

Climatology of the extreme heavy precipitation events in Slovakia in the 1951–2020 period

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In this study, we investigate extreme heavy precipitation events in the Slovak Republic in the period 1951–2020 in terms of their spatial and temporal distribution with goal to create dynamic-climatological analysis of those patterns of the atmospheric circulation that can eventually lead to the occurrence of the extreme multi-day precipitation events. Heavy precipitation is defined as maximum precipitation total over five consecutive days (Rx5D) where a non-zero daily precipitation total must be recorded every day of selected 5-day period. Spatial and temporal distribution of multiday precipitation totals is affected by many factors, mainly by the processes taking place in the troposphere eventually represented by the synoptic scale atmospheric circulation and by the orographic diversity of the area, which together significantly affects distribution of precipitation in the selected area. Our study is therefore constructed as an analysis of relationships between localized tropospheric circulation defined by the Czechoslovak catalogue of the typified synoptic situations (Brádka, 1968), the predominant wind patterns and the spatiotemporal distribution of Rx5D.

KEY WORDS: extreme precipitation, precipitation events, dynamic climatology

Introduction

Current changes in the global climate system, which are strongly correlated to the ongoing human-caused climate change, have an undeniable impact on the mean state of the climate. Long-term increase of the global temperature particularly well expressed in the Arctic and Polar regions of the oceans in the Northern hemisphere can be directly linked to the continually diminishing sea ice areas (Bintanja et al., 2013; Vihma, 2014). It is very likely, that the rise in the ocean surface temperature in the North Atlantic Ocean and the Arctic Ocean affects the dynamics of atmospheric flows and consequently, the processes of genesis, vertical and horizontal dimensions, stability, and patterns of movement of low- and high-pressure areas. Warner (2018) proposes that there is a strong positive correlation between the October sea ice extent and the DJF (December – January – February) values of the NAO index (North Atlantic index). This can, via presupposed stratospheric path, impact the strength of the polar stratospheric vortex, specifically to cause its weakening, which is subsequently manifested in the troposphere by weakening of zonal winds and more pronounced meandering the jet stream. These modifications in the synoptic scale atmospheric circulation might lead to a change in the distribution of precipitation during the year in Slovakia, displaying as an increase in the share of convective based stormy downpours in the total precipitation sums (Faško et al., 2015; Markovič et al.,

2016) and the increasing extremity of precipitation events. Better understanding of the established circulation patterns associated with the extreme heavy multiday precipitation events can help us correctly and more precisely access and model trends and risks linked to human-caused climate change.

In Slovakia, general studies have been previously published that dealt with multi-day precipitation totals (Lapin et al. 2004; Stehlová et al., 2001; Jurčová et al., 2002; Gaál and Lapin, 2002) however, these studies using shorter time series of daily precipitation were mostly very localized and due to the limited number of precipitation stations with processed maximum multi-day precipitation totals and time-consuming process of obtaining this data, only limited set of precipitation stations with authentic data has been used in the analysis. Dynamic-climatological analysis of extreme precipitation events was previously published only for maximum 2-day precipitation totals (Markovič, 2019). Our study uses new authentic data set of maximum 5-day precipitation totals (Rx5D) from 486 precipitation stations owned and operated by Slovak Hydrometeorological Institute (SHMI), with available, complete, and consistent time series of daily precipitation from the period 1951–2020. Our spatiotemporal climatological analysis of the extreme heavy precipitation events in Slovakia is constructed as a causal analysis of relationships between spatially localized tropospheric circulation, defined by the Czechoslovak catalogue of the typified synoptic situations (Brádka,

1968), the predominant atmospheric flow and the spatial and temporal distribution of maximum 5-day precipitation totals.

Data and study area

For needs of our analysis it was essential to create new Rx5D data set obtained from the network of precipitation stations operated by the SHMI performing precipitation observations during the 1951–2020 period (Fig. 1). Eventually, 486 stations with mean elevation 375 meters a.s.l. were selected, excluding those, which could not be incorporated due to the data inconsistency or due to short, incomplete, or unreliable time series of observations. Small portion of time series selected for the analysis still contained brief interruptions. Missing data, however, did not in any case exceed 5% of the total number of Rx5D for each station, and therefore could be fixed or calculated by using an expert approach based on the regression analysis and analogy between data measured at geographically related stations. From selected precipitation stations were prepared Rx5D maps. Spatial and vertical distribution of precipitation stations has proven to be inadequate for used interpolation tool. To improve the vertical distribution calculated for selected set of stations, resulting in a more realistic spatial distribution of Rx5D within the territory of Slovakia, there were (only in the process of creating maps) used 60 supplementary (virtual) points. (Fig. 1) These points were located in the mountain areas, at elevations over 500 meters above the sea level with mean elevation 1049 meters a.s.l. 31 additional points were

placed in positions located at the elevation between 500–1000 meters. Remaining 29 points were placed in the elevations between 1000–2000 meters. Exact placements of supplementary points were identified using method based on expert spatial analysis of the existing field of precipitation stations conducted by Dr. Pavel Faško.

