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Characteristics of Convective and Stratiform Precipitation in a Changing Climate

(Charakteristiky konvektivních a vrstevnatých srážek v měnícím se klimatu)

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Abstract: Precipitation can be divided into two main types according to its formation mechanism: convective and stratiform. These types differ not only in their origin, but also in their characteristics, intensity, and impacts on the landscape and water management. This study analyses present-day characteristics of both precipitation types and assesses their future changes. We focus on the warm half of the year (April–September), when precipitation is particularly important for agriculture. Four precipitation characteristics are evaluated: total seasonal precipitation, number of rainy days, rain intensity index and seasonal maximum. Present climate conditions are described using observed time series from 19 meteorological stations for the period 1982–2021. Individual precipitation events are classified as convective or stratiform using an automated algorithm based on SYNOP reports. Future changes are assessed using simulations from the ALADIN-CLIMATE/CZ model. To account for uncertainties in future greenhouse gas emissions, two emission scenarios (SSP2-4.5 and SSP5-8.5) and two future periods (2060–2079 and 2080–2099) are considered.

Keywords: convective precipitation – stratiform precipitation – regional climate model – climate change projections – Central Europe

Abstrakt: Srážky lze podle mechanismu vzniku rozdělit na dva základní typy: konvektivní a vrstevnaté. Tyto typy se liší nejen svým původem, ale také svými charakteristikami, intenzitou i dopady na krajinu a hospodaření s vodou. Cílem této studie je analyzovat současné charakteristiky obou typů srážek a posoudit jejich budoucí změny. Zaměřujeme se na teplou polovinu roku (duben–září), kdy jsou srážky klíčové zejména pro zemědělství. Hodnotíme čtyři srážkové charakteristiky: celkový sezónní úhrn, počet srážkových dnů, index intenzity srážek a sezónní maximum. Pro popis současného klimatu používáme pozorované časové řady z 19 meteorologických stanic za období 1982–2021. Jednotlivé srážkové události rozdělujeme na konvektivní a vrstevnaté pomocí automatizovaného klasifikačního algoritmu založeného na SYNOP hlášeních. Budoucí vývoj hodnotíme na základě výstupů modelu ALADIN-CLIMATE/CZ. S ohledem na nejistotu budoucích koncentrací skleníkových plynů analyzujeme dva emisní scénáře (SSP2-4.5 a SSP5-8.5) a dvě časová období (2060–2079 a 2080–2099).

Klíčová slova: konvektivní srážky – vrstevnaté srážky – regionální klimatický model – projekce změny klimatu – střední Evropa

Introduction

Precipitation is commonly classified into convective and stratiform types, which differ in their formation mechanisms, typical rainfall intensity, spatial extent, and hydrological impacts. Convective precipitation is typically characterized by high rainfall intensities and short duration and may lead to flash flooding.

It is often accompanied by hazardous weather phenomena such as lightning and hail. In contrast, stratiform precipitation generally exhibits lower rainfall intensity, but its longer duration and broader spatial extent can result in high cumulative precipitation totals, prolonged soil saturation, and widespread flooding. In a warming climate, changes in atmospheric moisture content, instability, and circulation patterns may influence the frequency, intensity, duration, and spatial organization of both convective and stratiform precipitation.

A major challenge in the analysis of convective and stratiform precipitation is their reliable distinction. Many commonly used classification methods rely on radar or satellite observations, which provide detailed information on precipitation structure and intensity, but their spatial or temporal coverage is often insufficient for climatological analyses (Anagnostou 2004; Wang et al. 2021). Station-based approaches, particularly those based on SYNOP observations, therefore represent a practical alternative for the long-term analysis of precipitation type variability and change (Rulfová and Kyselý 2013).

Only a limited number of studies have examined changes in convective and stratiform precipitation separately, and many of them focus on relatively small regions (Rulfová and Kyselý 2014; Feloni et al. 2019; Chernokulsky et al. 2019). Convection-permitting climate models provide a more realistic representation of convective processes than coarser-resolution models and are therefore increasingly used to investigate future changes in extreme precipitation (e.g., Poncet et al. 2025). However, despite growing interest in precipitation change under climate warming, studies that explicitly distinguish between convective and stratiform precipitation in analyses of future trends remain rare (Rulfová et al. 2017). Most existing research still focuses on total precipitation rather than on its individual components.

