regional member in detailed applications.*

For general communication and initial screening, the outputs can be summarized using percentiles or ranges across models and scenarios. More detailed impact assessments, however, may require the individual daily time series from each model. This is particularly important for the design and evaluation of specific assets, where the temporal sequence of events and high-precipitation cases represented by ALADIN-CLIMATE/CZ may be more informative than an aggregated uncertainty range.

## Application in PERUN impact studies and climate proofing

The scenario system was designed primarily as an input to impact models. A common set of daily temperature, precipitation, radiation, humidity and wind data enables internally consistent calculations of reference evapotranspiration, soil-water balance, drought indicators, crop and forest responses, hydrological variables and heat-related indices. The selected mini-ensemble is computationally manageable while retaining substantially more uncertainty than a single-model approach.

Two levels of output are useful. The first consists of aggregated monthly, seasonal and annual indicators for cadastral units or administrative regions. These products are suitable for general risk screening, communication and comparison of future periods. The second consists of daily gridded series from individual GCMs and ALADIN-CLIMATE/CZ. These daily series are required when the response of a

specific technology, structure, catchment or adaptation measure depends on event sequences and extremes rather than only on climatological averages. Although the underlying scenario products are available on a 500×500 m grid, a subset of grid points with a spacing approximately corresponding to the native 2.3 km resolution of ALADIN-CLIMATE/CZ was selected for applications within PERUN. This spatial density is sufficiently detailed for most impact studies while substantially reducing data volume and computational demands.

The same principles directly support climate proofing. European guidance for infrastructure climate proofing emphasizes recent climate projections, a range of plausible futures, explicit treatment of uncertainty and the use of information appropriate to the location and asset being assessed (European Commission 2021). ClimRisk is an established web-based climate information platform developed by CzechGlobe (CzechGlobe 2026). Within PERUN, its scenario basis was extended by integrating outputs from the validated CMIP6 mini-ensemble with ALADIN-CLIMATE/CZ, thereby combining a broad range of large-scale climate responses with high-resolution regional information. These integrated climate data subsequently provide the underlying information base for ClimateProofing.cz, which is a separate user-oriented framework for assessing climate risks and the resilience of specific assets and projects.

The combined approach also supports the precautionary principle. Adaptation measures should be tested against conditions that are plausible even when they are not represented by the ensemble median. For water-sensitive infrastructure, this means considering both the warm and potentially dry outcomes represented by GCMs and the wetter or more intense precipitation outcome added by ALADIN. Such a framework is more useful for robust decisions than selecting a single “best” model based only on historical validation.

## Discussion

The PERUN scenario system separates three related tasks: evaluation of historical model performance, representation of future uncertainty, and preparation of spatially detailed data for impact applications. Historical validation identifies major deficiencies and incomplete datasets, but it cannot determine which plausible future response will occur. The selection therefore excludes clearly weak or incomplete models while preserving a range of climate responses. The models are not ranked according to credibility but are treated as complementary representations of plausible future conditions.

Earlier EURO-CORDEX simulations provided valuable regional detail but also showed substantial differences from their driving GCMs in projected precipitation, radiation and surface-energy partitioning over Central Europe (Skalák et al. 2025). This supported the use of validated CMIP6 GCMs as the multi-model and multi-scenario core of the PERUN dataset, while retaining regional information through ALADIN-CLIMATE/CZ. Its 2.3 km convection-permitting simulation complements the GCM mini-ensemble by providing greater detail on terrain-related and precipitation processes and by extending the range considered in impact assessments toward wetter conditions and stronger precipitation intensities.

Applying the Advanced Delta Change Method to both the GCMs and ALADIN-CLIMATE/CZ ensures consistent preparation of the main scenario products. The method transfers model-specific changes in climatic means, variability and precipitation distributions to the observational reference dataset. The resulting 500×500 m fields should not, however, be interpreted as dynamically simulated climate at that resolution: their fine spatial structure originates from the station dataset and its interpolation, while the climate-change signal is supplied by each model and SSP. The transformed series also retain the temporal sequencing of the reference observations. A separately bias-adjusted ALADIN-CLIMATE/CZ product therefore remains available for applications requiring a continuous model-generated time series.

The GCM mini-ensemble is constrained by CMIP6 data availability. CNRM-CM6-1-HR was retained because its approximately 50 km grid provides the highest resolution among the long-term ScenarioMIP

simulations considered, whereas the other selected models have resolutions close to 100 km. Coarser models and simulations with incomplete variables or scenario coverage were excluded. The resulting seven-model ensemble is therefore a practical compromise between validation performance, spatial resolution, scenario availability and the need to preserve a useful range of plausible climate responses.

## Conclusions

Climate scenarios prepared for the PERUN project combine a validated seven-member CMIP6 GCM mini-ensemble with ALADIN-CLIMATE/CZ, the project's dedicated convection-permitting regional simulation. The GCM component represents uncertainty associated with large-scale climate responses and SSP pathways, while ALADIN-CLIMATE/CZ contributes high-resolution regional information at a native grid spacing of 2.3 km, particularly for the complex terrain of the Czech Republic and for precipitation processes relevant to regional risk assessment.

The combined approach does not interpret differences between the GCM and ALADIN-CLIMATE/CZ projections as a simple ranking of credibility. A relatively wet regional projection may represent a relevant future outcome, particularly for intense precipitation and flood-related hazards. Retaining ALADIN-CLIMATE/CZ therefore broadens the range of conditions considered and reduces the risk that adaptation decisions are based only on the central part of the GCM distribution.

The resulting dataset provides daily values for seven meteorological variables on a common 500×500 m application grid, with the fine spatial structure derived from the observational reference data and the climate-change signals supplied by the individual models and SSPs. It supports current PERUN applications as well as subsequent hydrological, agricultural, forestry, infrastructure and adaptation studies. The integrated GCM and ALADIN-CLIMATE/CZ information is also made available through ClimRisk and provides the climate-data basis for the separate ClimateProofing.cz application. Aggregated indicators can be used for screening and communication, while individual daily model series remain available for detailed impact and risk assessments.

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