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Characteristics of extreme precipitation and its trends in the future climate according to the ALADIN-CLIMATE/CZ model

(Charakteristiky extrémních srážek a jejich vývoj v budoucím klimatu dle modelu ALADIN-CLIMATE/CZ)

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Abstract: Intense torrential rainfall poses many risks, such as flash floods, landslides, damage to infrastructure, as well as disruption to transport or energy supplies. The expected increase in both the frequency and intensity of such events, resulting from ongoing climate change, implies a potential rise in economic losses and demands on crisis management and civil protection services. The contribution presents the results of an analysis of future trends in extreme 1–48-hour precipitation characteristics, based on hourly precipitation totals from ALADIN-CLIMATE/CZ model simulations conducted as part of the PERUN project. Trends in the characteristics of annual maxima of 1–48-hour precipitation totals across the Czech Republic is shown, as well as changes in the derived design values for precipitation totals for the period 1985–2099 according to the SSP5-8.5 and SSP2-4.5 scenarios. Based on this analysis, an increase in the intensity of extreme precipitation events across various time scales (from hourly to multi-day totals) according to both projected climate change scenarios was detected. The changes are highly spatially variable, reflecting the strong regional variability of extreme convective precipitation.

Keywords: extreme precipitation – design values – climate change – climate model

Abstrakt: Intenzivní přívalové srážky přináší mnohá rizika, jako jsou bleskové povodně, sesuvy půdy, poškození infrastruktury, narušení dopravy či dodávek energií. Očekávané navýšení četnosti jejich výskytu i intenzity v důsledku probíhající klimatické změny znamená možné navýšení ekonomických škod či nároků na krizové řízení i ochranu obyvatel. V tomto příspěvku jsou prezentovány výsledky analýzy budoucího vývoje charakteristik extrémních 1–48hodinových srážek vycházející z dat hodinových srážkových úhrnů ze simulací modelu ALADIN-CLIMATE/CZ provedených v rámci projektu PERUN. Ukázány jsou trendy v charakteristikách ročních maxim 1–48h srážkových úhrnů na území Česka a také změny v odvozených návrhových hodnotách srážkových úhrnů v období 1985–2099 dle SSP5-8.5 a SSP2-4.5 scénářů. Na základě této analýzy bylo nalezeno zesilování intenzity extrémních srážkových událostí napříč různými časovými měřítky (od hodinových až po vícedenní úhrny) dle obou napočtených scénářů změny klimatu. Změny jsou prostorově velmi proměnlivé, což odráží silnou regionální variabilitu extrémních konvektivních srážek.

Klíčová slova: extrémní srážky – návrhová hodnota srážky – klimatická změna – klimatický model

Introduction

In recent decades, changes in the nature of extreme precipitation have been observed in Europe. In particular, intense short-term rainfall events are becoming more frequent and intense in many regions of Europe (e.g., C3S/ECMWF and WMO 2026). Ongoing climate change is generally expected to lead to a further intensification of precipitation extremes due to the increased water-holding capacity of the warmer atmosphere. However, the thermodynamic contribution can be significantly modified by dynamic processes at regional scales (IPCC 2021).

Regional climate models (RCMs) are used to estimate future changes in climate variables and provide also information on changes in precipitation extremes at the regional level. However, their outputs suffer from uncertainties, which stem primarily from natural climate variability or the models' limited ability to accurately represent complex physical processes in the climate system (e.g., processes associated with convection).

Convection-Permitting Models (CPMs) represent a significant progress in simulating short-term precipitation extremes. They allow for the explicit simulation of convective processes without the need for parameterization thanks to the high spatial resolution. CPMs better capture the structure and intensity of thunderstorm systems and often provide more realistic estimates of changes in short-term extreme precipitation (e.g. Prein et al. 2015; Kendon et al. 2017). CPMs are most beneficial on timescales of hours (Van de Vyver et al. 2021). Although CPMs offer new possibilities for assessing climate risks, their results are still subject to uncertainties.

This paper presents the results of an analysis of future trends in extreme 1–48-hour precipitation characteristics based on hourly precipitation totals from simulations of the convection-permitting ALADIN-CLIMATE/CZ model conducted as part of the PERUN project. Trends in the characteristics of annual maximum 1–48hour precipitation totals across the Czech Republic, as well as changes in the derived design values for precipitation totals under the SSP5-8.5 and SSP2-4.5 scenarios are assessed.