Maximum multiday precipitation totals

The sums of multi-day atmospheric precipitation totals can be calculated by two slightly different methods – the standard and the modified method (Lapin et al., 2004). Standard processing method of multi-day precipitation totals represents situations where a non-zero daily precipitation total must be recorded every day of selected n -day period. Possible occurrence of day (or days) during which the precipitation was not registered, or its amount was not measurable (0.0 mm) means, that the total precipitation amount for the considered period is excluded from the analysis. Such a relatively strict view of multi-day continuous precipitation totals is particularly preferred in hydrological treatments. In climatology, on the other hand, it is also interesting and helpful to include precipitation periods incorporating one day without registered precipitation, but which could not be the first or last day of this selected n -day period, because in that case we would be only dealing with shortened $n-1$ day period. This correction, of course, does not apply to 2-day totals. The monthly maximum sum of Rx5D therefore represents the highest value of all 5-day sums calculated from five successive days with

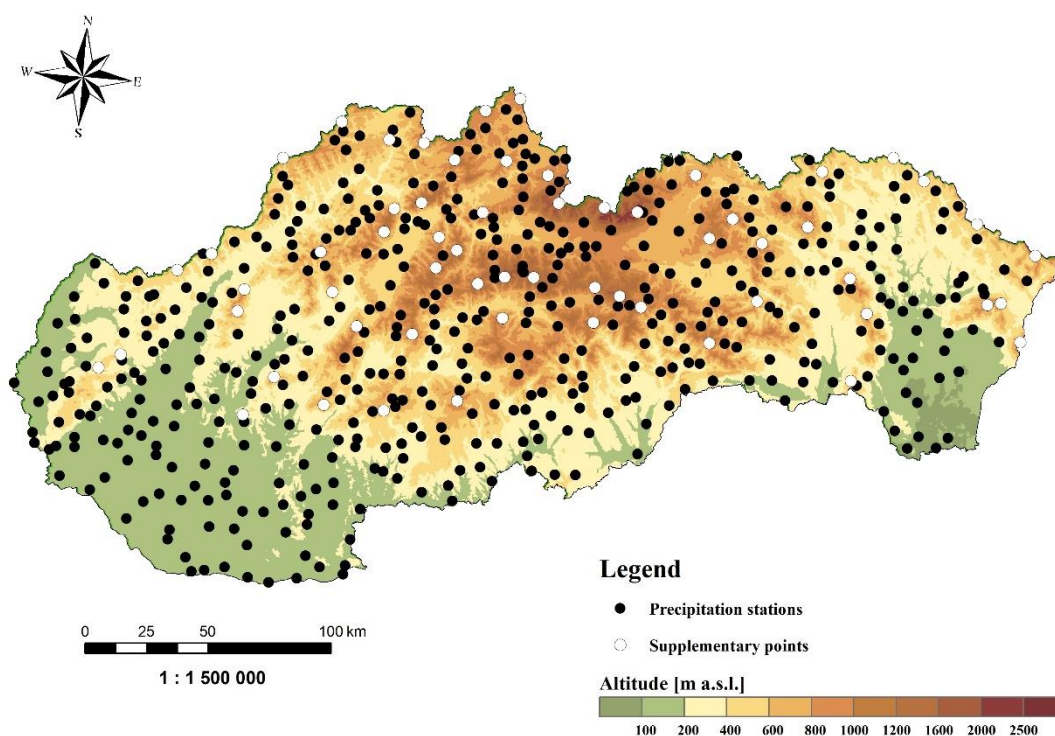


Fig. 1. Selected precipitation stations and supplementary points within the territory of Slovakia.

the observed non-zero precipitation totals over the period of one month. Sums of Rx5D measured at the turn of months was assigned to the month with higher share on total precipitation sum. This approach was also applied to maximum totals that occurred at the turn of years meaning, that there was the possibility that they could, in some cases, be also comprised of data outside of selected 1951–2020 period – data measured in December 1950 and January 2021, which were therefore subsequently included in our study.

Methodology

Our paper deals with a climatology of the extreme heavy precipitation events in within the network of precipitation stations operated by the SHMI. Presented methodology has been chosen to provide a more comprehensive view of the issue by not only identifying situations with recorded highest Rx5D, but also directly incorporating the necessary condition of sufficiently large area of their distribution presented as a mean spatial value of the monthly Rx5D.

Selection of the significant maximum 5-day precipitation totals

The method used in the process of selecting significant multi-day precipitation events was based on the analysis of mean monthly values of the maximum multi-day totals earned in a given month for each year of analysis as simple average of all station values. If, in any given year, the station did not record 5-day total and hence also the Rx5D, zero value was assigned to this station for the sake of preserving constant number of station values included in each step the analysis. After calculating the average monthly maximum values for the complete set of stations for all years in the 1951–2020 period, we defined the 5 highest values in each month of the calendar year and, together with the year of occurrence, there were selected for a subsequent synoptic analysis. This selection method eventually aggregated 60 different cases available for the consequent annual and half year occurrence analysis of significant weather conditions assigned to the surveyed Rx5Ds.

Identification of the period of occurrence

Occurrence of the extreme heavy precipitation events have been identified within the selected 5 years with the highest average sums. Previously calculated Rx5D were station-wide assigned to corresponding dates, based on regional analysis conducted using precipitation reports and databased datasets from selected profile stations in each river basin determined by station's designators. The final extent of each selected heavy precipitation event has thus been set within 5 to 8-day period.

