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Changes in precipitation conditions in Slovakia during northern and southern cyclonic situations in the 1991–2020 period

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Abstract— In Slovakia, the spatial distribution of precipitation is inhomogeneous, which is mainly caused by the prevailing airflow of individual synoptic types in combination with a diverse georelief. The article examines the precipitation conditions of Slovakia for all northern and southern types of cyclonic situations in the period 1991–2020. In the selected area we worked with precipitation totals from 798 stations provided by the Slovak Hydrometeorological Institute. We processed the separate dataset in Microsoft Excel and created distinct layers of precipitation totals for all the situations studied in ArcGIS software using a Python script. From the separate datasets, we created precipitation fields for the average annual precipitation total and fields for the percentage of the average annual precipitation fallen during all northern and all southern types of cyclonic situations out of the total average annual precipitation fallen during the whole period under study and for each decade, respectively. Based on the results obtained, we can observe changes in the frequency of occurrence and in the spatial distribution of precipitation, especially for southern, but also for northern cyclonic types of situations. These findings can be used in practice in several fields, especially in synoptic meteorology, climatology, and hydrology.

Key-words: precipitation conditions, climate change, northern and southern cyclonic situations, Slovakia

1. Introduction

In terms of geographical location, Slovakia lies in a temperate climate zone in the middle of Central Europe (*Fig. 1*), where different air masses (arctic, polar, tropical) alternate throughout the year. The distance from the Atlantic Ocean or the surrounding seas means that Slovakia's climate is transitional between oceanic and continental. It is, therefore, very important what synoptic situation brings atmospheric precipitation to our area.

Fig. 1. Location of Slovakia within Europe. (Source: Freeworldmaps, (2023), own modification)

Slovakia is a very rugged country in terms of relief. It is made up of the lowlands of the Pannonian Basin, basins, and the Carpathian Mountains. These lowlands, basins, and mountain ranges are part of a vertically and horizontally extensive geomorphological system on the surface of the earth, namely the Alpine-Himalayan system. This extends from northern Africa, across Europe, into southern Asia. In terms of geomorphology, Slovakia is divided into sub-systems, provinces, sub-provinces, areas, units, sub-units, and parts (*Mazúr* and *Lukniš*, 1978).

The orographic conditions and the diversity of the georelief of Slovakia imply considerable contrasts not only in altitude but also in temperature, precipitation, soils, geological composition, vegetation cover (*Lukniš et al.*, 1972). We were interested in the different precipitation patterns at the level of geomorphological units, depending on the altitude and mass of the geomorphological unit, uneven distribution of precipitation can occur at different distances from it. Precipitation is a key element of climate that determines the availability of freshwater, and soil moisture levels and can have a significant impact on society (*Nikolova et al.*, 2013). The knowledge gained about precipitation variability can carry important information about climate change.

In addition, knowledge of the behavior of different types of cyclonic situations can help us in issuing both meteorological and hydrological warnings. Therefore, the main aim of article is to investigate the changes in precipitation ratios and different distributions of precipitation in Slovakia under northern and southern types of cyclonic situations.

2. Theoretical background

The average annual rainfall is variable, mainly due to the topography, even though Slovakia is a relatively small country. In Slovakia, the average annual rainfall ranges from less than 500 mm in town Galanta, town Senec, and the eastern part of riverine island Žitný ostrov to about 2 000 mm in the High Tatras (SHMIa, 2023).

The spatial distribution, variability, and trends of precipitation have been of interest to several authors around the world (*Arora et al.*, 2006; *Meseguer-Ruiz et al.*, 2019). In addition, in recent years, authors have also been interested in the extremity of precipitation events themselves, which are generally increasing (*Casanueva et al.*, 2014; *Iqbal et al.* 2019; *Markovič et al.*, 2021)

For our purposes of calculating the share of the average annual precipitation fallen during different types of cyclonic situations in the total average annual precipitation, we have prepared a map of the average annual precipitation fallen during the period 1991–2020 (*Fig. 2*). Maps of average annual totals can also be found processed by the authors *Faško* and *Šťastný* (2002) for the period from 1961 to 1990 or in the Climate Atlas (*Bochníček et al.*, 2015) for the period from 1981 to 2010.