Data

The assessment of changes in the characteristics of extreme precipitation is based on hourly precipitation totals simulated by the ALADIN-CLIMATE/CZ Regional Climate Model (RCM), which belongs to the group of Convection-Permitting Models (CPMs). These simulations were conducted as part of the PERUN project. They were performed with a horizontal resolution of 2.3 km, using the historical, SSP5-8.5 and SSP2-4.5 scenarios.

The outputs of the ALADIN-CLIMATE/CZ were compared with the outputs of two other RCMs from CPMs group of the CORDEX FSP Convection project (Tab. 1). However, these outputs only cover a limited part of the assessed time period. Based on this limited sample, the ALADIN-CLIMATE/CZ outputs appear to be in relatively good agreement with other CPMs.

To compare model outputs with observations, measurements of precipitation intensity from 164 stations of the Czech Hydrometeorological Institute (CHMI) were used. These stations were selected due to the sufficient length (mostly more than 25 years) of joined digitalized pluviographs records and automatic rain gauge measurement series of rainfall in temporal resolution of 1 and 10 minutes from 1951–2022.

Table 1. The used regional climate models.

RCM	GCM	Scenario	from	to
GERICS-REMO2015	ECMWF-ERAINT	evaluation	2000	2009
	MPI-M-MPI-ESM-LR	historical	1996	2005
		rcp85	2041	2050
HadREM3-RA-UM10.1	ECMWF-ERAINT	evaluation	2000	2010
	HadGEM3-GC3.1-N512	historical	1998	2007
		rcp85	2040	2105
ALADIN-CLIMATE/CZ	CNRM-ESM2-1	historical	1980	2014
		rcp45	2015	2100

Methods

To assess changes in extreme precipitation, the annual maxima of precipitation totals with durations of 1–48 hours were used. The spatial statistical characteristics (e.g., Q50–median, Q90–90th quantile) over the territory of the Czech Republic were derived for each year, representing the most extreme precipitation values in the region. The time evolution of these characteristics was then assessed.

In addition, changes in design values for 2 to 100year precipitation events were calculated. Extreme precipitation quantiles were estimated using regional frequency analysis (RFA) with a buffer radius of 50 km. Changes in design values were evaluated for two projection periods (2035–2064 and 2070–2099) and compared to the historical reference period of 1985–2014. The changes are expressed as the relative ratio of design values (i.e., future to historical period).

Results

Comparison of ALADIN-CLIMATE/CZ with Observations

For short precipitation accumulation durations (1–2 h), the spatial statistics of simulated annual maxima are generally lower than those derived from station observations. The difference is smaller for the upper spatial quantiles, indicating better agreement between the upper tails of the observed and simulated spatial distributions.

The agreement between observations and model simulations improves with increasing accumulation duration. This is well illustrated in Fig. 1, showing a comparison of model outputs and observations for 1hour and 6hour precipitation totals. This behaviour is consistent with the fact that longer-duration precipitation totals are less sensitive to the exact location and timing of individual convective cores and integrate precipitation from moving and evolving precipitation systems.

Several factors may contribute to the differences at short durations. Although ALADIN-CLIMATE/CZ is a convection-permitting model with a horizontal grid spacing of 2.3 km, the most intense small-scale convective cores may still not be fully resolved. In addition, station observations and model grid-cell values have different spatial support. Conversely, the relatively sparse station network may fail to capture some localized precipitation maxima. The comparison is also affected by the different spatial sampling of the observational and model datasets, as the spatial statistics are calculated from 164 stations and from a substantially larger number of model grid points.

The underestimation of observed short-duration maxima should therefore be interpreted as a combination of model limitations, differences in spatial support and spatial sampling, and the high spatial and temporal variability of convective precipitation. Despite this bias in the absolute historical values, the model simulations show a consistent increase in extreme precipitation characteristics under future climate conditions, particularly under the SSP5-8.5 scenario. However, the magnitude of the projected changes should be interpreted with caution, as the analysis is based primarily on a single climate-model simulation.