This study investigates convective and stratiform precipitation in the Czech Republic using both station observations and high-resolution simulations from the ALADIN-CLIMATE/CZ model. We analyse changes in seasonal precipitation totals, the number of precipitation days, rain intensity index, and seasonal maxima under both present and future climate conditions.

Data and methods

The precipitation dataset is based on SYNOP observations from 19 stations of the Czech Hydrometeorological Institute. Daily totals of convective and stratiform precipitation were distinguished using a classification procedure that partitions 6-hour precipitation amounts into convective and stratiform components based on hourly weather observations and cloud-type information (Rulfová and Kyselý 2013). In this framework, convective precipitation is mainly associated with cumulus and cumulonimbus clouds and is usually represented in SYNOP records by phenomena such as showers, thunderstorms and hail. In contrast, stratiform precipitation is associated primarily with nimbostratus and altostratus clouds and with drizzle or long-lasting precipitation.

We focus on the warm half of the year (April–September), when precipitation is particularly important for agriculture. For both convective and stratiform precipitation, we analyse trends in seasonal precipitation totals (Sum), the number of rainy days (RDays), the rain intensity index (RII), and seasonal maximum (Rmax). A rainy day is defined as a day with more than 1 mm of convective or stratiform precipitation, whereas RII expresses the mean precipitation amount per rainy day. All indices were computed annually for each station over the 1982–2021 period. Temporal trends were quantified using Sen's slope estimator, and their significance was tested with the Mann–Kendall test at the 0.1 significance level.

Future changes in convective and stratiform precipitation are analysed using simulations from the convection-permitting regional climate model ALADIN-CLIMATE/CZ (Beranová et al. 2025), developed from the ALADIN numerical weather prediction system. Simulations are driven by the global climate model CNRM-ESM2-1 and provide hourly convective and stratiform precipitation outputs, which are aggregated to daily totals for this study.

Model performance is evaluated by comparing simulated convective and stratiform precipitation in the historical run with station observations for reference period 1991–2010 using the nearest grid point to each station. Future changes are then assessed for the periods 2060–2079 and 2080–2099 under the SSP2-4.5 and SSP5-8.5 scenarios (Riahi et al. 2017). Projected changes are expressed as percentage differences relative to the reference period and are analysed over all grid points within the Czech Republic.

Results

Fig. 1 presents trends in observed stratiform and convective precipitation characteristics at individual stations during 1982–2021 and Tab. 1 summarizes the mean trend across the 19 stations together with the minimum and maximum station values. For stratiform precipitation, negative trends prevail in both Sum and RDays, with mean trends of −1.2%/10yrs and −2.7%/10yrs, respectively. The trend in Sum is not statistically significant at any station, whereas RDays shows a significant negative trend at seven stations. In contrast, RII shows predominantly positive trends, averaging 1.8%/10yrs, although statistical significance is reached at only two stations. No trend is detected at eight stations, while two stations show negative trends. Positive trends also prevail in Rmax, with an average increase of 2.8%/10yrs, but statistical significance is again limited, occurring at only two stations.

In contrast to stratiform precipitation, convective precipitation exhibits a markedly different trend structure, with positive tendencies prevailing for all characteristics except RII. Sum shows a statistically significant increase at nine stations, whereas only three stations exhibit a slight decrease. The mean trend across all stations is +8.1%/10yrs. RDays displays a similarly robust increase, with significant positive trends at 11 stations and no negative trends observed, yielding an average trend +8.9% /10yrs. Trends in Rmax are less spatially consistent. Although the mean trend is +1.2%/10yrs, negative trends occur at more stations than positive trends, and only one station shows a statistically significant change. In contrast, RII exhibits a prevailing decrease, with an average trend of −1.2%/10yrs. Negative trends are found at 10 stations, including four statistically significant ones, whereas positive trends occur at six stations but are not statistically significant.