Assignment of typified synoptic situation

Process of defining the days, from which was each

selected multi-day situation constituted, was followed by assignment to the corresponding typified synoptic situation. Data sources selected for identification process were represented by specialized calendars of analyzed synoptic situations containing analysis on day-to-day basis. For the period 1951–1990 a calendar elaborated for the territory of former Czechoslovakia (ČHMÚ, 2017) was used, and since 1991 a calendar of situations identified exclusively for the territory of Slovakia (SHMÚ, 2021) was applied. Publication of each annual calendar is necessarily preceded by mutual communication between the Czech Hydrometeorological Institute and the SHMI. In these analyzes, however, are for technical reasons, not identified divisions among the synoptic situations of the same circulating type following directly one after another. The general large scale circulation typification used for the territory of Czechoslovakia and later of independent Slovakia is already from the process of its creation hampered by inaccuracies and the larger the territory we try to include under a narrowly defined typified situation, the greater are the potential detection inaccuracies. We have tried to minimize this impending identification errors with a detailed study of daily totals within multi-day precipitation situation, to ascertain given significant weather situation because, in most cases these large-scale circulating units are not stationary. Great diversity and dynamics of atmospheric processes often results in the extended stay period of selected 5-day precipitation situations over the territory of Slovakia and thus, in many cases, subsequently leads to detection of two, exceptionally, up to three influencing typified situations. In the final process of assessing the occurrence of typified conditions, there have been, after analyzing daily totals, selected one, if necessary two or three influencing situations. This approach allowed us to create the input set containing 99 influencing typified synoptic situations assigned to the set of 60 cases consisting of the five heavy precipitation events with the highest spatial means. This dataset was subsequently used in the impact analysis between typified synoptic situations and the spatial distribution of the maximum sums of Rx5Ds. More accurate identification of atmospheric circulation was achieved by the archived reanalyzed large-scale maps of geopotential levels 850 hPa and 500 hPa created by the US Global Circular Model - GFS or by the US Office for Ocean and Atmosphere (NOAA) (Wetterzentrale, 2021).

Results and discussion

The highest values of Rx5d exceeded 250 millimeters and were measured at precipitation stations located in the mountainous areas in the northern part of Slovakia at elevation over 600 meters a.s.l. Absolute maximum value of Rx5d, accounted for 274.7 mm, was measured in May 2014 in Tatranská Javorina on the northern slopes of the Belianske Tatry mountain range. Rx5Ds over 200 millimeters were detected only on 33 stations (7%) in the January–December period with only 4 stations exceeding this Rx5D value in the cold half-year (October

–March). Furthermore, it can be said, that the Rx5Ds greater than 100 millimeters was at least once recorded at 466 stations, representing almost 96% of the whole set. Spatiotemporal analysis of annual and seasonal maximum Rx5d (Fig. 2) points to the fact, that higher values of Rx5D were in the period 1951–2020 generally achieved in the warm half-year (April–September) (Fig. 3) with significantly pronounced orographic – windward and leeward effects during the cold half-year (October–March) (Fig. 4). Domains with high total values – over 180 millimeters are concentrated mostly in the mountainous northern parts, in the Vysoké Tatry and Západné Tatry mountain ranges, in the north parts of Orava and Kysuce regions and in the southwestern Slovakia in the Malé Karpaty mountain range. However, a relatively large region with high annual Rx5D values is localized also in the northeastern part of the republic. Most of the area of Slovakia is contained in a value range from 110 to 160 millimeters. Isolated areas of the lowest calculated values – under 100 millimeters, are situated mostly in the west on the Podunajská nížina lowland. Spatial distribution of Rx5Ds during warm half year (Fig. 3) resembles overall annual distribution. During the cold half-year are generally observed lower absolute values (Fig. 4), Areas of the highest achieved values – above 140 mm – are in the cold half-year, unlike in the previous cases, located mainly in the central part of the territory, namely in the region containing western parts of Nízke Tatry mountain range and Veľká Fatra mountain range. Areas with high values are also situated in its west and southeast neighborhoods. Relatively extensive area with sums below 80 millimeters is located in the southeast part of the territory in

the Východoslovenská nížina lowland.

Maximum mean values

The analysis of the highest values of the Rx5Ds can provide a good point of view on the distribution of extreme values, but it is not necessarily suitable for a large-scale study dealing with the effects of the significant typified synoptic situations on the spatio-temporal distribution of the extreme heavy precipitation events. Use of mean values calculated for a complete set of 486 precipitation stations represents a relatively simple and accurate means for determining precipitation events with greater spatial impact. Calculated mean value and accuracy of the detection of the real extreme precipitation event is greatly dependent on the number of stations reaching Rx5D simultaneously. Mean value of the maximum precipitation totals from the complete set of 486 precipitation stations used as a measure to detect the occurrence of the spatially significant precipitation events reached its highest values within the May–October period. The highest mean value and at same time, the only total with value in the 90-millimeter range, was recorded only recently in October 2020 with mean Rx5d value 90.0 millimeters. The second (80.7 mm) and third (78.3 mm) highest values were calculated for July 16 to July 21, 1997 and July 16 to July 22, 2001 respectively. (Table 1) Within the entire set comprised of 720 values of mean monthly Rx5Ds, values greater than 50 millimeters were achieved only 18 times, of which 6 in July and 5 in October. Values greater than 50 millimeters were never, within this data set, recorded in the period from January to April.