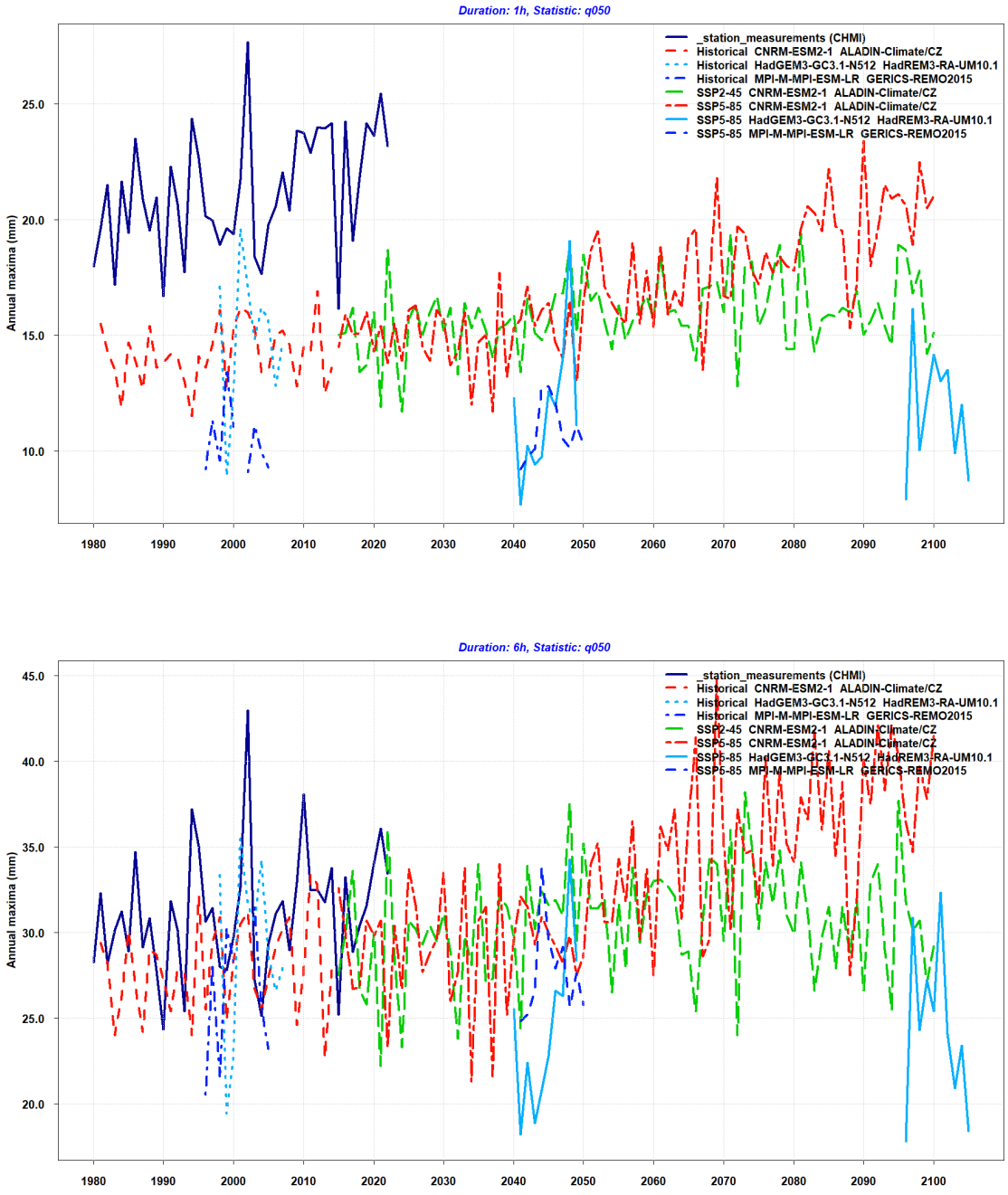


Fig. 1. Spatial characteristics of the annual maximum precipitation totals with durations of 1 hour (top) and 6 hours (bottom) given by the spatial 50th quantile (median) over the territory of the Czech Republic. The observed data (represented by CHMI station measurements) and available historical CPM simulations for the historical period, as well as values simulated by CPMs under the SSP5-8.5 and SSP2-4.5 scenarios for the future period (up to the year 2100) are shown.

