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Selected characteristics of precipitation events and their potential evolution with rising temperature in the 21st century

(Vybrané charakteristiky srážkových událostí a jejich možný vývoj s nárůstem teploty v 21. století)

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Abstract: This study examines changes in two characteristics of precipitation events (PE) in relation to the projected increase in ground temperature during the warm season throughout the 21st century. The study analyses observed hourly precipitation totals at 97 stations in the Czech Republic from 1998 to 2014, hourly precipitation totals from reanalysis for the period 1990–2014, and projected precipitation totals for the period 2026–2100 under two future climate scenarios (SSP2-4.5 and SSP5-8.5). PE is defined as a continuous series of hourly precipitation values with a threshold of at least 0.2 mm and a duration of 1 to 23 hours. The ALADIN-CZ numerical weather prediction model was used to calculate reanalysed PEs, and the ALADIN-CLIMATE/CZ regional climate model was used to calculate PEs for the 25-year periods 2026–2050, 2051–2075, and 2076–2100. The dependence of (i) the relative frequency of PE, and (ii) of the relative total precipitation of PE on duration and ground temperature was studied. The results show that there is a quantitative difference between observed and reanalysed PE. The main difference lies in the fact that reanalysed data provide longer duration PE for higher temperatures, for which observed data show no PE. Conversely, reanalysed and projected PEs show consistent results. The main finding of the study is that the duration of PEs shows no change with increasing temperature.

Keywords: precipitation – temperature – precipitation events – reanalysis – ALADIN

Abstrakt: Tato studie zkoumá změnu dvou charakteristik srážkových událostí (PE) v souvislosti s předpokládaným zvýšením přízemní teploty v teplé části roku v průběhu 21. století. Studie analyzuje naměřené hodinové srážkové úhrny na 97 stanicích v České republice v letech 1998–2014, hodinové srážkové úhrny z reanalýzy za období 1990–2014 a předpokládané srážkové úhrny pro období 2026–2100 pro dva budoucí klimatické scénáře (SSP2-4.5 a SSP5-8.5). PE je definována jako souvislá řada hodinových hodnot srážek s prahovou hodnotou nejméně 0,2 mm a trváním od 1 do 23 hodin. K výpočtu reanalyzovaných PE byl použit numerický model předpovědi počasí ALADIN-CZ a k výpočtu PE pro 25letá období (2026–2050, 2051–2075 a 2076–2100) byl použit regionální klimatický model ALADIN-CLIMATE/CZ. Studovala se závislost (i) relativní četnosti PE a (ii) relativní celkové srážky PE na délce trvání a teplotě vzduchu. Výsledky ukazují, že mezi pozorovanými a reanalyzovanými PE existuje kvantitativní rozdíl. Hlavní rozdíl spočívá v tom, že reanalyzovaná data poskytují delší PE pro vyšší teploty, pro které naměřená data již žádné PE nevykazují. Naopak reanalyzované a projektované PE

vykazují konzistentní výsledky. Hlavním výsledkem studie je, že délka trvání PE nevykazuje žádnou změnu s rostoucí teplotou.

Klíčová slova: srážky – teplota – srážkové události – reanalýza – ALADIN

Introduction

The impact of global climate change on precipitation patterns is influenced by thermodynamic processes, atmospheric circulation, and geographical characteristics (e.g., Myhre et al. 2019; Irwandi et al. 2023; Li et al. 2019; Schroeer and Kirchengast 2018; Lutsko and Cronin 2018; Shi and Durran 2015; IPCC 2023; Lenderink et al. 2011). It is reported that the increase in the intensity of extreme precipitation significantly exceeds the increase in average precipitation (e.g., Lenderink et al. 2011; Emori and Brown 2005). However, the link between intense precipitation and global warming is still not fully explained or described. Most studies are based on a fixed duration of precipitation. In contrast to this practice, in this study we focus on precipitation events lasting 1, 2, 3, … up to 23 hours and analyse their statistical characteristics as a function of surface temperature measured at a height of 2 m (T). Similar to our previous work (Sokol et al. 2024), we compare the results of measured precipitation and temperature values with the results of the reanalysis of the ALADIN-CZ numerical weather prediction (NWP) model and with climate projections calculated by the ALADIN-CLIMATE/CZ regional climate model.

