Analysis of future changes in short-term rainfall characteristics in the High Tatras Region in Slovakia

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Abstract. The paper focuses on the analysis of future changes in short-term rainfall characteristics in the High Tatras region. The analysis was performed at three climatological stations, namely: Podbanské, Tatranská Lomnica, Javorina. The area is located in the northern part of Slovakia in a mountainous region which belongs to a mountain climate with characteristic long cold winters and short summers with heavy rainfalls (June, July). The future changes were analysed from the predicted short-term rainfall intensities using the Community Land Model. The Community Land Model was a multidisciplinary project between scientists from several working groups in the USA. The model uses ecological climatology concepts, which explains the impacts of changes in vegetation on the climate. The model well relates to the current processes in the atmosphere; it is a semi-pessimistic scenario with a predicted global temperature increase is about 2.9 °C by the year 2100. The focus of the paper was put on the changes in seasonality, trend analysis. The analysed rainfall durations were available from 60 minutes up to 1440 minutes for the future period 2041-2100. The results were compared with the simulated data from the historical period 1961-2020. The analysis is focused on the seasonality changes in extreme rainfall which was analysed by Burn's vector methodology, then the trend testing provided by the Mann-Kendall trend testing method. Results show that there is a change in the short-term rainfall intensities characteristics for the future period, the seasonality of extreme rainfall intensities shows a shift to an earlier time period of the year, future trends are also showing increasing change compared to the historical period.

1. Introduction
The number of studies on the hydrological impact of climate change and increasing flood risk and droughts at a river basin level has increased significantly in recent years. Increased attention is also being paid to global climate change supported by concerns that, according to simulations from climate change models in various scenarios, climate deterioration is expected, and that these trends will have significant negative consequences on the natural environment and society [1, 2]. Changes in the global climate and the Earth's hydrological cycle have contributed to increased heavy precipitation, with consequent increased surface runoff and flood risks [3], which are likely to continue in the future [4]. Changes in precipitation can affect society more directly than variations in most other meteorological observables, but precipitation is difficult to characterize due to fluctuations at almost all time and space scales [5]. Design precipitation is the essential input for hydrological models used in estimating design flows. They are required in the design of many urban water structures, such as urban drainage.
systems, metro systems, highways, railways, bridges, and dams. In a given region, design precipitation is generally derived from historical precipitation data from a large set of measurement stations. However, due to climate change, the frequency and extent of extreme precipitation events have increased in many places around the world, regardless of average annual precipitation trends [6].

The general objective of the statistical analysis of trends is to examine whether recent historical changes in the frequency and amplitude of precipitation extremes can be identified and whether they can be considered statistically significant compared to the natural time variability of precipitation intensities [7–9]. Most trend testing techniques assume year-on-year independence. If short-term and/or long-term persistence is present in the time series, these trend testing techniques (such as linear regression, Mann-Kendall test, Spearman trend classification tests, etc.) cannot be applied correctly. Persistence is caused by, e.g. annual, decade or multi-decade climate fluctuations [10]. Trends in precipitation totals are also addressed in the work of Wu and Qian [11]. Their study examines annual and seasonal precipitation trends at 14 precipitation stations in Shaanxi Province, China using innovative trend analysis, the Mann-Kendall test, and linear regression analysis. Although it has been documented that daily extreme precipitation is increasing worldwide, a faster increase can be expected for extremes lasting less than one day. After a careful procedure of quality control, Barbero et al. [12] compared trends in hourly and daily precipitation extremes using a large network of stations in the United States between 1950 and 2011. In their work, they suggest that trends in daily extremes due to climate change are generally better detected at station levels than in the case of hourly extremes.

Iliopoulou et al. [13] indicate that a comprehensive understanding of the seasonality of extreme precipitation is essential for climate studies, flood forecasts, various hydrological applications, flood risk management and much more. Their study aimed to identify seasonality in extreme precipitation and to quantify its impact in a theoretically and yet practically appropriate way. Data sets with 27 daily precipitation records of at least 150 years were examined. The results suggest that the seasonal properties of precipitation extremes mainly affect the average seasonal maxima values and their variability, while the shape of their probability distribution does not differ substantially depending on the season.