Trends in the Characteristics of Annual Maximum 1–48-Hour Precipitation Totals

The simulations under both scenarios show a long-term increase in characteristics of extreme precipitation totals for all analyzed durations. The SSP5-8.5 scenario shows a significantly stronger increase than the SSP2-4.5 scenario. According to the SSP5-8.5 scenario, there will be a sustained increase in extreme precipitation totals, while in the milder SSP2-4.5 scenario, the increase will continue until the middle of the 21st century, after which there will be a plateau or even a slight decline (depending on the selected statistical characteristic and duration).

More significant changes occur for shorter precipitation durations. The model indicates a 30–40% increase in extreme precipitation totals according to the SSP5-8.5 scenario, compared to the 2001–2020 period (Tab. 2).

The temporal evolution of the spatial 50th quantile values of annual maximum precipitation totals simulated by the ALADIN-CLIMATE/CZ model under the SSP5-8.5 and SSP2-4.5 scenarios is shown in Fig. 2.

Table 2. Average values of the 50th and 90th quantiles calculated from annual maximum precipitation totals over the Czech Republic for 20-year periods from 2041 to 2100, expressed relative to the 2001–2020 period as simulated by the ALADIN-CLIMATE/CZ model under the SSP2-4 and SSP5-8.5.

		SSP2-4.5				SSP5-8.5			
Spatial quantile	**Duration [h]**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**
Q50	1	1.06	1.08	1.09	1.09	1.00	1.08	1.21	1.37
	2	1.06	1.10	1.13	1.10	1.02	1.08	1.20	1.36
	3	1.07	1.11	1.13	1.09	1.03	1.08	1.21	1.35
	6	1.04	1.09	1.13	1.05	1.01	1.03	1.18	1.30
	12	0.99	1.09	1.11	1.04	1.01	1.06	1.22	1.30
	24	0.95	1.04	1.07	1.00	1.02	1.03	1.20	1.19
	48	0.88	0.96	1.02	0.94	0.95	0.97	1.12	1.13
Q90	1	1.03	1.06	1.16	1.15	1.01	1.20	1.24	1.41
	2	1.01	1.07	1.15	1.13	1.02	1.15	1.23	1.38
	3	1.01	1.08	1.15	1.11	1.03	1.12	1.24	1.35
	6	0.99	1.07	1.09	1.06	1.03	1.07	1.25	1.29
	12	0.96	1.01	1.03	1.02	0.96	1.06	1.25	1.24
	24	0.86	0.97	1.00	0.95	0.88	0.97	1.10	1.11
	48	0.86	0.96	1.07	0.91	0.90	1.00	1.13	1.15

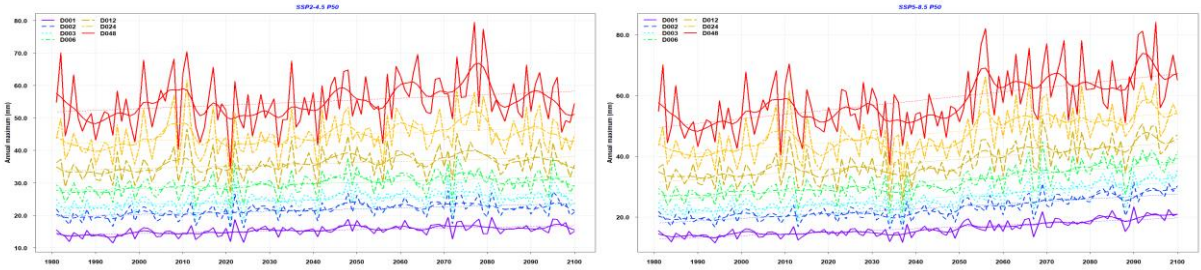


Fig. 2. Temporal evolution of annual maximum precipitation totals with durations of 1, 2, 3, 6, 12, 24, and 48 hours, simulated by the ALADIN-CLIMATE/CZ model under the SSP5-8.5 and SSP2-4.5 scenarios. The figure shows the spatial 50th quantile values of annual maximum precipitation totals over the territory of the Czech Republic.