Data

We focused on the warm half of the year (April–September) and on the territory of the Czech Republic. We used three types of data, as in the study (Sokol et al. 2024): (i) hourly precipitation measured by rain gauges at weather stations together with the corresponding 2-m air temperature, (ii) hourly precipitation and 2-m air temperature obtained from reanalysis using the ALADIN-CZ NWP model (Brožková et al. 2019; Sokol et al. 2022), and (iii) hourly precipitation and the corresponding 2-m air temperature projected by the ALADIN-CLIMATE/CZ (AC) climate model (Beranová et al. 2025) for two climate scenarios. We define a precipitation event (PE) as a continuous period of precipitation lasting from 1 to 23 hours, with an intensity of at least 0.2 mm·h^{-1}.

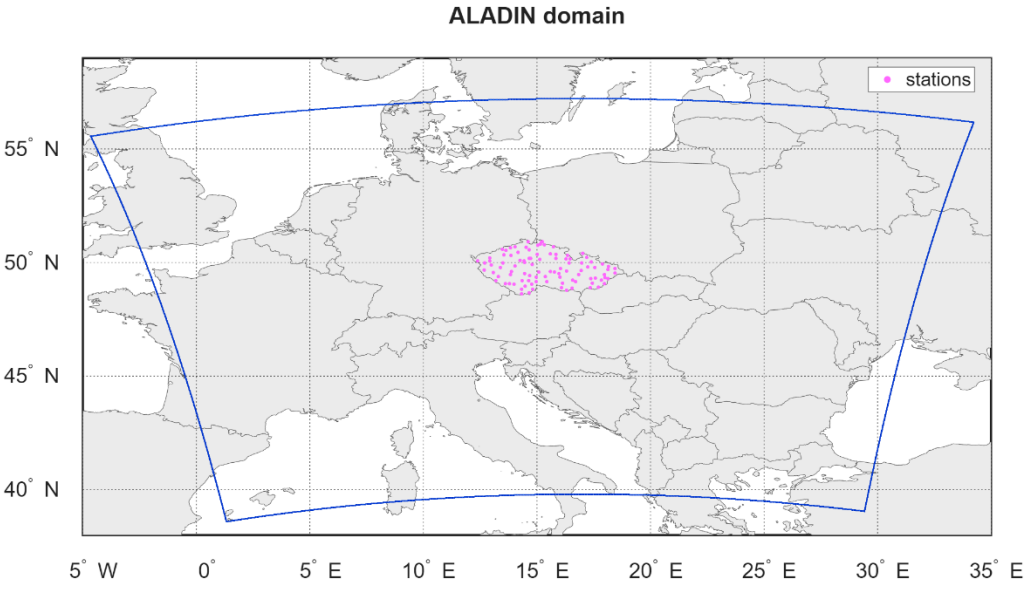


Fig. 1. Model domain (blue border line) of the ALADIN-CZ and the ALADIN-CLIMATE/CZ models. Pink dots show the position of rain gauge stations.

We used hourly precipitation data from 97 stations in the Czech Republic for the warm half of the year (April–September) during the period 1998–2014, obtained from the CLIDATA climatological database of the Czech Hydrometeorological Institute (Coufal and Tolasz 1998; Tolasz and Coufal 1998). The database contains hourly precipitation data for days with a daily precipitation total of at least 5 mm,

which account for approximately 87% of all days in the warm half of the year. Fig. 1 shows the model domain and the locations of the stations.