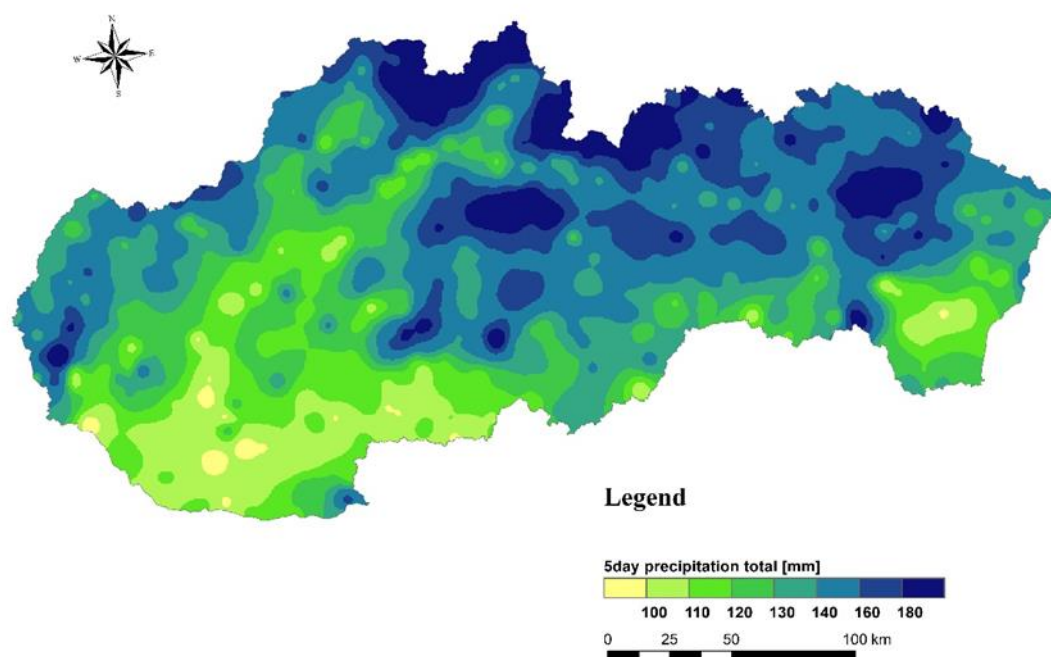


Fig. 2. Maximum 5-day precipitation totals in Slovakia in the 1951–2020 period.

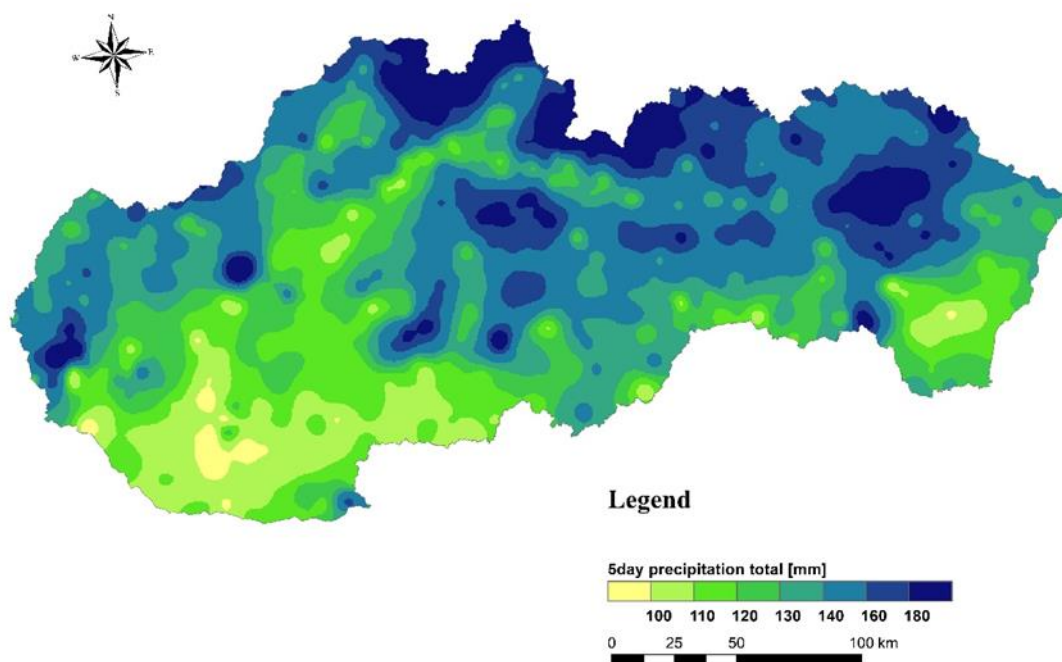


Fig. 3. Maximum 5-day precipitation totals during the warm half-year in Slovakia in the 1951–2020 period.

