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# Analysis of rainfall time structures on a scale of hours

Miloslav Müller[a,b,*], Vojtěch Bližňák[a], Marek Kašpar[a]

[a] Institute of Atmospheric Physics CAS, Department of Meteorology, Boční II 1401, Prague 4 141 31, Czech Republic
[b] Charles University, Faculty of Science, Department of Physical Geography and Geoecology, Albertov 6, Prague 2 128 43, Czech Republic

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## ABSTRACT

The paper is motivated by the enormous variability of short-term rainfall time structures which need to be discretized into several typical variants and explained from the viewpoint of rainfall types producing them. We present six variants of the time structure of 6-h rainfalls in Czechia, distinguished by a novel methodology for designing synthetic hyetographs. Reference 6-h rainfall episodes were extracted from radar-derived precipitation time series with a time resolution of 10 min, adjusted by daily data from rain gauges. The variants were distinguished by three indexes that quantify the precipitation concentration within time steps from one to six hours. The episodes with steady precipitation intensity during the entire episode are mainly stratiform or possibly mixed and frequently take much longer than six hours because of circulation patterns producing them; central and northeastern cyclonic types are most represented. All other variants of episodes frequently occur when a trough is situated above Central Europe. Episodes with steady intensity lasting about three hours are still mainly stratiform or mixed while two variants represented by "two-humped" hyetographs are usually mixed or convective. Two variants of most concentrated episodes are mainly convective or possibly mixed; they are characterized by enhanced frequency of southwestern and eastern cyclonic types. Future research on cluster frequencies among maximum precipitation episodes in various regions will enable the improvement of design hydrographs of small streams where runoff is basically influenced by the rainfall time structure.

## 1. Introduction

The effects of rainfall, such as flooding or landslides, mainly depend on precipitation amounts but also on rainfall distribution in space and time (Peleg et al., 2017). Thus, the performance of hydrological models strongly depends on the quality of precipitation data (Amengual et al., 2015; Dai et al., 2015). Locally, the effects of the same precipitation totals can be substantially enhanced or reduced because of differences in rainfall time structures (Guan et al., 2015). The main factors influencing the rainfall time structure are physical processes producing the precipitation. Generally, stratiform and convective precipitation can be recognized with respect to their lifting mechanisms. In midlatitudes, the first type is mainly produced by extratropical cyclones and/or atmospheric fronts connected with them; among them, it can be also produced or at least enhanced by upslope flows (Kunkel et al., 2012). Therefore, stratiform precipitation is usually wide-spread, steady, and long-lasting. On the contrary, convective precipitation is more localized and concentrated in time because of the dynamics of convective storms producing them (Leon et al., 2016). Nevertheless, both precipitation types can be combined because of convective storms nested into stratiform rain bands, or can follow one after another as it happens during the passage of a mesoscale convective system (Schiro and Neelin, 2018).

The differences between stratiform and convective precipitation have to be considered when designing curves representing the typical course of precipitation, called design storm hyetographs (Hailegeorgis and Alfredsen, 2017). Prodanovic and Simonovic (2004) presented three of the main approaches to designing storm hyetographs. The simplest approach uses only one point of the intensity-duration-frequency (IDF) curve and approximates the precipitation intensity course by a predefined geometrical shape. The simplest one – a rectangle – should represent purely stratiform rains while triangles (Ellouze et al., 2009) or even more complex shapes, such as the Desbordes hyetograph (Desbordes, 1978), can reflect also the attributes of convective rains. Alternatively, the design hyetograph can be constructed from all points of the IDF curve, as e.g., the Chicago hyetograph (Keifer and Chu, 1957), or can be directly obtained from rainfall records, as, e.g., four Soil Conservation Service design storms (Urban hydrology, 1986). The solutions substantially differ in the ratio between the maximum and the mean precipitation intensity, as well as in the runoff response (Alfieri et al., 2008).

Czechia is located within the fully humid temperate zone, with

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[*] Corresponding author at: Institute of Atmospheric Physics CAS, Department of Meteorology, Boční II 1401, Prague 4 141 31, Czech Republic.
*E-mail addresses:* muller@ufa.cas.cz (M. Müller), bliznak@ufa.cas.cz (V. Bližňák), kaspar@ufa.cas.cz (M. Kašpar).

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higher elevations belonging mainly to the boreal climate (Tolasz et al., 2007). Both the stratiform and the convective precipitation can produce extreme events there but their proportion strongly depends on the definition of extremes as well as on the topography of the region. If the definition is based on areal precipitation totals within large regions (~$10^4$ km$^2$ or more) during at least one day, stratiform precipitation significantly prevails among extreme events in Czechia (Kašpar and Müller, 2008; Müller et al., 2015). Even at individual sites, stratiform events can prevail among daily precipitation maxima in Czechia, namely in mountains (Štekl et al., 2001). The shorter is the considered sub-daily time window, the higher is the percentage of convective events among the precipitation maxima, namely in lowlands (Šálek et al., 2012). Therefore, when Kulasová et al. (2004) designed synthetic hyetographs for Czechia, both their solutions reflected the differences in altitude. The so-called CHMU-hyetographs disaggregate the design 1-day precipitation total into hourly increments with respect to the percentage of the maximum design 1-h total, positioned into the 12th hour. The shapes of the hyetographs are very similar in the whole country; only the kurtosis makes a difference among hyetographs that represent locations with different topography, with mountain stations characterized by less-concentrated precipitation. Alternatively, four so-called UFA-hyetographs significantly differ among each other with respect to their shapes as they represent four regions that the country was divided into with respect to the precipitation climatology and altitude. The authors determined that the design 1-day rainfall was fully concentrated into six hours within two mainly lowland regions that covered more than 80% of the Czech territory because of the dominance of convective precipitation among precipitation maxima apart from mountain regions.