Relative Changes in Design Precipitation

Relative changes in design precipitation show an increase in extreme precipitation across all durations and return periods (Fig. 3).

In the SSP2-4.5 scenario, relative changes range from approximately 10–30%, with higher values occurring in the more distant future period. In the SSP5-8.5 scenario, relative changes are more pronounced and increase with both return period and time horizon.

The highest relative increase in design precipitation reaches approximately 40–55% and is particularly evident for short precipitation durations and high return periods (50 and 100 years) in the more distant future period of 2070–2099.

The differences between individual rainfall durations are gradual, and the relative changes do not show a sudden increase for short-duration rainfall.

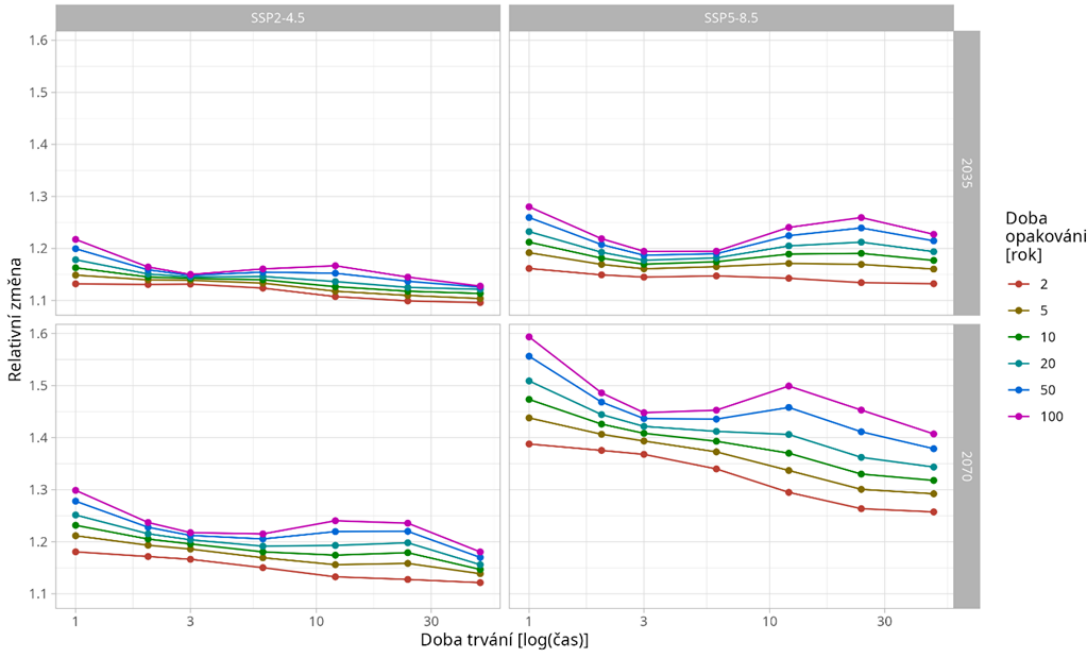


Fig. 3. Relative changes in design precipitation for the SSP2-4.5 (left) and SSP5-8.5 (right) scenarios. The figure shows the ratio of design estimates for future periods (2035–2064 and 2070–2099) relative to the reference period 1985–2014, depending on the duration of precipitation (1–48 h) and the return period. The top figures correspond to the projection period 2035–2064, and the bottom figures to the period 2070–2099. The values represent the median of relative changes in design precipitation across all grid points of the model in the Czech Republic and surrounding areas.

Conclusion

The ALADIN-CLIMATE/CZ simulations indicate an increase in the intensity of extreme precipitation across a range of accumulation durations, from hourly to multi-day totals, under both SSP2-4.5 and SSP5-8.5. The projected increase is generally stronger under SSP5-8.5, particularly for short-duration extremes and toward the end of the 21st century. Changes in design precipitation are also positive across the analysed durations and return periods, with the largest increases occurring for short durations and high return periods under SSP5-8.5.

The analysis is based primarily on a single convection-permitting climate model. Consequently, model uncertainty cannot be quantified, and the magnitude of the projected changes should be interpreted with caution. The availability of sufficiently long simulations from other convection-permitting regional climate models was limited.

Acknowledgments

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