PEs derived from the reanalysis were defined in the same way as those derived from the observed data, using a threshold of 0.2 $mm \cdot h^{-1}$. The reanalyses were obtained from ALADIN-CZ model runs initialized at 00:00 UTC, with forecast data from 06:00 UTC to 06:00 UTC on the following day. Boundary and initial conditions were derived from ERA5 data, and the calculations were performed for the period April–September during 1990–2014. For comparison with observations, hourly precipitation and surface air temperature data from the grid cells closest to the rain-gauge stations were used. The reanalysis period covered 25 years.

Two projections of future climate were used for three 25-year periods extending to the year 2100 (2026–2050, 2051–2075, and 2076–2100). The first projection, designated SAD, used the CMIP6 SSP5–8.5 scenario (IPCC 2021), representing a very high-emission pathway with a substantial increase in coal use. The second projection, designated SAE, used the CMIP6 SSP2–4.5 scenario (IPCC 2021), representing a medium-emission pathway in which socioeconomic development follows historical trends without major changes. The ALADIN-CLIMATE/CZ model was used for the simulations, with the CNRM-ESM2-1 model serving as the driving global model.

The temperature assigned to the analysed precipitation data has a significant impact on the calculated temperature–precipitation relationship (e.g., Lenderink et al. 2011; Martínková and Hanel 2016; Busuioc et al. 2017). Based on our previous experience (Sokol et al. 2024), we used the air temperature measured one hour before the onset of precipitation, as this value is minimally affected by the precipitation that follows.

In our analysis of *PEs*, we focused on the following characteristics:

- The relative frequency of a *PE* of a given duration:

$$F(t,T) = n(t,T) / N, \qquad (1)$$

where *n(t,T)* denotes the number of *PEs* of duration *t* [h] at the pre-event temperature *T* [°C] and $N = \sum t \sum T\, n(t,T)$ denotes the total number of *PEs* [-].

- The relative total precipitation given by:

$$F_w(t,T) = w(t,T) / N_w, \qquad (2)$$

where *w(t,T)* denotes the total precipitation of duration *t* [h] at the temperature *T* [°C] and $N_w = \sum t \sum T\, w(t,T)$ the total precipitation in all *PEs* [mm].

In total, we analysed *N*=64 311 PEs, maximum value of *F*=2.67%, and N_w=3 968.9.

Method

The values of F as a function of *PE* duration and *T* are shown in Fig. 2 based on rain-gauge data. The relationship between *F* and *T* (Fig. 2a) clearly shows an increase in the number of *PEs* with increasing temperature up to approximately 14 °C, followed by a sharp decline. Above 25 °C, the number of *PEs* is very low, approaching zero. Fig. 2b shows that *PEs* occur most frequently at temperatures between 14 and 17 °C and have durations of up to 5 hours. *PEs* lasting 1–5 hours likely correspond to both convective and stratiform precipitation. The cumulative distribution (Fig. 2c) confirms that 1-hour *PEs* occur most frequently. Overall, 31% of *PEs* lasted 1 hour, while 24% lasted 2 hours. *PEs* lasting longer than 6 hours (less than 3%) or longer than 10 hours (approximately 1%) were much less frequent. Fig. 2

indicates that short-duration *PEs* dominate during the warm half of the year, which is consistent with expectations and empirical experience.