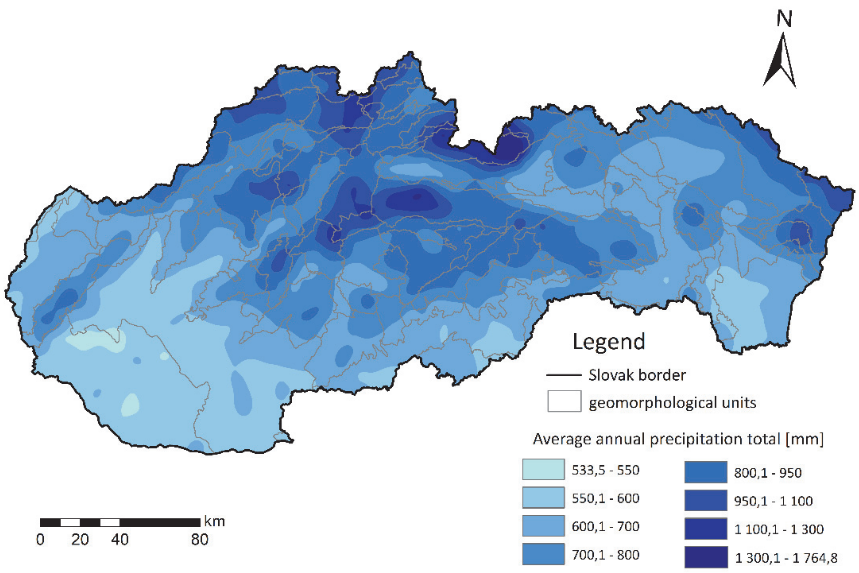

Fig. 2. Average annual precipitation between 1991 and 2020 (Source: SHMI data, own processing).

Sobíšek et al. (1993) define weather typing as a system of synoptic types that have been created using daily synoptic maps for meteorological forecasts, climatological assessments, etc. Classification of synoptic types is the assignment of a classification type to each day, even if the weather on that day does not meet the characteristics of that type (*Benco,* 2009). This is because both the atmospheric circulation and the synoptic type itself are dynamic and constantly changing mechanisms.

In the past, different synoptic classification of weather situations were used for territory of Czechoslovakia. The oldest was by *Hess* and *Brezovský* (1952), in Katalog der Grosswetterlagen Europas. This classification, originally developed for the western German territory, did not gain widespread acceptance in our local climatic conditions. Subsequently, several modified synoptic classification were created by *Rein* (1959), *Brádka et al.* (1961), and *Červený* (1965).

At present, the synoptic classification according to the Hydrometeorological Institute under the then leadership of J. Brádka, described in detail in the Catalogue of Weather Situations of the Czechoslovak Socialist Republic (*Brádka et al*., 1968), is valid for our territory. This contains 25 sample synoptic situations, of which 10 are anticyclonic and 15 cyclonic. All types are characterized by a certain flow direction or its short-term changes, the pressure field regime, the way of transition of individual frontal systems, and the air masses flow or their alternation. A detailed description of all types of cyclonic situations can be found on the SHMI website (SHMIb, 2023). Cyclonic situations differ from each other not only in their characteristics, and the trajectory of movement, but also in the spatial distribution of precipitation, different intensities of precipitation, and different occurrences within a calendar year. Since 1991, the Czech and Slovak sides started to prepare their proposals for the types of situations throughout the year separately (Czech Meteorological Society, 2023).

The northern types of cyclonic situations are characterized by the predominant flow from northern directions into our area. NWc (northwest cyclonic situation) and Nc (north cyclonic situation) bring moisture and associated precipitation processes to our area mainly from the northeast Atlantic region. The NEc (northeast cyclonic situation) has a moisture source in the Mediterranean area, which can be deduced from the prevailing flow in *Fig. 3*. The center of the cyclone in this type of situation is generally in the Balkan region, based on which the prevailing northeasterly flow is in our area.

