Changes in the IDF curves of short-term rainfall in mountainous and lowland areas of Slovakia

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Abstract. Rainfall intensity-duration-frequency (IDF) curves are of great practical importance in the water resources management, e.g., for the design of hydraulic structures and urban drainage systems, and for the estimation of flash flood risks and flood protection design. Due to the impacts of climate change, there is an evidence that short-term rainfalls have been observed to occur at a higher frequency than before in Europe; the need for a re-evaluation of the design values of short-term rainfall has therefore become important. This study analyzes observed and projected changes in the short-term rainfall events during the warm season (April – October) in an ensemble of a set of Regional Climate Model (RCM) simulations. The analysis was aimed at the seasonality and changes in the scaling exponents that influence the estimation of IDF curves on ungauged sites. The analysis was performed for the selected stations in southern lowland and northern mountainous parts of Slovakia. The characteristics of maximum rainfall events were analyzed for two scenario periods, i.e., one past and one future (1960 – 2000 and 2070 – 2100) and compared to the characteristics of the actual events observed in the past. The main findings from the analysis show a shift in the seasonality, which is different for the rainfall durations and also for the stations analyzed. It can be observed from the comparisons of the IDF that the derived design short-term rainfall values are higher for mountainous regions. A significant difference can be seen in the duration of 240 min. This finding reveals that in the future, very extreme short-term rainfall can be expected in the mountainous areas of Slovakia.

1. Introduction
Rainfall can change from year to year and over decades and centuries, and these changes are shown in their quantity, duration, intensity, periodicity, and frequency. Steady but light rain soaks in the soil and is useful for plants, but the same amount of rainfall over a short period of time can cause local flooding and direct runoff and leave the soil dry. If the frequency and intensity of precipitation vary, the climate may be different even with the same amount of precipitation [1]. These extremes are increasingly noticeable worldwide. Precipitation extremes have a significant impact on society; they affect people's lives by floods, droughts, property and infrastructure damage, and loss of human lives. Therefore, it is essential to understand and quantify their size and frequency at the present time and not only examine future changes in precipitation [2]. Changes in precipitation extremes due to global warming are usually
reflected in changes in the amount of rainwater in the atmosphere and the global climate models used to predict precipitation changes [3].

Global Climate Models (GCMs) are complex mathematical models that try to simulate all the physical processes relevant to the climate, including those in the atmosphere, the oceans, land, and ice. GCMs are realistic simulations of the atmosphere, where the atmosphere is driven with the observed seasonal and range-changing solar radiation flow in the upper atmosphere. The models solve the numerical equations for the grid, which usually has a horizontal resolution of the order of 200 km and has 6 to 12 levels in the vertical resolution. The GCM resolution can be from 200-600 km and have 10-20 vertical layers and, in some cases, up to 30 layers (oceans). A GCM is used for simulating future climate changes, and it has been shown that a GCM can also simulate observed climate changes as well as climate change in the past [4]. Regional Climate Models (RCMs) are numerical climate prediction models that are driven by specified lateral and oceanic conditions from a GCM or an observation-based data set (reanalysis) that simulates processes in the atmosphere and on the Earth's surface; they work with a high resolution of topographical data, contrasts between the land and sea, surface characteristics, and other components of the Earth’s system. Because RCMs apply only to a limited area, the values at their boundaries, which are referred to as “boundary conditions”, must be explicitly specified. An RCM works by increasing the resolution of a GCM. A GCM determines the concentrations of greenhouse gases and volcanic eruptions worldwide on a very large scale, while an RCM can cover an area of over 5000 km x 5000 km, but mostly uses an area from 50 km x 50 km to 10 km x 10 km [5].

This work is aimed at assessing changes in the seasonality and scaling exponents in 2 different areas, i.e., the mountains and lowlands. The design values of the rainfall were derived by a scaling exponent. The intensity, duration, frequency curves (IDF curves) estimated for the actual observation and for the Community Land Model (CLM) simulation were also compared.