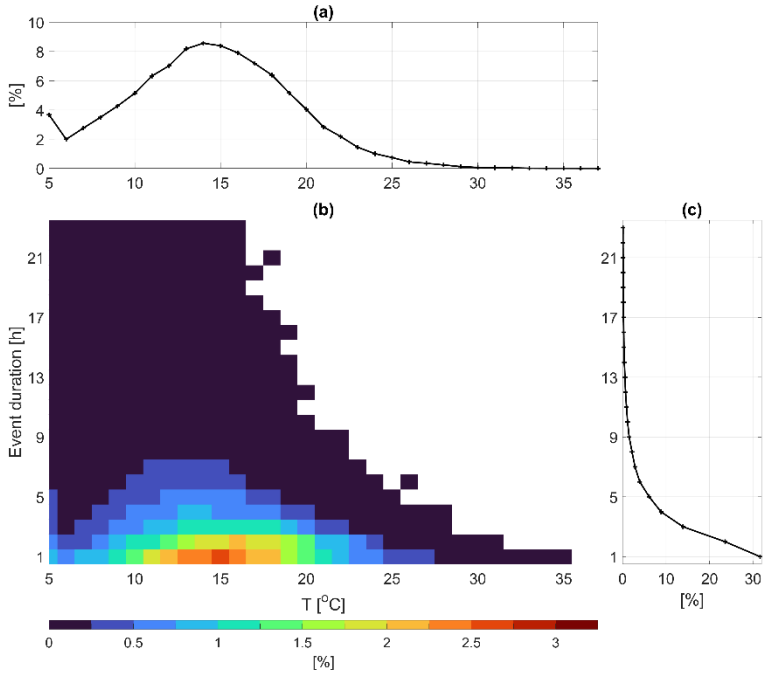


Fig. 2. Distribution of F [%] calculated using equation (1) from rain-gauge data. Panel (a) shows the frequency of PEs as a function of T. Panel (b) shows the frequency of PEs, expressed by colours, as a function of duration (y-axis) and T (x-axis). Panel (c) shows the frequency of PEs as a function of duration only.

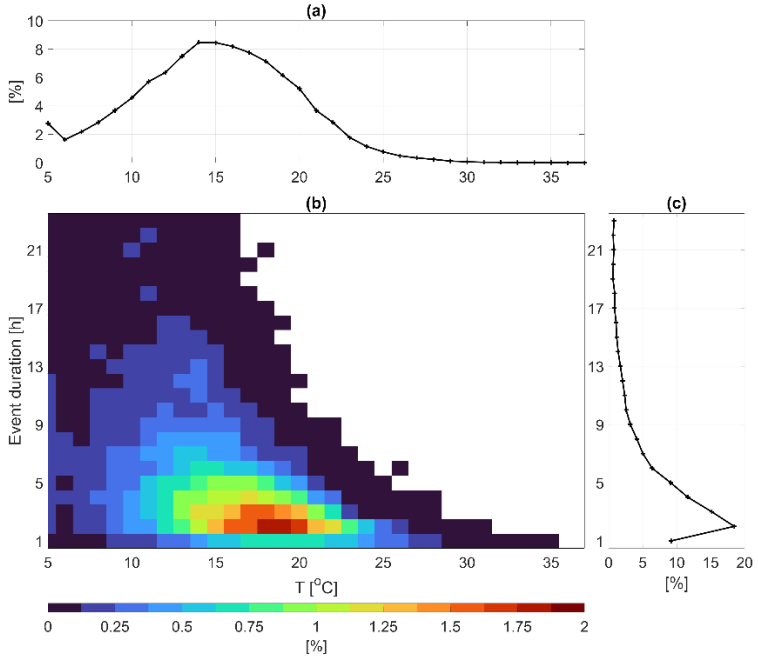


Fig. 3. The same as Fig. 2, but for F_w [%] calculated using equation (2).

Fig. 3 shows the distribution of F_w as a function of event duration and T based on rain-gauge data again. The results in Fig. 3a are very similar to those in Fig. 2a; however, the maximum values occur at slightly higher temperatures than in the case of F. The maximum values of F_w occur at temperatures of 18–19 °C. Fig. 3c shows that, in terms of F_w, *PEs* lasting 2 hours dominate with a frequency of 18%, whereas 1hour *PEs* account for only 9%. The higher contribution of 2hour *PEs* compared to 1hour *PEs* in the case of

F_w may still be related to short convective events that only slightly exceeded one hour in duration. However, the available data do not allow this hypothesis to be verified.

We performed the same analysis using *PEs* derived from the ALADIN-CZ reanalysis. The reanalysis covered the period from April to September during 1990–2014, during which a total of 725 906 *PEs* were identified. The maximum value of F was 0.85%, and N_w=1 113.2.