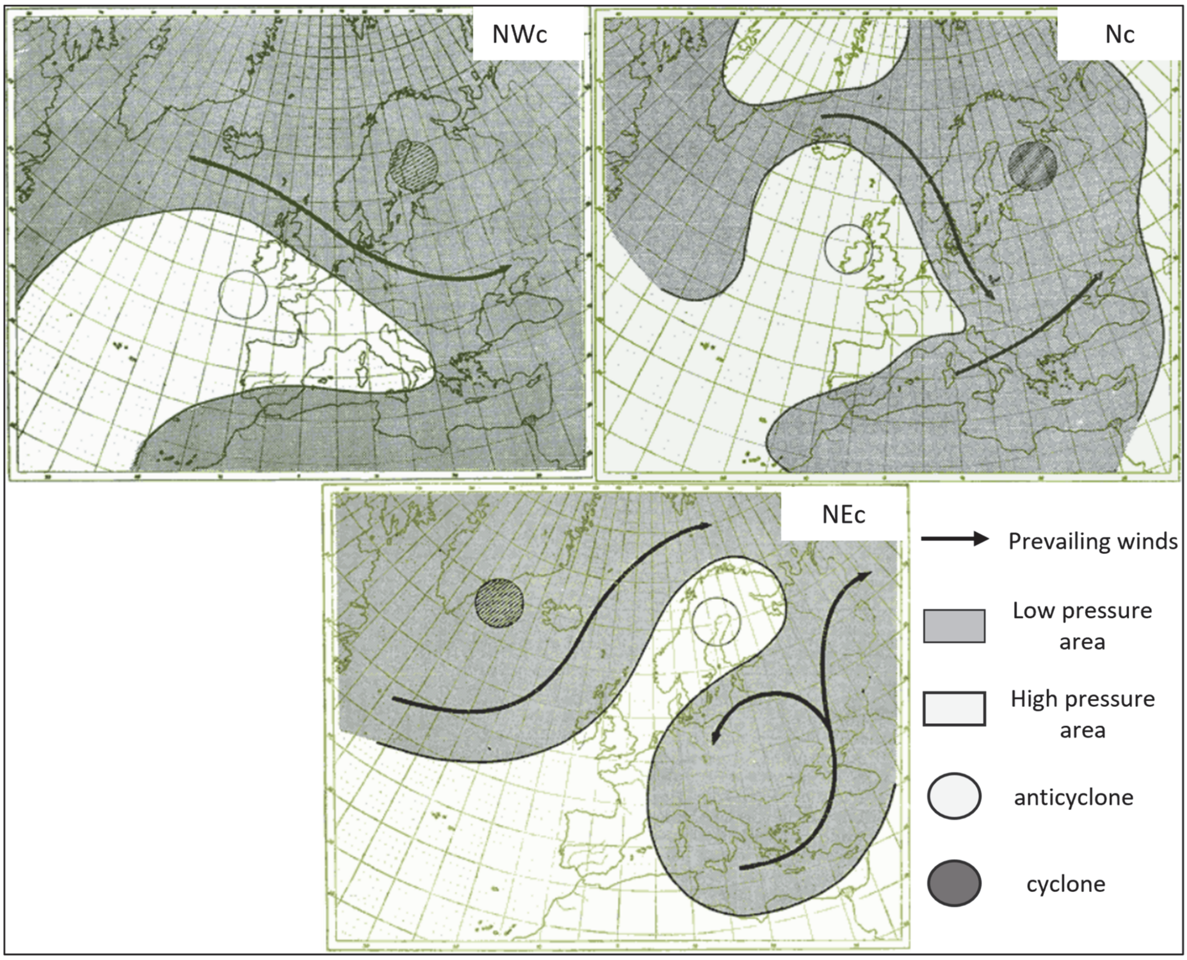

Fig. 3. Schematic representation of the surface pressure field in Europe during different northern types of cyclonic situations (Source: SHMI, own processing).

The southern types of cyclonic situations are characterized by the opposite of the northern types by the flow from the southern directions into our area (*Fig. 4*). SEc (southeast cyclonic situation) brings to our area precipitation from the Adriatic region, where the center of its “controlling” cyclone is generally located. Situations SWc1, SWc2, and SWc3 (southwesterly cyclonic situation of type 1, type 2, and type 3) bring moisture to our area mainly from the eastern Atlantic region. The SWc1 situation is more meridional compared to the more zonal SWc2 and SWc3 situations, which may give rise to shallow frontal waves in the northern Italy area, which advance northwards across our territory in this type of situation.