However, Fig. 1 demonstrates that individual regions can hardly be represented by only one design hyetograph each because of an enormous variability in the time structure of precipitation episodes even at the same altitude. We suggest that instead of dividing the country into several regions, the problem of rainfall design can be solved by constructing several synthetic hyetographs regardless the topography and quantifying their proportion throughout the country. This paper addresses the methodology, which (i) reduces the variability of the rainfall time structure by clustering reference precipitation episodes and (ii) enables the construction of synthetic storm hyetographs for individual clusters. Adjusted Czech radar precipitation data are applied because of their spatial coverage and high time resolution of 10 min. The clusters of detected precipitation episodes are further analyzed with respect to their relations to stratiform and convective rains to enable future explanation of regional distribution of the variants within the country. In this way, the procedure elucidates general patterns in precipitation behavior in the studied region. Finally, possible applications of the procedure are suggested in the conclusions.

## 2. Data and methods

To obtain reliable precipitation information at high spatial and temporal resolutions (Thorndahl et al., 2017), we applied radar-derived data combined with daily rain gauge measurements (Fig. 1), both covering warm parts (May–September) of the years 2002–2011 because high short-term precipitation intensities typically occur in these months in the Czech Republic (Bližňák et al., 2018). The original radar reflectivity data (Section 2.1) were first transformed into radar-only rainfall intensities (Section 2.2) and then adjusted by rainfall station data (Section 2.3). Finally, reference precipitation events were selected from the database (Section 2.4).

### 2.1. Original radar and rain gauge data

Radar reflectivity data were recorded by two Czech C-band Doppler radars (Brdy, Skalky) every 10 (2002–2008) and 5 (2009–2011) minutes and transformed into 1 km by 1 km square boxes. The spatial coverage includes the entire CR and the closest neighborhood (Novák, 2004). The composite product of the two radars was used which prefers the higher reflectivity values in pixels covered by both radars. Optimal locations of the radar sites (Fig. 1) cause that apart from very small border regions of the CR, the reflectivity products are not influenced by terrain blockage of the radar echo. The most distant pixels in the CR are located approximately 160 km from the nearest radar and the height of the lowest radar beam (0.1° elevation angle) is less than 2000 m above sea level for the large majority of pixels in the CR (Sokol and Bližňák, 2009). The Czech Hydrometeorological Institute (CHMI) manages both weather radars and carefully controls radar reflectivity products. The standard operational routines include checking by the Doppler filter to remove ground clutter and correction the vertical profiles of reflectivity (Novák and Kráčmar, 2002). In general, the quality of the Czech radar data is high and comparable to other data from European radar networks (Michelson et al., 2005).

Because the employed adjustment method (Section 2.3) requires rain gauge data at only daily resolution, measurements from the entire dense Czech weather station network could be utilized. The data were available from approximately 700 rain gauges for the study period (several times more than the number of automated rain gauges at that time). The daily rain gauge records were carefully checked by the CHMI before they were included in the database. Rain gauges recorded precipitation totals from 06 UTC to 06 UTC of the next day.

### 2.2. Radar-derived precipitation estimates

The basic radar product was 10-min radar-derived rain rates calculated in the following way. The interpolated reflectivity at 2 km above sea level (PseudoCAPPI 2 km) was converted into rain intensity. The altitude of this level overcomes the mountains at the state border by as much as several hundred meters (Fig. 1). For the most distant pixels from radar sites, the reflectivity from the lowest elevation 0.1° was used instead of linear interpolation between the adjacent beams. We used the standard Z–R relationship with respect to the Marshall-Palmer relationship between measured radar reflectivity and derived rain rates (Novák and Kráčmar, 2002) as it is the most common method to obtain precipitation information (e.g., Zhang et al., 2016). The main advantage of this approach is a straightforward relationship between measured reflectivity and derived precipitation. In addition, most of the $Z$-R relationships do not differ significantly for precipitation intensities between 20 and 200 mm/h (Rendon et al., 2013; Libertino et al., 2015). On the contrary, there are number of problems arising from the characteristics of both the radar and the precipitation and their detailed description can be found in many reviews (e.g., Villarini et al., 2014).

Subsequently, 10-min averages were calculated from neighboring values (two and three values from measurements with temporal resolutions of 10 and 5 min, respectively; in the latter case, the double weight was assigned to the term in the middle of the 10-min interval). If one of the values was missing, the average was not calculated and the 10-min interval was assigned a missing value.

The prepared 10-min radar-derived precipitation estimates were then accumulated from 06 UTC to 06 UTC of the next day to create daily radar-derived precipitation estimates that temporally matched daily rain gauge measurements. In total, 144 10-min radar integrations were summed together. If more than 18 integrations were missing, then the resulting daily radar-derived precipitation estimate was assigned a missing value. If the number of missing radar integrations was between 1 and 17, missing values were replaced by estimates based on linear interpolation between the adjacent preceding and subsequent 10-min radar integrations. Missing data were usually caused by the malfunction of one or both weather radars or by regular testing and checking of radar devices; such periods usually lasted from several hours to several days. On average, 94.3% of the days were covered by data, which is sufficient for the purposes of the study.