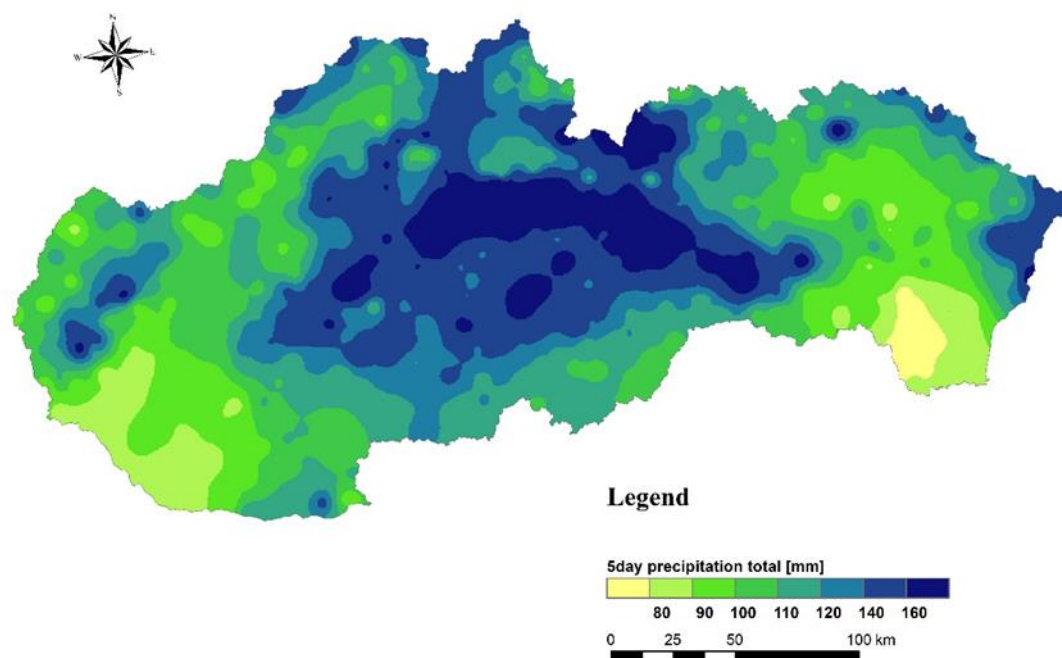


Fig. 4. Maximum 5-day precipitation totals during the cold half-year in Slovakia in the 1951–2020 period.

Dynamical-climatological analysis of maximum average values

Form of a cluster analysis was selected to maintain the transparency and informative value of obtained results. Clusters were based on the relative geographic position of the typified synoptic situation in relation to the territory of Slovakia. Using this approach, 25 typified synoptic situations were clustered to the 9 main groups (clusters). These clusters consisted of one, two or three typified situations. We subsequently obtained 7 clusters for cyclonic types – 1. trough of low pressure over the central Europe and trough moving over the central Europe (B/Bp), 2. cyclone over the central Europe (C), 3. the upper-level cyclone (Cv), 4. eastern cyclonic situation (Ec), 5. northern cyclonic situations (Nc/NEc/NWc), 6. southern cyclonic situations (SEc/SWc) and 7. western cyclonic situations (Wc/Wcs).

Anticyclonic and transient situations were thus each assigned into its own one cluster – 8. entrance to the frontal zone (Vfz) and 9. anticyclonic situations. In section of our analysis, we worked with the collection of 60 cases consisting of five Rx5D events with the highest spatial mean values for each month of year. Considering, that the extent of each selected extreme heavy event has been previously set within 5 to 8-day period each event could be represented by up to three typified situations. The final analyzed input set consisted of 98 individual typified synoptic situations – 21 one-situation events, 37 two-situation events and 1 three-situation event. Relative dominance of the B/Bp and Nc/NEc/NWc clusters with exactly the same relative occurrence (29%) was observed when analyzing relative occurrence of significant synoptic types during events with the highest calculated mean values, regardless of the month of their occurrence (Fig. 5). Significant relative representation

Table 1. Ranking of the 10 highest mean monthly values of the Rx5D in Slovakia in the 1951–2020 period

Rank	Mean [mm]	Year	Month	Date	Situation	Max [mm]
1	90.0	2020	October	10. – 17.	NWc-C	174.3
2	80.7	1997	July	16. – 21.	C-NEc	253.6
3	78.3	2001	July	16. – 22.	B-Bp	274.0
4	77.2	1984	September	21. – 25.	B	219.7
5	74.5	1980	October	08. – 12.	B-Bp	268.8
6	72.2	2010	May	13. – 18.	B-NEc	219.7
7	65.5	2007	September	04. – 08.	Ec	215.8
8	62.4	2011	July	18. – 22.	B-C	155.2
9	61.3	1960	July	23. – 27.	C	229.6
10	59.8	1964	October	09. – 15.	B-C	211.6