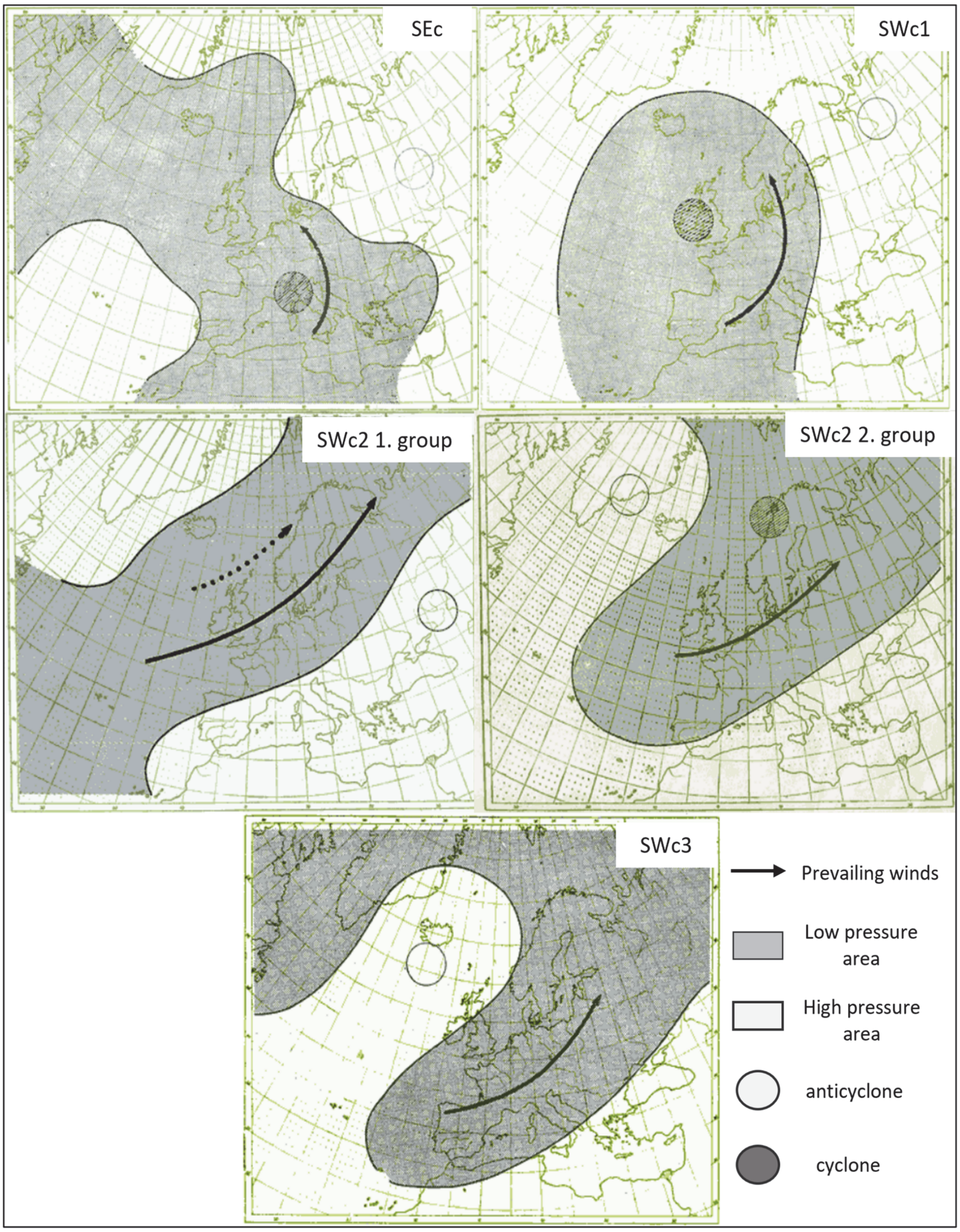

Fig. 4. Schematic representation of the surface pressure field in Europe during individual southern cyclonic types (Source: SHMI, own processing).

However, in this case it is a traditional (subjective) classification. Due to continuous development (objective), algorithmic methods of circulation classification are commonly used in most European countries. Among a number of algorithmic methods, the Simulated Annealing and Diversified Randomisation (SANDRA) classification scheme (*Philipp et al.*, 2007) is a quite reliable and widely used alternative. SANDRA is based on conventional k-means clustering. It is numerically less expensive and overcomes many limitations of established automatic clustering methods (*Hansen* and *Belušić*, 2021). Numerous studies have been developed in Europe, investigating the relationship between climatological variables and circulation patterns expressed by different classifications of circulation types. The differences in the construction of various types lie in their adaptation to the geographical and atmospheric conditions of the domain or subdomain. A comparison of circulation type classifications from the COST733 action "Harmonisation and Applications of Weather Types Classifications for European Regions" can be found in *Beck* and *Phillip* (2010). The use of the traditional subjective method (e.g., in the case of the Czech Republic and Slovakia) is still applied despite the advanced classification methods (*Řehoř et al.*, 2020). A comparison of traditional subjective and objective classification methods analyzed for conditions in Central Europe can be found in *Řehor et al.* (2021). The reason for choosing a traditional subjective classification method was to maintain consistency with previous publications to which this paper is directly related.