This study contains the results of the analysis of the Community Land Model (CLM) Scenario data. This model was created in the USA as a collaborative project between scientists from many research working groups as the National Center for Atmospheric Research and Community Earth System Model, Land Model and Biogeochemistry working group. The model assesses ecological climatology concepts, which is a multidisciplinary structure, used to understand the impact of changes in the vegetation caused by humans and nature to the climate. The model describes physical, chemical, and biological processes by which terrestrial ecosystems influence and are influenced by the climate on various spatial and temporal scales. The CLM addresses several aspects that allow the study of two-way interactions between human activities in the countryside and the climate, changes in land cover/land use, agricultural practices, and urbanization included [14–16]. The data used in the analysis of future changes in short-term rainfall intensities were provided by Dr Martin Gera [17]. The CLM scenario data were divided into three groups, three time periods for the past period (1961-2020), the close future period (2041-2070) and the distant future period (2071-2100). The analysis was made for rainfall durations from 60 minutes up to 1440 minutes. The CLM scenario is based on the SRES A1B scenario which is semi pessimistic scenario, and it relates well to the current processes in the atmosphere with an increase in the global temperature of about 2.9°C by the year 2100. The area of interest is located in the northern part of Slovakia, in the High Tatras Nation Park. Three climatological stations were selected namely: Podbanské (Western part of High Tatras), Tatranská Lomnica (Central part of High Tatras) and Javorina (Eastern part of High Tatras). Area of High Tatras belongs to a slightly warm climatic area with mountain climate and with low-temperature inversion. The locations of the climatological station are presented in Figure 1.
2. Methodology

In this paper, several methods were used for the analysis of the future changes in short-term rainfall. The analysis of seasonal changes was done by Burn’s vector methodology, and trend testing was done by Mann-Kendall testing.

2.1. Burn’s Seasonality Analysis

The occurrence of extreme seasonal phenomena is estimated by Burn’s vector method [19]. The method describes the variability of the occurrence of the maximal rainfall events. The expected day of the occurrence during the year is given by the direction of the vector. Variability of the expected day of occurrence is described by the length of the vector.

The date of occurrence \( D_i \) of the extreme event in the angular value \( \theta_i \) is given by:

\[
\theta_i = D_i \frac{2\pi}{365},
\]

(1)

the abscissa \( x \) and ordinate \( y \) of Burn’s vector are calculated as:

\[
x = \frac{1}{n} \sum_{i=1}^{n} \cos (\theta_i),
\]

(2)

\[
y = \frac{1}{n} \sum_{i=1}^{n} \sin (\theta_i),
\]

(3)

The orientation of Burn’s vector \( \theta_i \) is calculated as:

\[
\theta_i = \tan^{-1} \left( \frac{x}{y} \right).
\]

(4)

The seasonal concentration index \( r \) can be calculated as:
The orientation of the vector varies in values from 0 to $2\pi$. The 1st of January corresponds to 0, and the 31st of December, which corresponds to $2\pi$. The seasonal concentration index can have a value between 0 (the occurrences are uniformly distributed throughout the year) and 1 (the occurrence happens every year on the same date). The results are interpreted in Burn’s diagrams.

2.2. Mann-Kendall trend test

The properties of the trend are determined by The Mann-Kendall [20, 21] Trend Test. The method is used for the determination and assessing of the properties and significance of the trend of a selected quantity over time. The test is based on the correlation between the order of rows and their time order. The significance of a downward or upward trend is dependent on a steadily decreasing or increasing variable over time. The trend does not have to be linear. The test for time series $X = \{x_1, x_2, \ldots, x_n\}$ is given by [20, 21]:

$$S = \sum_{i < j} a_{ij},$$  \hspace{1cm} (6)

where $S$ is the testing statistic:

$$a_{ij} = \text{sign} \left( x_j - x_i \right) = \text{sign} \left( R_j - R_i \right) = \begin{cases} 1 & x_i < x_j \\ 0 & x_i = x_j \\ -1 & x_i > x_j \end{cases},$$  \hspace{1cm} (7)

Where $R_{ij}$ are series of observations and $x_{ji}$ are time series. The test depends on the order of the values as the actual value of the elements. The statistical test depends only on the order of the observation and not on their own values. This property is the result of statistics that do not depend on distribution. Variation of test statistics $S$ is given by [20]:

$$\text{Var}(S) = \frac{1}{18} n(n - 1)(2n + 5) - \sum_{j=1}^{m} t_j (t_j - 1)(2t_j + 5),$$  \hspace{1cm} (8)

where $n$ is the number of observations, $m$ is the number of groups in the corresponding order, and it is appropriate observation. The significance of the trend is determined using the standardized variable $u$ at the required significance level $\alpha$ given by [21]:

$$u = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \end{cases}.$$  \hspace{1cm} (9)
3. Results and discussions

The analysis was performed at the three climatological stations located in the High Tatras region. Selected stations are located around the mountains from the west to the east. The analysis was made for the rainfall durations from 60 minutes up to 1440 minutes. The data were divided into three periods (historical, near future and farther future) and the warm period of the year was analysed. The purpose of this analysis is to evaluate the difference in the short-term rainfall characteristics between the stations in the different locations around the mountains.