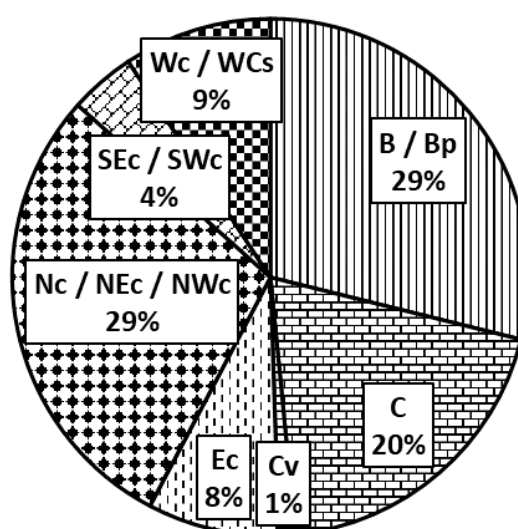


Fig. 5. Relative representation of typified synoptic situation on occurrence of highest average Rx5D [%] from January to December in Slovakia in the 1951–2020 period.

was also observed in case of cyclonic circulation types with central position C (20%). No other cluster managed to reach at least 10% relative occurrence. The highest spatial mean value 90.0 millimeters measured during heavy precipitation event from 10. to 17. October 2020 occurred during NWc situation transitioning into C situation.

The cluster-based analysis of the absolute frequency of occurrences of the typified synoptic situations during the months of calendar year (Fig. 6) provides more detailed look on their temporal distribution. From 2 to 6 detected influencing clusters were identified for each month of the year, the most (6) in March. February, April, May, and August recorded 5 clusters, and the least (2) were

recorded in November, which also saw considerable prevalence of a Nc/NEc/NWc cluster.

A better view on distribution, and the possible change in the impact of selected clustered circulating types during year can be achieved by a separate analysis using, in climatology common division into the warm half-year (April–September) (Fig. 7 left) and the cold half-year (October–March) (Fig. 7 right).

In the warm half-year cluster B/Bp maintained its most influential position with 6% increase in the relative occurrence. Cyclonic situation with a central orientation (C) increased its occurrence and become the second most prevalent circulation type (3% increase). Increase in the relative occurrence was detected for circulation

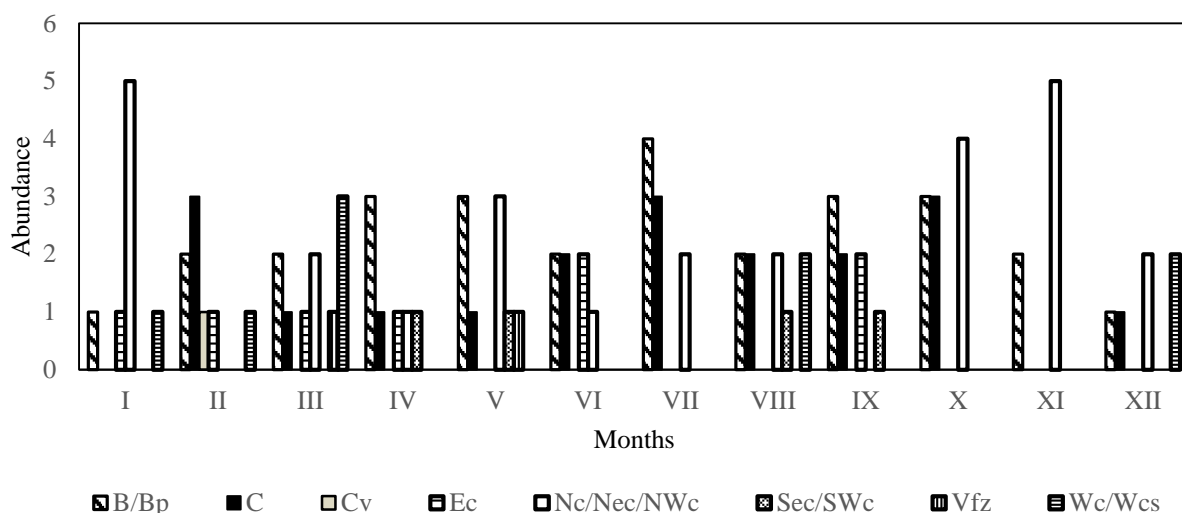


Fig. 6. Absolute frequency of occurrences of the typified synoptic situations during the months of calendar year from January to December in Slovakia in the 1951–2020 period