3. Material and methods

The analysis of changes in precipitation conditions was based on precipitation totals from the SHMI precipitation gauging stations throughout Slovakia in the period 1991–2020. The station network had 798 stations over the 30 years under study, with precipitation totals measured steadily at approximately 600 stations each year. Station network was relatively evenly distributed, except for the highest parts of Slovakia. For the statistical treatment of all northern and southern types of cyclonic situations, we used a classification of synoptic types based on the Catalogue of Weather Situations of Czechoslovakia (*Brádka et al.*, 1968) available in the Calendar of Individual Weather Situations (SHMIb, 2023). Since 1991, the Czech and Slovak sides started to prepare their proposals for the types of situations throughout the year independently (Czech Meteorological Society, 2023). Therefore, it was important to investigate the issue from 1991 at the earliest, so that the homogeneity of the data would not be disturbed.

In the Microsoft Excel environment we statistically processed the individual weather situations studied, for which we used the aforementioned calendar of the synoptic classification. Based on it, we recorded the number of days with the occurrence of southern and northern cyclonic situations together but also individually. Then we created a line graph with a linear trend, which showed the evolution of the total number of days of all southern and northern types of situations in the studied period. We further detailed each situation (NWc, Nc, NEc, SEc, SWc1, SWc2, and SWc3). For each year under study, warm half-year (April to September) and cold half-year (October to March), we recorded the number of days with the occurrence of each situation. After then we created a line graph for each situation that displayed the 5-year moving averages of the number of days with that situation in the year, warm half-year, and cold half-year. Because of the huge variability in the occurrence of individual northern and southern cyclonic situations, we preferred to work only with the 5-year moving averages, since using a linear trend would result in a coefficient of determination (R^2) close to 0.

However, annual and daily precipitation totals (from 7.00 a.m. to 7.00 a.m. of the following day) were the subject of the main treatment. Additional but important data were geographic coordinates, indications, and names of rain gauge stations. Precipitation totals were sorted in the Microsoft Excel environment based on the cyclonic types studied according to the calendar of individual weather situations (SHMIb, 2023). Furthermore, annual and daily precipitation totals were processed in ArcGIS software using the Topo to Raster interpolation method. The aforementioned method calculates an estimate of the interpolated value from four adjacent points using an iterative finite difference method (ArcGIS, 2024). According to *Šercl* (2008), the isolines produced by this interpolation most closely resemble the isolines that would be a map would be drawn by an experienced expert. In addition, a script in Python environment was used to streamline the creation of the individual partial raster for spatial distribution of precipitation (referred to as rasters hereafter). A simplified flowchart of the processing of the resulting maps is shown in *Fig. 5*. The detailed methodology can be found in the work on Precipitation conditions of Slovakia in northern and southern cyclonic situations (*Zaujec*, 2022). However, this article is based on adjusted partial rasters that were created only when processing the average annual precipitation totals of all individual cyclonic situations (*Halaj* and *Zaujec*, 2023).

To create maps of average annual precipitation totals of all northern and southern cyclonic types, respectively, we summed all partial raster of the entire period and divided them by the number of years of the period under study (the entire 30-year period, or 10 years). We then obtained the resulting raster from which we could create individual maps (*Figs. 9* and *10*). In each quadrant representing a decade or the whole period, respectively, we chose the same 8-class scale with an assignment of the value of the maximum and minimum rainfall totals in the period under study.

In *Figs. 11* and *12* are presented the proportion of the average annual precipitation fallen during all northern cyclonic types, and southern cyclonic types out of the total average annual precipitation for the whole period (1991–2020). We also used similarly processed partial raster for the average annual rainfall in Slovakia (e.g., *Fig. 2*, but also for the average annual rainfall in individual decades) for each decade (1991–2000, 2001–2010, 2011–2020). Similar to the previous type of results, we divided the resulting maps into 4 quadrants, with each map consisting of the same 8-class scale with the maximum and minimum fraction of precipitation of all northern and southern cyclonic situations, respectively, assigned to the total mean annual precipitation. So, what does the changes in precipitation ratios and overall distribution of precipitation totals look like across all northern and southern cyclonic types over the last few decades?