2. Community Land Model (CLM) simulation
The Community Land Model (CLM) was created as a collaborative project between scientists from the Terrestrial Sciences Section (TSS) and the Climate and Global Dynamics Division (CGD) at the National Center for Atmospheric Research (NCAR) and the Community Earth System Model (CESM) Land Model and Biogeochemistry Working Groups in the USA (Boulder, Colorado). Other main working groups that contribute to the CLM are the Chemistry-Climate, Paleoclimate, Climate Change, and Land Ice Working Groups [6].

The CLM model formalizes and assesses ecological climatology concepts. Ecological Climatology is a multidisciplinary structure used to understand how changes in vegetation caused by nature and human affect the climate. It studies the physical, chemical, and biological processes by which terrestrial ecosystems influence and are influenced by the climate on various spatial and temporal scales. The main theme is that terrestrial ecosystems are important determinants of the climate through their energy, water, chemical elements, and trace gases. Parts of the model consist of surface heterogeneity, biogeophysics, the hydrological cycle, biogeochemistry, ecosystem dynamics, and the human dimension. The soil surface is represented by five types of primary sub-grid of land cover (glaciers, lakes, wetlands, urban environments and vegetation) in each cell of the grid. The vegetation portion of the cell of the grid is further subdivided into smaller portions of functional plant types, each with its own leaf and stem area index and vegetation height. The biogeophysical part of the model corresponds to the immediate exchange of energy, and water and the momentum with the atmosphere. These are aspects of micro-meteorology, plant height physiology, soil physics, radiation transfer, and hydrology. Another part of the model is the hydrological cycle and the direction of a river network. The hydrological cycle over land includes catching precipitation water by plant leaves and wood (interception); vegetation throughfalls and flows down on vegetation (stemflow); it also includes infiltration, drainage, soil water, and snow. These are directly related to bio-geophysics and also affect the temperature, precipitation and
runoff. Total runoffs (surface and sub-surface runoffs) are directed downstream into the oceans by a river model. The River Transport Model (RTM) is synchronously linked to the CLM model for hydrological applications, as well as for improved bonding between the land-ocean-sea and ice-atmosphere in CCSM models. The biogeochemical section deals with the immediate exchange of chemical components with the atmosphere, chemical components from industrial activity, land use, uncontrolled ecosystems and the ocean. The last major part of the model is ecosystem dynamics, which include an ecosystem’s carbon balance, sequence, and biogeography. The ecosystem carbon balance corresponds to the carbon cycle, but also to changes in the composition of communities and the structure of vegetation in response to disturbances (e.g., fire, land use) and climate change. There are two time periods for dynamics, i.e., the sequence takes into account changes in the community’s composition and vegetation structure over a period of several hundred years, usually after failures such as fires or changes in land use. Changes in vegetation also occur in response to climate change, over longer periods of time, such as centuries and millennia. The CLM addresses several aspects that permit the study of two-way interactions between human activities in the countryside and the climate, including changes in land cover/land use, agricultural practices, and urbanization [6–8].

3. Methodology

The methods used for the detection of future changes in short-term rainfall are based on the Burn’s vector methodology and the simple scaling methodology. Subsequently, the derived design values of the rainfall depths for future horizons were compared with the historical observations.

3.1. Burn’s vector

Burn’s vector methodology [9] is the method most often used to estimate the occurrence of extreme seasonal phenomena. There are several studies analyzing seasonality, e.g., the detection of future changes in seasonality in extreme short-term rainfall in selected stations of Slovakia [10]. This method describes the variability of the date when the maximum rainfall occurs, so that the direction of the vector corresponds to the expected day of the occurrence during the year, while its length describes the variability around the expected date of the occurrence. The date of occurrence (D) represents the average position of an event that is plotted in polar coordinates per unit circle. First, we calculate the orientation of the vector to indicate when the maximum value for the given year occurred. The position of the event’s occurrence is shown in a unit circle by an angle we define as [9]:

The date of occurrence $D_i$ of the extreme event in the angular value $\theta_i$:

$$\theta_i = D_i \frac{2\pi}{365}, \quad (1)$$

The abscissa $x$ and ordinate $y$ of the Burn’s vector are calculated as:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} \cos(\theta_i), \quad (2)$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} \sin(\theta_i). \quad (3)$$

The orientation of the Burn’s vector $\bar{\theta}$ is calculated as:

$$\bar{\theta} = \tan^{-1} \frac{\bar{x}}{\bar{y}}, \quad (4)$$

The seasonal concentration index $r$ can be calculated as:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \quad (5)$$
The orientation of the vector can have a value from 0, which corresponds with 1 January, to 2π, which corresponds with 31 December. The seasonal concentration index can have a value between 0 and 1; the 0 means that the occurrences are uniformly distributed throughout the year, while the 1 means that the occurrence happens every year on the same date. The results are interpreted in the Burn’s diagrams.