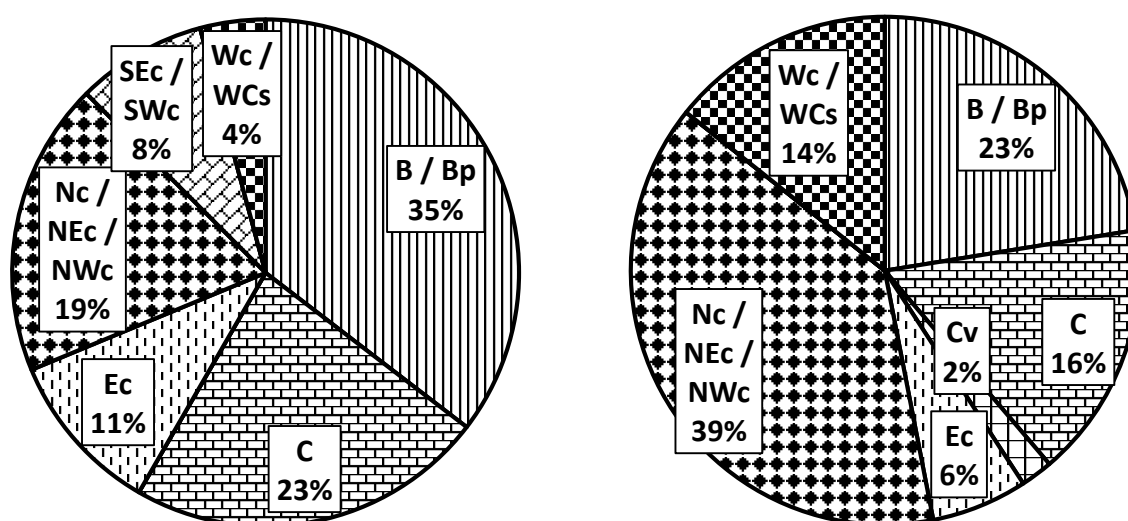


Fig. 7. Relative representation of the typified synoptic situations on occurrence of the highest average Rx5D [%] in the warm half-year (left) and cold half-year (right) in Slovakia in the 1951–2020 period.

clusters Ec (3% increase) and SEc/SWc (4% increase) while western cyclonic situations occurrence decreased by 5%. It can be also further noted, that, during this period, Cv circulation type didn't even participate in the genesis of situations with highest maximum precipitation totals.

Summer months of July and August can be presented as a typical period, during which can be observed large-scale atmospheric circulation necessary for occurrence of the extreme precipitation events with a good spatial distribution. Summer months are usually characterized by high percentage of the convective precipitation, but warm and humid atmosphere can during favorable atmospheric circulation provide ideal condition for heavy precipitation events influencing even lowland areas. Spatial distribution of stations with the highest values of the Rx5Ds calculated for five situations with the highest mean values is displayed in the Fig. 8. Most stations are in the mountain areas in the central part of the territory with a patch of stations located in the eastern part of Slovakia, even in the Východoslovenská nížina lowland. This heavy precipitation event occurred during situation Bp transitioning into NEc situation in 2004. Heavy precipitation event in 1997 (C-NEc), significantly impacted even areas in the west of Slovakia in the Malé Karpaty mountain range, Biele Karpaty mountain range

and Javorníky mountain range.

In the cold half-year can be observed a significantly different relative distribution of clusters detected during heavy precipitation events (Fig. 7). Unlike in the warmer half-year, in this part of year there was recorded (in comparison to the year-round relative distribution) a significant increase in the relative representation of Nc/NEc/NWc cluster (10% increase), which means, that this cluster become the most prevalent with relative occurrence of 39%. Decrease in the relative occurrence was detected for cluster B/Bp (6% decrease) and C (4% decrease) (but during the month of January February and March, even the highest average values during these circulation types. Cyclonic circulation cluster with the southern orientation SEc/SWc didn't even participate in the genesis of the extreme heavy precipitation.

The spatial distribution of the maximum values calculated for 5 events with highest mean maximum precipitation totals displayed for October (Fig. 9) represents a typical placement on the southern westward slopes in the mountainous regions in the central part of Slovakia during wide range of synoptic situations. The absolutely highest mean value calculated for the whole Rx5D data set was set during NWc-C extreme heavy precipitation event in October 2020.