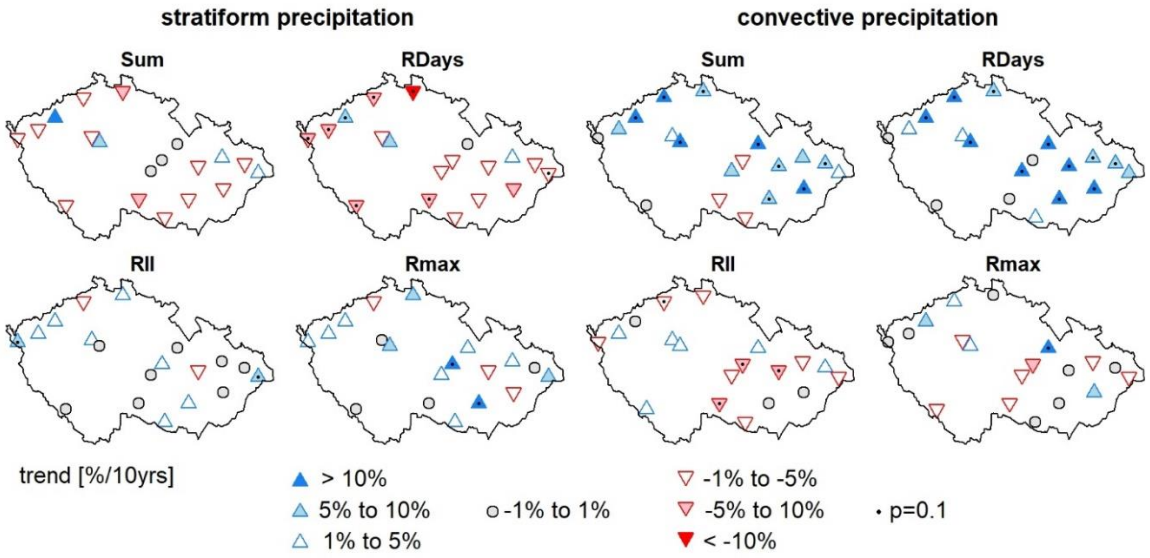


Fig. 1. Trends in stratiform (left) and convective (right) precipitation characteristics at 19 stations for the period 1982–2021. Black dots inside the triangles indicate statistically significant trends at the 0.1 level.

Table 1. Trend magnitudes expressed as relative changes (%/10 years) in the examined characteristics. Trends are calculated for the period 1982–2021. Average, minimum (min), and maximum (max) values across the 19 stations are presented.

	Stratiform precipitation			**Convective precipitation**		
	average	min	max	average	min	max
Sum	−1.2	−6.6	10.3	8.1	−4.7	25.6
RDays	−2.7	−10.3	7.6	8.9	0.0	24.0
RII	1.8	−2.7	6.2	−1.2	−5.5	3.6
Rmax	2.8	−3.9	11.7	1.2	−5.4	24.0

The reliability of climate change projections depends strongly on the ability of climate models to realistically simulate precipitation. Fig. 2 compares the characteristics of stratiform, and convective precipitation simulated by the ALADIN-CLIMATE/CZ model with those observed at stations during the reference period 1991–2010. The model substantially overestimates Sum and RDays, with larger biases for stratiform than for convective precipitation. On average, the model simulates 64 stratiform and 48 convective precipitation days per season, more than twice the observed means of 27 and 21 days, respectively. This excessive value of RDays contributes to an overestimation of Sum. For stratiform precipitation, the model simulates a mean Sum of 352 mm, compared with 224 mm in the observations. A similar bias is found for convective precipitation, for which the model produces an average of 226 mm, whereas the observed station mean is 166 mm.

By contrast, the model underestimates both RII and Rmax, and these negative biases are more pronounced for convective precipitation. In the station observations, RII is similar for stratiform and convective precipitation, averaging 7.3 and 7.6 mm/day, respectively. The model, however, simulates substantially lower values, with means of 5.1 mm/day for stratiform and 4.2 mm/day for convective precipitation. A comparable pattern is found for Rmax. Observed values are again similar for stratiform and convective precipitation, reaching 32 and 29 mm, respectively, whereas the model simulates lower maxima of 25 and 20 mm.