The values of N and N_w are substantially higher than those obtained from the observations, mainly because the analysed period is longer and the model data contain no missing values. It is interesting to note that the average precipitation per *PE* is similar for both datasets, amounting to 6.58 mm for the reanalysis and 6.24 mm for the observations. In contrast, the maximum observed precipitation total of 130.8 mm is nearly twice as large as the maximum value of 67.8 mm obtained from the reanalysis.

Figures 4 and 5 reveal a structure of F and F_w similar to that obtained from the observed *PEs* (Figures 2 and 3). The main difference is apparent at higher temperatures. In the ALADIN-CZ reanalysis, non-zero values occur throughout the entire temperature range; however, the values of F (Fig. 4) and F_w (Fig. 5) are considerably lower than those derived from the observations.

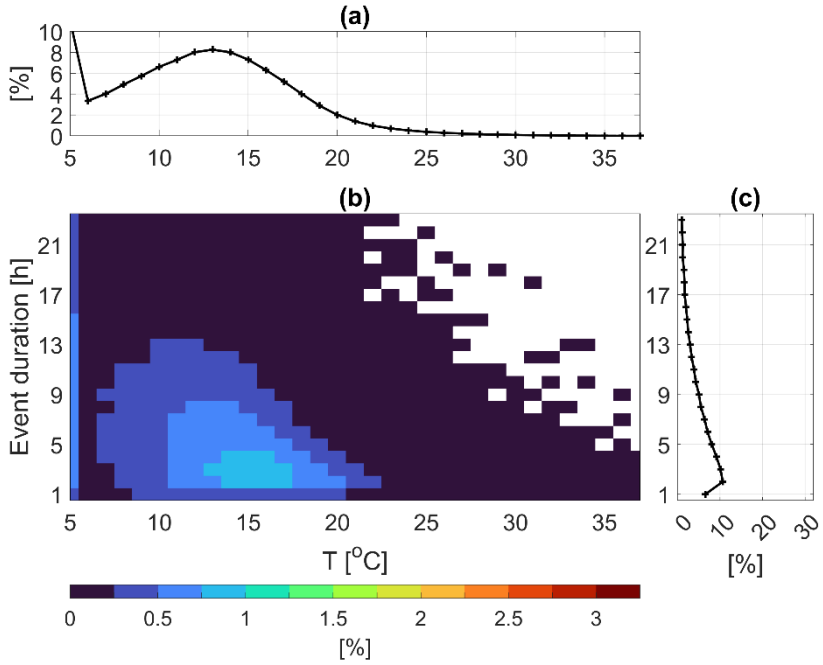


Fig. 4. Distribution of F [%] calculated by equation (1) of reanalysed PEs. The upper plot (a) shows the frequency of PEs as a function of ground temperature recorded before the onset of a PE. Plot (b) shows the frequency of PEs expressed by colours as a function of their duration (y-axis) and ground temperature (x-axis). Plot (c) on the right shows the frequency of PEs as a function of their duration.