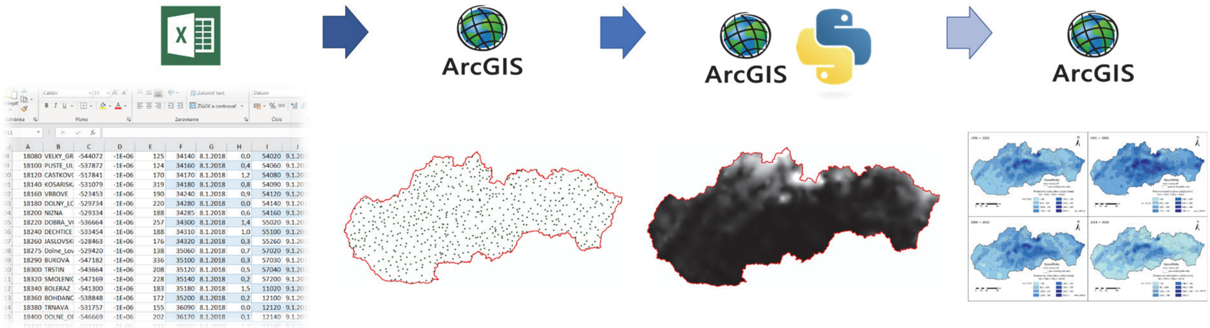

Fig. 5. Simplified scheme of data processing into map form.

4. Results

Over the 30 years from 1991–2020, all cyclonic types occurred on a total of 6582 days, of which the northern and southern types studied accounted for more than 42%. However, there has been a decline in the occurrence of cyclonic types of situations over the period studied, at the expense of an increase in anticyclonic types (*Fig. 6*).

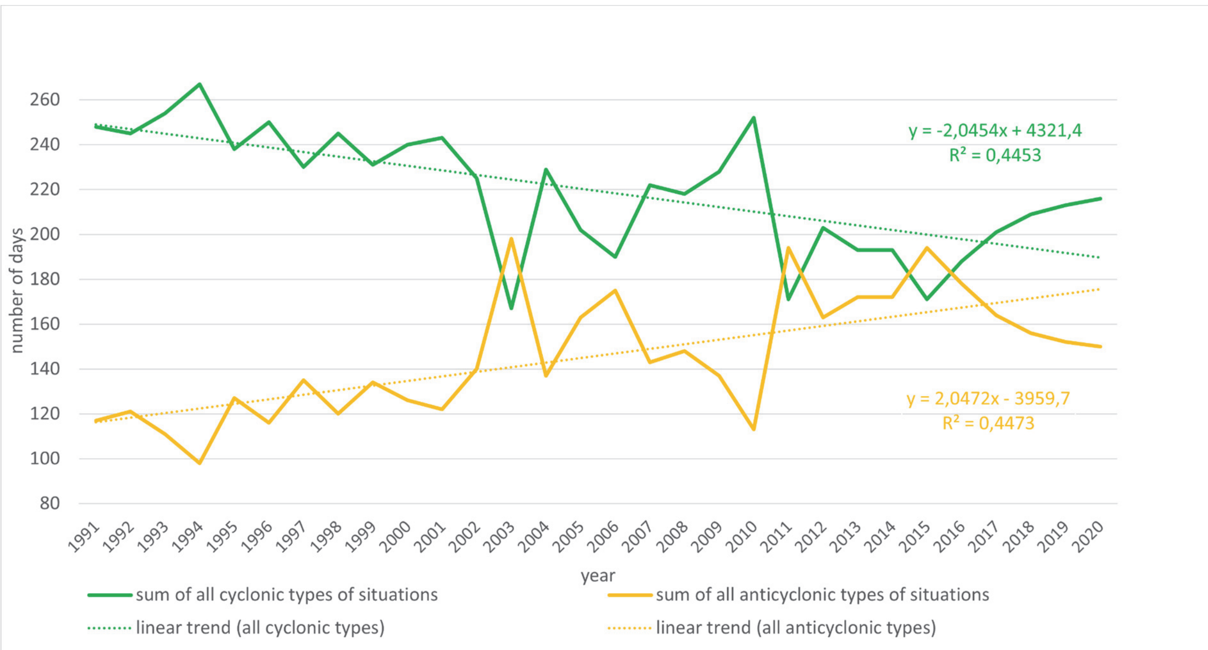

Fig. 6. Number of days with all cyclonic and all anticyclonic situations between 1991–2020 (Source: SHMI data, own processing).