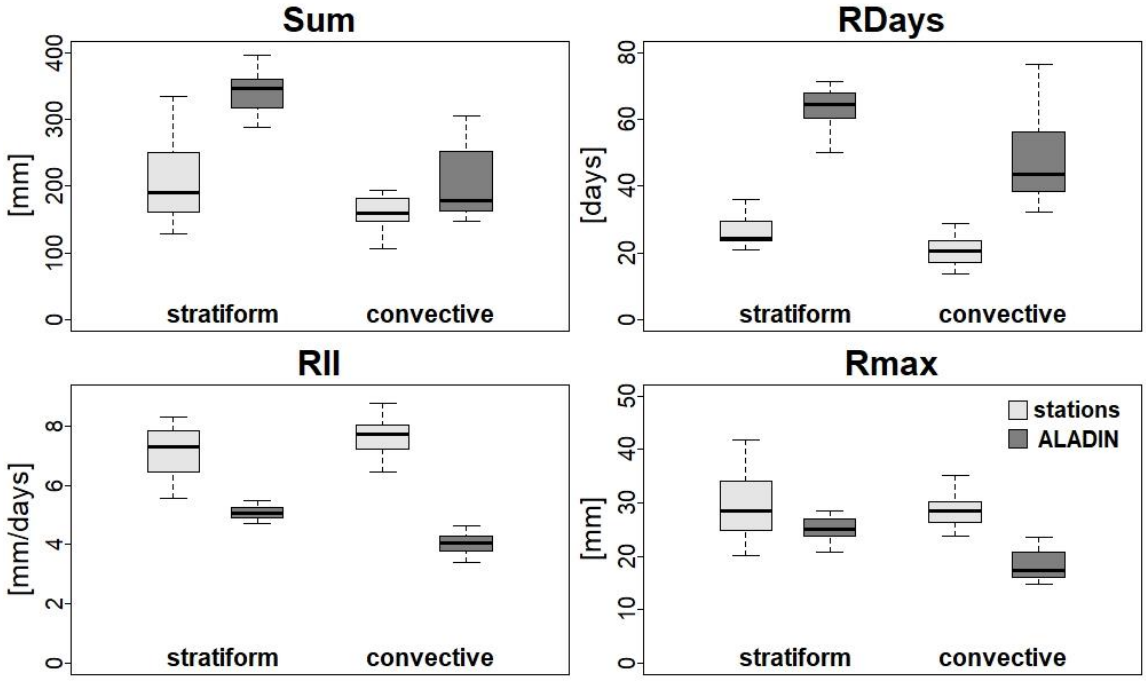


Fig. 2. Comparison of stratiform and convective precipitation characteristics between station data and historical run of the ALADIN-CLIMATE/CZ model for the period 1991–2010. Boxplots represent values from 19 stations (light grey) and nearest model grid points (dark grey).

Projected changes in stratiform and convective precipitation characteristics are summarized in Tab. 2 and their spatial distribution under the SSP5-8.5 scenario for the late 21st century (2080–2099) is shown in Fig. 3. Overall, projected changes differ between the two scenarios, with generally larger changes projected under SSP5-8.5 than under SSP2-4.5.

For stratiform precipitation, the most consistent signal is a decrease in RDays. For the period 2080–2099, the mean projected reduction exceeds 11% under both scenarios. Changes in Sum are comparatively small, although a decrease of about 10% is projected under SSP2-4.5 in 2080–2099. In contrast, both RII and Rmax are projected to increase, especially under SSP5-8.5, where the mean increases exceed 12%. Together, these results indicate a future shift toward less frequent but more intense stratiform precipitation events.

For convective precipitation, changes in Sum are relatively small under SSP2-4.5. In contrast, SSP5-8.5 shows a clear increase in convective precipitation totals, exceeding 17% in 2080–2099 relative to the reference period. The remaining convective precipitation characteristics exhibit a consistent direction of change across both scenarios. The model projects a modest decrease in RDays, accompanied by an increase in RII. However, the reduction in RDays is more pronounced under SSP2-4.5 than under SSP5-8.5. The largest projected changes are found for extreme convective precipitation. Under SSP5-8.5, Rmax is projected to increase by 37.3% for the late 21st century relative to the reference period.