The first step in the paper was to analyse the trends in the rainfall intensities in the time series. The Mann-Kendall trend testing was used described in the previous chapter. The result shows that there is a change in the short-term rainfall trend characteristics in the area. The change is not significant at the 90% of the significance level, but the results show there is an increasing trend in short-term rainfall intensities for the future periods. At all the climatological stations, the increasing trends can be seen for the future period. In the Podbanské climatological station, wherein the near future period (future 1) the decreasing trend for the 60 minutes to 240 minutes durations was detected. It is the most visible difference in the trend changes between the analysed stations. The results are presented in Table 1.

| Table 1. Trends in short-term rainfall intensities in the analysed periods |
|-----------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Station | Period | 60 min | 120 min | 180 min | 240 min | 1440 min |
|-------|-------|--------|--------|--------|--------|--------|
| Podbanské | historical (1960-2020) | - | - | - | - | - |
| | future 1 (2041-2070) | - | - | - | - | + |
| | future 2 (2071-2100) | + | - | + | + | + |
| Tatranská Lomnica | historical (1960-2020) | - | - | - | - | - |
| | future 1 (2041-2070) | + | - | + | + | + |
| | future 2 (2071-2100) | + | + | + | + | + |
| Javorina | historical (1960-2020) | - | - | - | - | - |
| | future 1 (2041-2070) | + | + | + | + | + |
| | future 2 (2071-2100) | + | + | + | + | + |

shadow – significant trend in 90% of significance level

In the next step, the seasonality changes in the short-term rainfall intensities were analysed. The results show that the seasonal maximal rainfall events occur in the month of July in each analysed duration. Also, the difference in the occurrence of the extreme rainfalls can be seen between the Podbanské station, and the Tatranská Lomnica and Javorina climatological stations. In the Podbanské climatological station, the occurrence is at the end of the month of July or the beginning of August. The other two stations have the occurrence in the half of the month of July. The shift in the seasonality of extreme events was to the earlier time in the year compared to the historical period. The smallest differences between the historical period and the future periods are at the Tatranská Lomnica climatological station where the difference is within eight days in all durations analysed. Similar results can be seen at the Javorina Climatological station where the difference is between 6-8 days in
all durations analysed. The most significant differences were detected at the Podbanské climatological station, where the range of the differences was between 3-16 days in all durations analysed. The most significant differences were detected in the 1440 minutes, where the shift between the seasonality of extreme events. The results are presented in Figure 2 and Figure 3.

Figure 2. Seasonality changes for the 60 minutes – 240 minutes rainfall durations
Figure 3. Seasonality changes for the 1440 minutes rainfall durations

4. Conclusions
This study presents the results of the analysis of the future changes in the short-term rainfall intensities trends and seasonality in the High Tatras Region of Slovakia. The analyzed was performed at the climatological stations: Podbanské, Tatranská Lomnica and Javorina.

The analysis was performed by using Mann-Kendall trend testing methodology for the detection of the trends in the rainfall intensities and by using Burn’s vector methodology for the seasonality changes in the extreme rainfall events. The analysis was done for the historical period (1961-2020), the near future period (2041-2070) and the far future (2071-2100); for the warm period of the year. The main results can be concluded as follows:
- There is an increasing trend for the future periods for all climatological stations, but the trends are not significant on the 90% of the significance level.
- The biggest shifts in the seasonality events for the future periods are in the 1440 minutes duration up to 16 days and the lowest shifts, of 6-8 days in the seasonality occurrence, are for the future periods for the daily duration.
- The most significant differences in seasonality for the historical and future period are at the Podbanské climatological station.

The results confirm that the short-term rainfall intensities will change and will be more extreme for the future period in the area observed.