3.2. Simple scaling
A simple scaling method is used to process rainfall data for a period of time shorter than one day. Simple scaling determines the design values for the duration shorter than one day and for a selected time period by using daily rainfall records that are commonly available. Applying simple scaling to the relationship between the intensity, duration, and periodicity (IDF) properties of the precipitation is possible. Determining the scaling properties of the precipitation is based on the general shape of the following IDF formula [11]:

\[ I = \frac{a(T)}{b(d)} \]  
\[ b(d) = (d + \theta)^\eta \]

where \( \theta, \eta \) are the parameters (determined by the estimation \( \theta > 0, 0 < \eta < 1 \)).

Simple scaling for the scaling of the statistical moments was applied in this paper. The scaling exponents could be estimated with a linear regression from the slope between the logarithmic moment values and the scaling parameters for the different order of the moments. If there is a linear dependence between the scaling exponent and the moment order, it is a scaling exponent of the first order. This property is referred to as ‘wide sense simple scaling’. The following formula is used for deriving the scaling coefficients [12, 13]:

\[ \beta_n = n\beta \]

where \( \beta_n = n\beta \) represents the scaling exponent of the \( n \)-th order.

The scaling exponents and properties have also been examined in several studies, e.g., on the use of the simple scaling of heavy rainfall in a regional estimation of IDF curves in Slovakia [14], and an analysis of future changes in the trends and scaling coefficients for short-term rainfall in southwestern Slovakia [15], the impact of global warming on precipitation patterns in Ilorin and the hydrological balance of the Awun basin [16] or developing rainfall intensity-duration-frequency curves for Alabama under future climate scenarios using artificial neural networks [17].

4. Data analysis
The data used in the analysis was created by a CLM simulation and were provided by Dr. Martin Gera from Comenius University in Bratislava, Department of Astronomy, Physics of the Earth, and Meteorology. The Regional Climate Scenario (RCM) used consists of the rainfall intensities of two time periods, i.e., the past period (1960-2000) and the future period (2070-2100). The rainfall intensities were derived in 60-minute time steps. The RCM scenario selected for the simulation of the climate was the SRES A1B scenario, which is a semi-pessimistic scenario with an increase in the global warming temperature of about 2.9° by the year 2100. This scenario relates well to the current processes in the atmosphere. For a comparison of the results from the simulation, the actual measured data in hourly time steps were used, which were provided by the Slovak Hydrometeorological Institute. The data consists of rainfall intensities for the 1960-2009 and 1995-2009 periods.

The area of interest is divided into two locations, which are located in the southern and northern parts of Slovakia. For these locations two climatological stations were selected that differ according to their geographical location as well as their climate conditions. The southern part of Slovakia is represented
by the Hurbanovo climatological station, which 115 meters above sea level. The area belongs to an area in Slovakia that constitutes a warm climate district. It is also one of the driest regions in Slovakia with an annual rainfall of less than 500 mm per year. The northern part of Slovakia was represented by the Liptovská Teplička climatological station, which is located 920 meters above sea level. The area belongs to a slightly warm climatic area with a mountainous climate and a low temperature inversion. The locations of the stations are presented in Figure 1.

Figure 1. Map of the locations of the selected Hurbanovo and Liptovská Teplička climatological stations

5. Results and Discussion
This study was aimed at an analysis of future changes in the seasonality, scaling exponents, and design values of the extreme short-term rainfall in two climatological stations located in two different areas (a southern warm lowland and a northern mountainous region). The analysis was performed for the past, actual, and future periods for durations of 60 up to 1440 minutes.