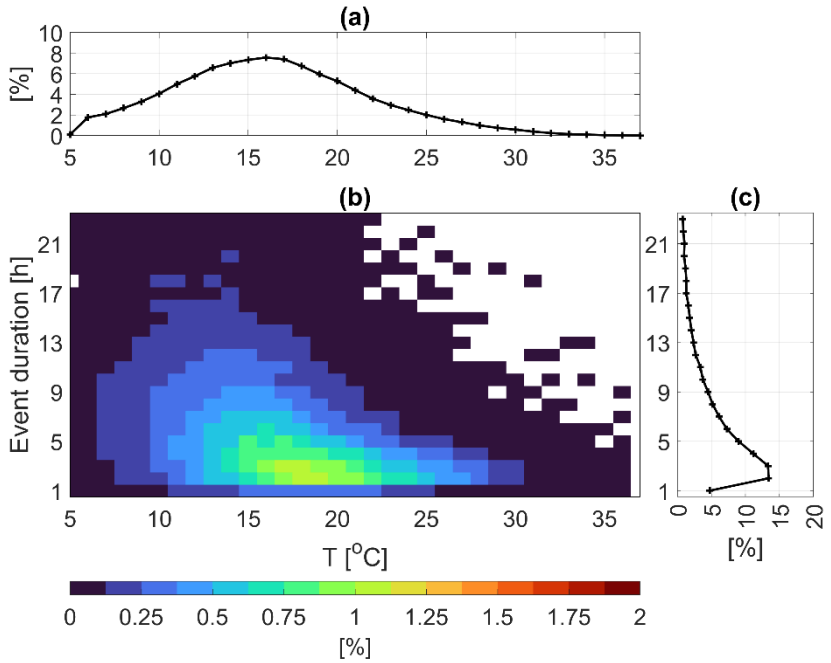


Fig. 5. The same as Fig. 4 but for F_w [%] calculated using equation (2).

As in the case of the observed and reanalysed *PEs*, we analysed projected *PEs* for both the SAD and SAE scenarios. Because the structures of *F* and F_w are very similar, only the results for F_w are presented (Fig. 6). Compared with the reanalysis, the projected distributions are smoother and extend over a broader temperature range. In the SAE scenario, the highest values shift towards temperatures higher by approximately 1–2 °C. In the SAD scenario, the shift is more pronounced, reaching approximately 18–22 °C. Fig. 6 suggests that increasing temperature does not substantially affect *PE* duration and that 2–3hour *PEs* are likely to remain the most common type of precipitation event in the future.