Table 2. Mean projected changes in stratiform and convective precipitation characteristics, expressed as percentages relative to the model's historical run for the reference period 1991–2010. Values represent averages across all grid points within the Czech Republic.

	Stratiform precipitation				**Convective precipitation**			
	Sum	RDays	RII	Rmax	Sum	RDays	RII	Rmax
Scenario SSP2-4.5								
2060–2079	1.1	−3.3	5.5	10.0	6.0	−1.3	8.0	15.9
2080–2099	−10.3	−11.9	2.0	1.8	−1.7	−7.5	7.6	10.4
Scenario SSP5-8.5								
2060–2079	4.5	−5.8	12.1	19.9	12.3	−0.5	15.2	26.5
2080–2099	−2.8	−13.2	12.6	13.3	17.5	−3.4	25.0	37.3

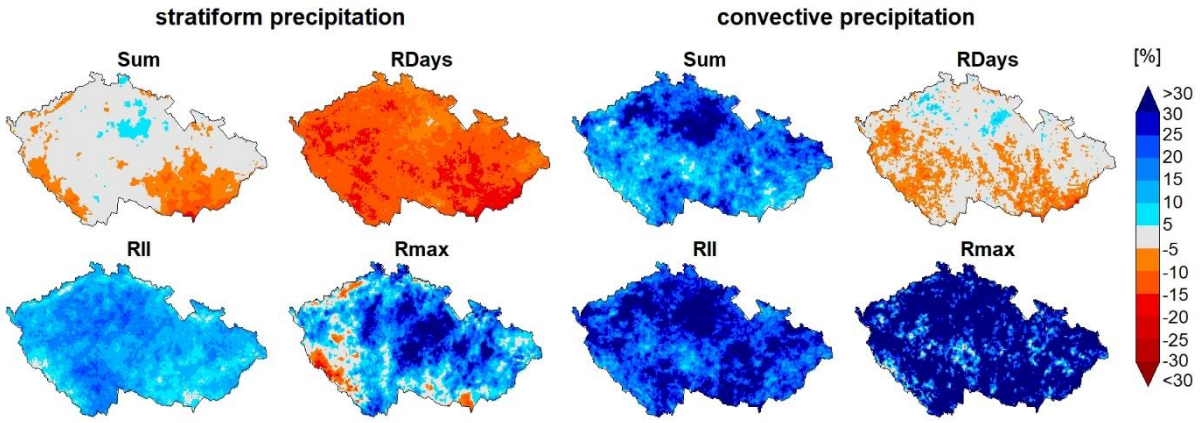


Fig. 3. Projected changes in stratiform (left) and convective (right) precipitation characteristics for 2080–2099 under the SSP5-8.5 scenario, expressed as percentages relative to the model's historical run for the reference period 1991–2010.

Conclusion

This study investigated warm-season (April–September) changes in stratiform and convective precipitation over the Czech Republic using a combination of long-term station observations for 1982–2021 and high-resolution simulations from the ALADIN-CLIMATE/CZ regional climate model. The analysis aimed to quantify observed trends, assess the model's ability to represent precipitation

characteristics, and examine future changes under the SSP2-4.5 and SSP5-8.5 scenarios. The principal results can be summarized as follows:

- The ALADIN-CLIMATE/CZ model substantially overestimates Sum and RDays, while underestimating RII, particularly for convective precipitation.
- Stratiform precipitation in observations exhibits a generally weak decreasing tendency in Sum and RDays, while Rmax shows a small increase. Most of these trends are not statistically significant. Future projections indicate a decrease in RDays, accompanied by increases in RII and Rmax, particularly under SSP5-8.5.
- Convective precipitation in observations reveals statistically significant increases in Sum and RDays, while RII tends to decrease. Future projections indicate further strengthening of convective precipitation, particularly under SSP5-8.5, with increases in Sum, RII and Rmax. The largest projected changes are found for Rmax, with increases exceeding 35% relative to the reference period.

Overall, the results indicate a future shift towards more intense warm-season precipitation in the Czech Republic, especially for convective events. This increase in precipitation intensity and extremes may contribute to a higher frequency and severity of hydrological hazards in the Czech Republic.

Acknowledgments

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