The first step was an analysis of the changes in the seasonality of extreme events. The results are presented in the Burn’s diagrams below (Figure 2). The analysis shows that in the mountainous region, there is a more significant shift in the occurrence of extreme rainfalls between the actual observations and the simulated future period than in the lowland area. The shift is between 2-3 weeks for the earlier period for the duration of 180 to 1440 minutes; the mountainous area is represented by the Liptovská Teplička climatological station. For the lowland area, which is represented by the Hurbanovo climatological station, there is a shift of 2-3 weeks for later the period than the actual observations show in durations from 60 to 120 minutes, and in durations 180-1440 the shift is 3-4 days for the later period than the actual observations show.
The next step was an analysis of the scaling exponents and design values of the rainfall depths. An approach based on the scaling of the statistical moments was applied for the estimation of the scaling exponents. The relationship between the log-transformed values of the moments of the various orders and the various rainfall durations at the Hurbanovo climatological station is presented in Figure 3.

![Figure 2. Seasonality analysis in the climatological stations analyzed](image)

![Figure 3. Log-transformed values of the moments of the various orders versus various rainfall durations at the Hurbanovo climatological station for the future period of 2070-2100](image)

The relationship between the scaling exponents of the moments and the order of the moments is presented in Figure 4. The scaling exponents decrease with the order of the moments, which confirms that a linear relationship exists between the scaling exponents and the order of the moments.
Figure 4. Relationship between the scaling exponents of the moments and the order of the moments at the Hurbanovo climatological station for the future period of 2070-2100

The same analysis was done for all the periods analyzed at both climatological stations. The scaling exponents derived are presented in Table 1. The scaling exponents have lower values than the values of the scaling exponents from the actual observations. We suggest that lower values of scaling exponents could be caused by less extreme events which are suggested during the future period. On the other hand, the lower scaling exponents are not a signal that the future IDF curves would be lower. This also confirmed the fact that the downscaled design values of the short-term rainfall depths are radically higher than shown in Figures 5-7. At both of the stations analyzed, the higher values are for the future period. The actual observations show that the design values of the short-term rainfall have much less of a difference between the two stations, which represent different areas. For the future period, the difference between the amounts of precipitation seems to be two times higher in the mountainous areas than in the lowland areas.

Table 1. Derived scaling exponents for the stations analyzed

| Station          | Actual ((1961-1995-2009)) | Historical (1960-2000) | Future (2070-2100) |
|------------------|---------------------------|------------------------|-------------------|
| Liptovská Teplička | 0.762                     | 0.669                  | 0.6228            |
| Hurbanovo        | 0.7713                    | 0.6184                 | 0.6773            |
Figure 5. IDF curves for the Liptovská Teplička station for the future period (2070-2100) and periodicity $P=0.01$

Figure 6. IDF curves for the Hurbanovo station for the future period (2070-2100) and periodicity $P=0.01$
6. Conclusions
The paper was aimed at analyzing the changes in seasonality, scaling exponents and design values of short-term rainfalls at two climatological stations, namely, Hurbanovo and Liptovská Teplička. The locations of the chosen stations differ from each other; i.e., the first belongs to a warm, lowland area, while the second belongs to a colder and mountainous area. The analysis was performed for actual, historical and future time periods and for 60 minutes up to 1440 minutes short-term rainfall durations. The actual measured data and data from an RCM simulation were analyzed. The main results can be summarized as follows:

- The stronger shifts in the occurrence of extreme rainfall are in the mountainous areas; the shifts are between 1 week for the durations of 60 and 120 minutes and between 2-3 weeks for the durations of 180, 240 and 1440 minutes.
- In the lowland areas, the more significant shifts are only in the durations of 60 and 120 minutes, and it is 2.5-3.5 weeks; in the durations of 180, 240 and 1440 minutes, the shift is 3-4 days.
- There is a shift in an earlier period in mountainous areas of the occurrence of extreme rainfalls than the actual observation shows; for the lowland areas, there is a shift to a later period than the actual observation shows.
- The design values for the future have higher values as in the actual or historical simulated periods.
- In a comparison of the locations, the higher design values of the short-term rainfall are in the mountainous region than in the warmer lowland location where the design values are lower. There is a great difference between the design values of the short-term rainfalls in the mountainous areas to the duration of 240 minutes with a 200% growth.

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