Of the specific northern and southern types of cyclonic of situations studied, the NEc situation occurred most frequently, specifically on 720 days. On the contrary, the SWc3 situation occurred the least, in 250 days. In total, all situations occurred on 2794 days, of which the northern situations occurred on 1636 days and the southern situations on 1158 days. The situations studied occurred most frequently in 2001 (128 days) and in the lowest number of days in 2015 (42 days). Interestingly, all but the southern and northern situations declined over the study period (*Fig. 7*). From the trend line, we can read a more pronounced reduction of southern over northern cyclonic situations. However, it is worth mentioning the significant variability in the occurrence of southern and even more northern types of cyclonic situations from year to year.

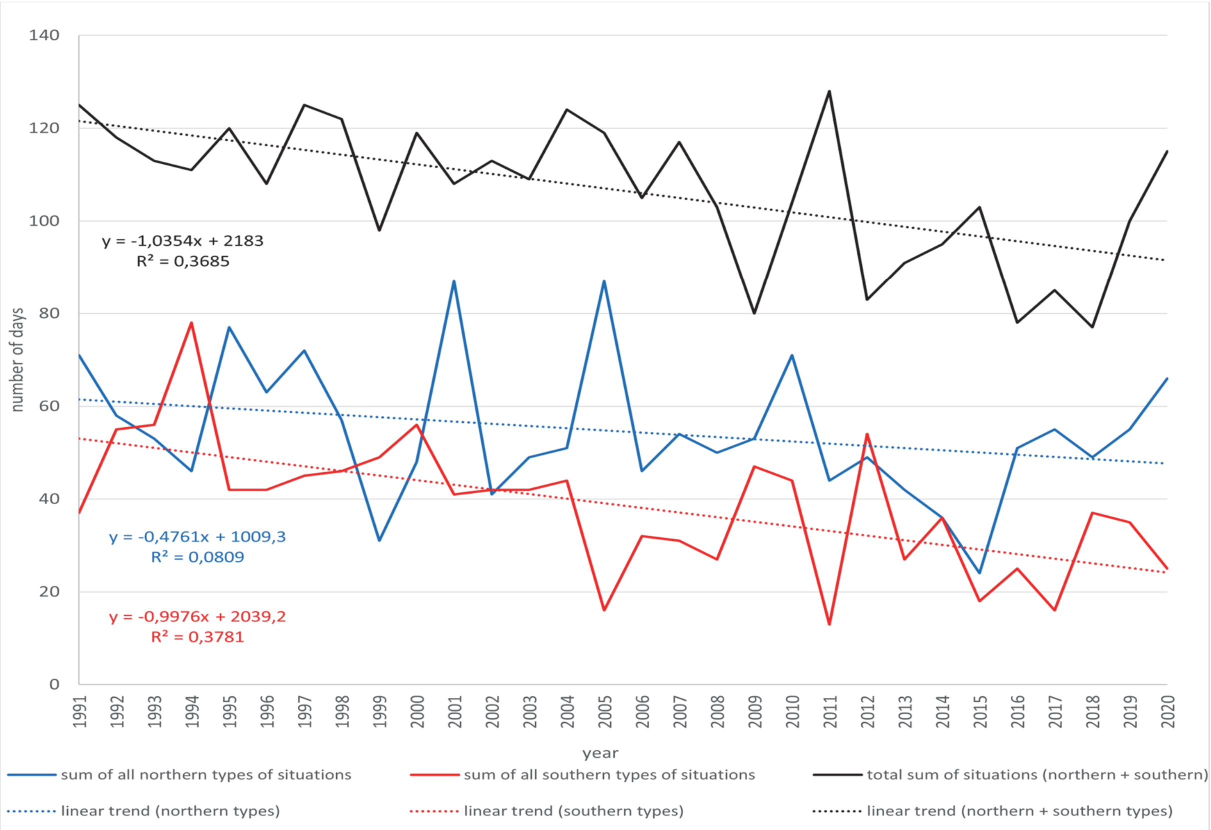

Fig. 7. Number of days with all northern and southern cyclonic situations between 1991–2020 (Source: SHMI data, own processing).

The NWc situation occurred on 577 days during the period under study, with the lowest occurring towards the end of the first decade and the beginning of the second decade, respectively, based on 5-year moving averages. Conversely, at the end of the period under study, this type of situation occurred the most, on an average of 23 days per year. For the most frequently occurring situation NEc (720 days per period), we can see that the situation generally occurred most frequently in the first decade under study, but it was significantly less in the last decade as we can see in *Fig. 8*. Overall, the Nc situation occurred on 339 days, and similar to the NEc type, the most frequent occurrence was in the first decade studied and the least frequent occurrence was in the last years studied. For the NEc and Nc situation, we observed a significant decrease in occurrence over the study period, which was also reflected in the overall decrease of all northern cyclonic situation types between 1991 and 2020 (*Fig. 7*).