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References
[1] D. R. Easterling, G. A. Meehl, C. Parmesan, S. A. Changnon, T. R. Karl, and L. O. Mearns, *Climate extremes: Observations, modeling, and impacts*. American Association for the Advancement of Science, 22 September 2000.
[2] G. Maracchi, O. Sirotenko, and M. Bindi, “Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe,” In: *Climatic Change*. Springer. p. 117–135, May 2005.
[3] K. E. Trenberth. “Changes in precipitation with climate change,” *Climate Research*. Vol. 47, no. 1, p. 123–138. March 2011.
[4] R. Dankers, N. W. Arnell, D. B. Clark, P. D. Falloon, B. M. Fekete, S. N. Gosling, J. Heinke, H. Kim, Y. Masaki, Y. Satoh, T. Stacke, Y. Wada, and D. Wisser, “First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble,” *Proceedings of the National Academy of Sciences of the United States of America*. Vol. 111, no. 9, p. 3257–3261. 4 March 2014.
[5] K. E. Trenberth, A. Dai, R. M. Rasmussen, and D. B. Parsons, “The Changing Character of Precipitation,” *Bulletin of the American Meteorological Society* [online]. Vol. 84, no. 9, p. 1205–1218. September 2003.
[6] A. G. Yilmaz, and B. J. C. Perera, “Extreme Rainfall Nonstationarity Investigation and Intensity-Frequency-Duration Relationship,” *Journal of Hydrologic Engineering*. Vol. 19, no. 6, p. 1160–1172, 1 June 2014.
[7] S. Pagliara, C. Viti, B. Gozzini, F. Meneguzzo, and A. Crisci, “Uncertainties and trends in extreme rainfall series in Tuscany, Italy,” Effects on urban drainage networks design. *Water Science and Technology*. Vol. 37, no. 11, p. 195–202. 1 June 1998.
[8] C. Denault, R. G. Millar, and B. J. Lence, “Assessment of possible impacts of climate change in an urban catchment,” *Journal of the American Water Resources Association*. Vol. 42, no. 3, p. 685–697. 1 June 2006.
[9] H. Madsen, K. Arnbjerg-Nielsen, and P. S. Mikkelsen, “Update of regional intensity-duration-frequency curves in Denmark: Tendency towards increased storm intensities,” *Atmospheric Research*. Vol. 92, no. 3, p. 343–349. 1 May 2009.
[10] P. Willems, and P. You, *Multidecadal oscillations in rainfall extremes*. 2010.
[11] H. Wu, and H. Qian, “Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s,” *International Journal of Climatology*. Vol. 37, no. 5, p. 2582–2592. 1 April 2017.
[12] R. Barbero, H. J. Fowler, G. Lenderink, and S. Blenkinsop, “Is the intensification of precipitation extremes with global warming better detected at hourly than daily resolutions?,” *Geophysical Research Letters*. Vol. 44, no. 2, p. 974–983, 28 January 2017.
[13] T. Iliopoulou, D. Koutsoyiannis, and A. Montanari, “Characterizing and Modeling Seasonality in Extreme Rainfall,” *Water Resources Research*. Vol. 54, no. 9, p. 6242–6258. 1 September 2018.
[14] NCAR/UCAR. *Community Land Model*. 2016.
[15] U. Böhm, M. Kücken, W. Ahrens, A. Block, D. Hauffe, K. Keuler, B. Rockel, and A Will, “CLM – the climate version of LM: brief description and long-term applications,” *COSMO News*. Vol. 6, p. 225–235. 2006.
[16] UCAR, “University Corporation for Atmospheric Research,” CLM Home. 2019.
[17] M. Lapin, I. Bašták-Durán, M. Gera, J. Hrvoji, M. Kremler, and M. Melo, “New climate change scenarios for Slovakia based on global and regional general circulation models. *Acta Met. Univ. Comen*. Vol. 37, p. 25–74. 2012.
[18] Google Maps. High Tatras National Park, Google [Online] 2020 [Accessed 16. 06. 2020]
Available at: <http://maps.google.com/>.

[19] D. H. Burn, “Catchments similarity for regional flood frequency analysis using seasonality measures,” *Journal of Hydrology*. 1997.

[20] H. B. Mann, “Nonparametric Tests Against Trend,” *Econometrica*. Vol. 13, no. 3, p. 245. July 1945.

[21] M. G. Kendall, *Rank Correlation Methods*. Griffin, London. 1975.