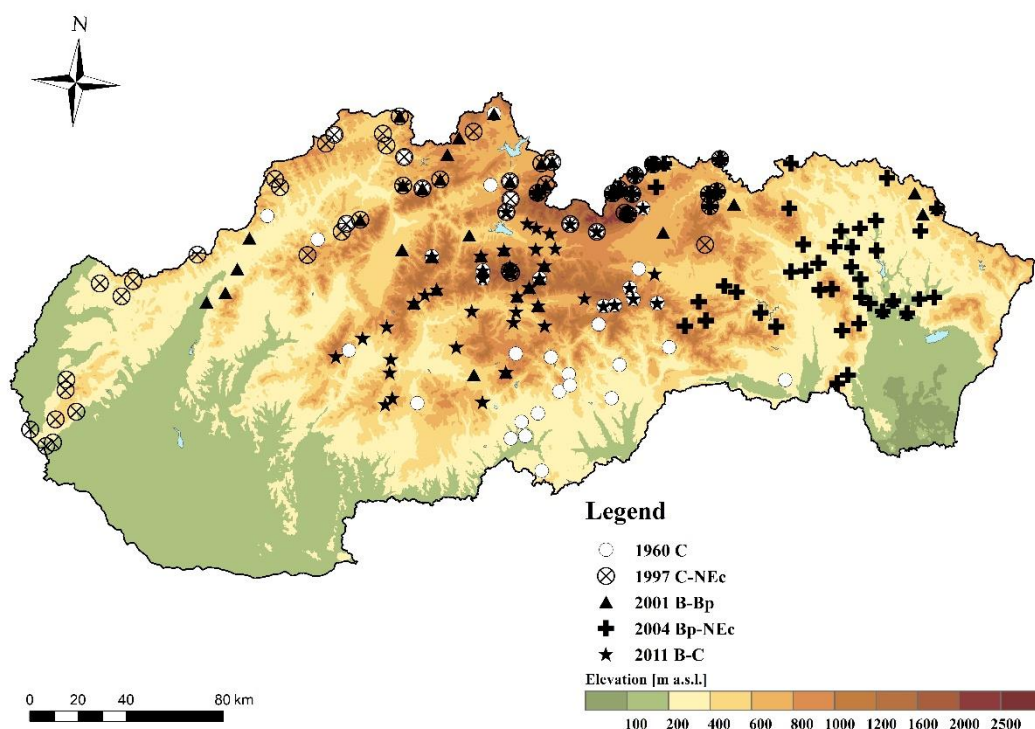


Fig. 8. Placement of 50 stations with the highest Rx5D measured during occurrence of typified synoptic situations with the highest calculated mean values in Slovakia in July in the 1951–2020 period.

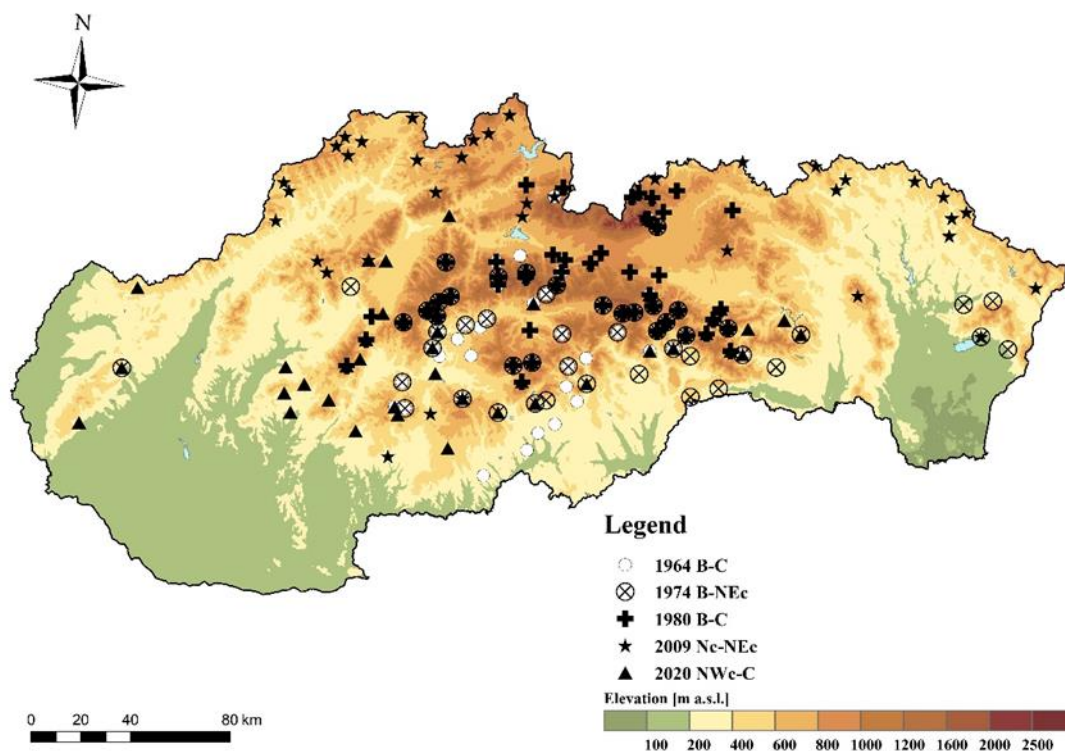


Fig. 9. Placement of 50 stations with the highest Rx5D measured during occurrence of typified synoptic situations with the highest calculated mean values in Slovakia in October in the 1951–2020 period.

Conclusion

Spatiotemporal analysis of annual and seasonal maximum Rx5d points to the fact, that higher values in the period 1951–2020 of Rx5d were generally achieved in the warm half-year (April–September) with significantly pronounced orographic – windward and leeward effects during the cold half-year (October–March). Mean value of the maximum precipitation totals from the complete set of 486 precipitation stations used as a measure to detect the occurrence of the spatially significant precipitation events reached its highest values within the May – October period. The highest mean value was recorded during heavy precipitation event in October 2020 with mean Rx5d value 90.0 millimeters. The maximum mean values, independent of the month of occurrence, were recorded during the presence of the typified synoptic situations characterized as low-pressure trough (B/Bp) and the cyclonic situations with northern orientation (Nc/NWc/NEc). Changes in the spatial distribution of Rx5d during the year were clearly identified in the separate warm half-year (April–September) and cold half-year (October–March) analyzes. Spatially significant precipitations events recorded in the warm half-year were, in more than 1/2 of the identified events, caused by the cyclonic situations with central position (C) and by the low-pressure trough (B/Bp). Cold half-year is, on the other hand, defined by a dominant influence of the cyclonic situations with

northern orientation (Nc/NWc/NEc) complemented by the low-pressure troughs (B/Bp).

Our analysis highlights the fact, that regional Czechoslovak typification of significant synoptic situations can, despite its often-present subjectivity, provide very good results that correlate with the long-term climatological knowledge of atmospheric circulation over the territory of Slovakia. It also provides good basis for the future objective dynamic-climatological analysis.

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