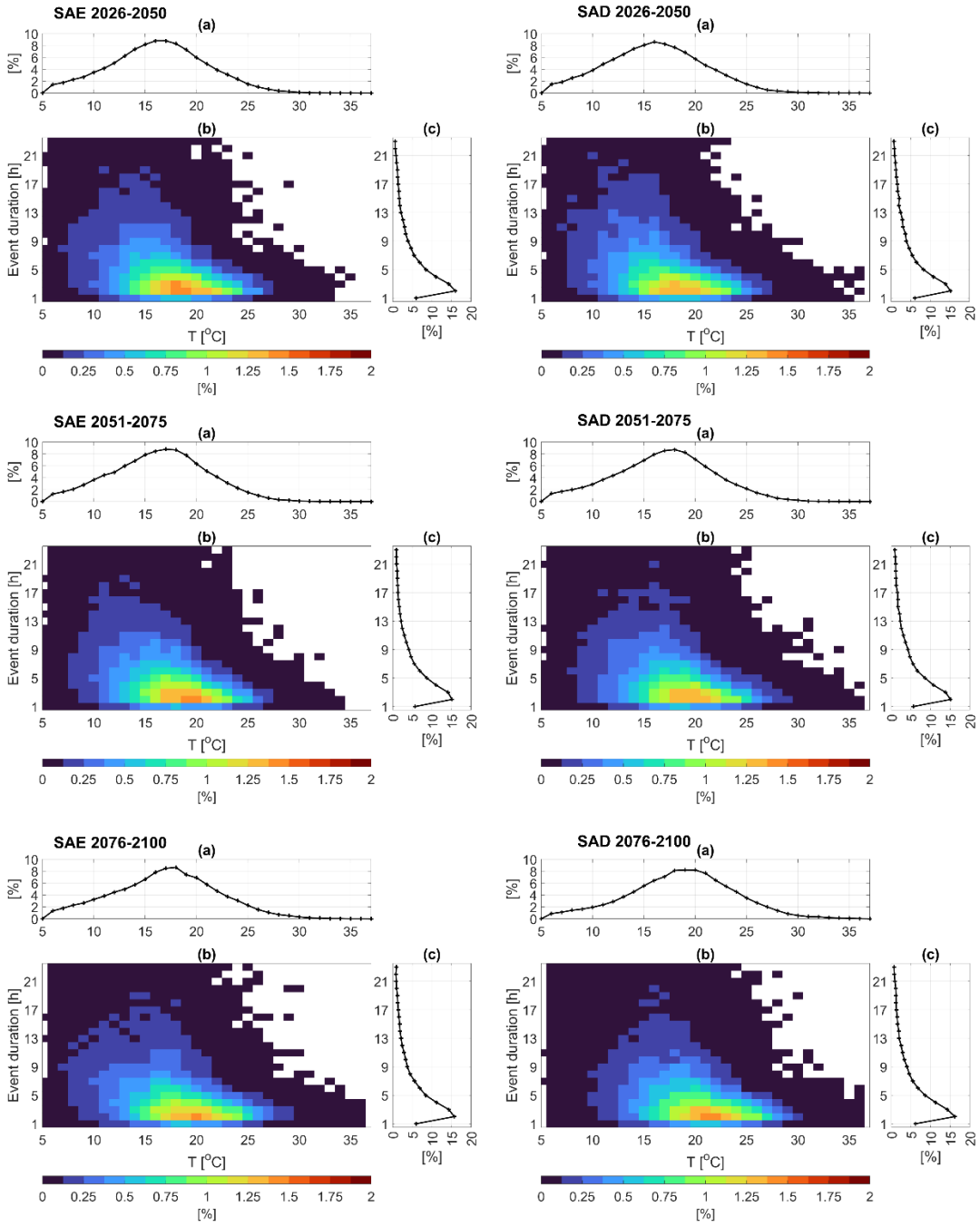


Fig. 6. F_w calculated using equation (2) for projected PEs under the SAE (left column) and SAD (right column) scenarios. Rows from top to bottom correspond to the periods 2026–2050, 2051–2075, and 2076–2100, respectively.

Discussion

The analysis of *PE* characteristics as a function of temperature is undoubtedly subject to considerable uncertainty. This is primarily because precipitation results from a sequence of atmospheric processes operating on a wide range of spatial and temporal scales. In addition, precipitation modelling is complex and therefore inherently uncertain. The results of *PE* analyses also depend on the definition of a *PE* and on the temporal resolution of the data, which in our case is 1 hour. To distinguish individual *PEs*, we used the commonly applied threshold of 0.2 mm·h^{-1}, with precipitation intensities below this threshold considered non-precipitating conditions.

Previous studies have shown that the choice of temperature used in the analysis has a substantial influence on the resulting temperature – precipitation relationship (Sokol et al. 2024; Lenderink et al. 2011). In our opinion, the observed or modelled temperature measured before the onset of precipitation is the most appropriate choice, because at that time the temperature has not yet been significantly affected by the subsequent precipitation.

The results of our study, as well as those of similar studies, depend on the ability of the model used to simulate precipitation. The ALADIN-CLIMATE/CZ model is a convection-permitting model with a high horizontal resolution (2.3 km), whose characteristics were evaluated by Beranová et al. (2025). Its performance can be considered comparable to that of similar state-of-the-art regional climate models.

In this study, we analysed *PEs* using the variables F and F_w, defined by equations (1) and (2), as functions of temperature and *PE* duration. We used normalized (relative) variables in order to assess the structure of *PEs* while at least partially reducing the impact of systematic model errors. The detailed results are presented and discussed in Section 3. More details concerning presented analysis are given in (Sokol et al. 2026).

Conclusion

The conclusions of this study can be summarized as follows:

The main difference between observed and modelled PEs lies in the concentration of short and weak precipitation events. While the observed data show a high concentration of weak 1hour events, the modelled data exhibit the highest concentration of 2hour and 3hour events.

The consistency between reanalysed and projected PEs allows us to estimate the relative impact of increasing temperature on future precipitation events. However, the quantitative expression of differences between observed and reanalysed PEs remains an important source of uncertainty.

Increasing temperature does not appear to substantially affect the duration of precipitation events in the future.

High temperatures do not necessarily imply high total precipitation amounts. For all analysed datasets, total precipitation associated with PEs increases with temperature up to a certain threshold. Beyond this threshold, total precipitation decreases despite further warming.

Acknowledgments

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