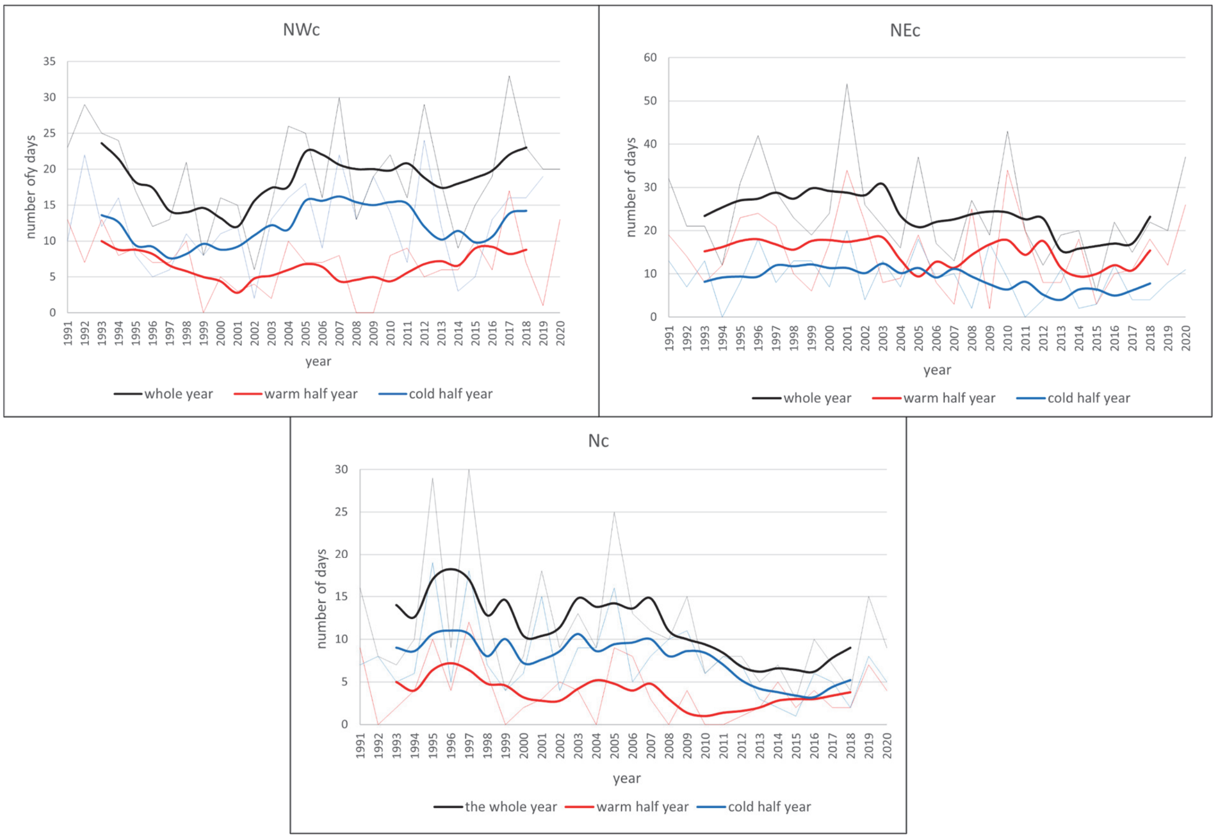

Fig. 8. Number of days with individual northern cyclonic situations between 1991–2020 (rough curves = 5-year moving averages) (Source: SHMI data, own processing).

The SEc situation occurred on 281 days during the study period, occurring most frequently in the middle of the first decade studied and least frequently in the middle of the second decade. The different SWc types occurred differently over the study period, as can be read from *Fig. 9*. Of these, the SWc2 situation occurred most frequently at 352 days, followed by the SWc1 situation at 275 days, and the SWc3 situation occurred least frequently at 250 days. It is worth noting the significant decrease in the type of SWc3 situation, which occurred on only 14 days in the last decade, while in 6 years of the mentioned decade, this situation did not occur even once. In comparison, in the first and second decade, the situation occurred on 135 and 101 days, respectively. This situation is the main cause of the overall decline in all southern cyclonic situation types combined (*Fig. 7*).

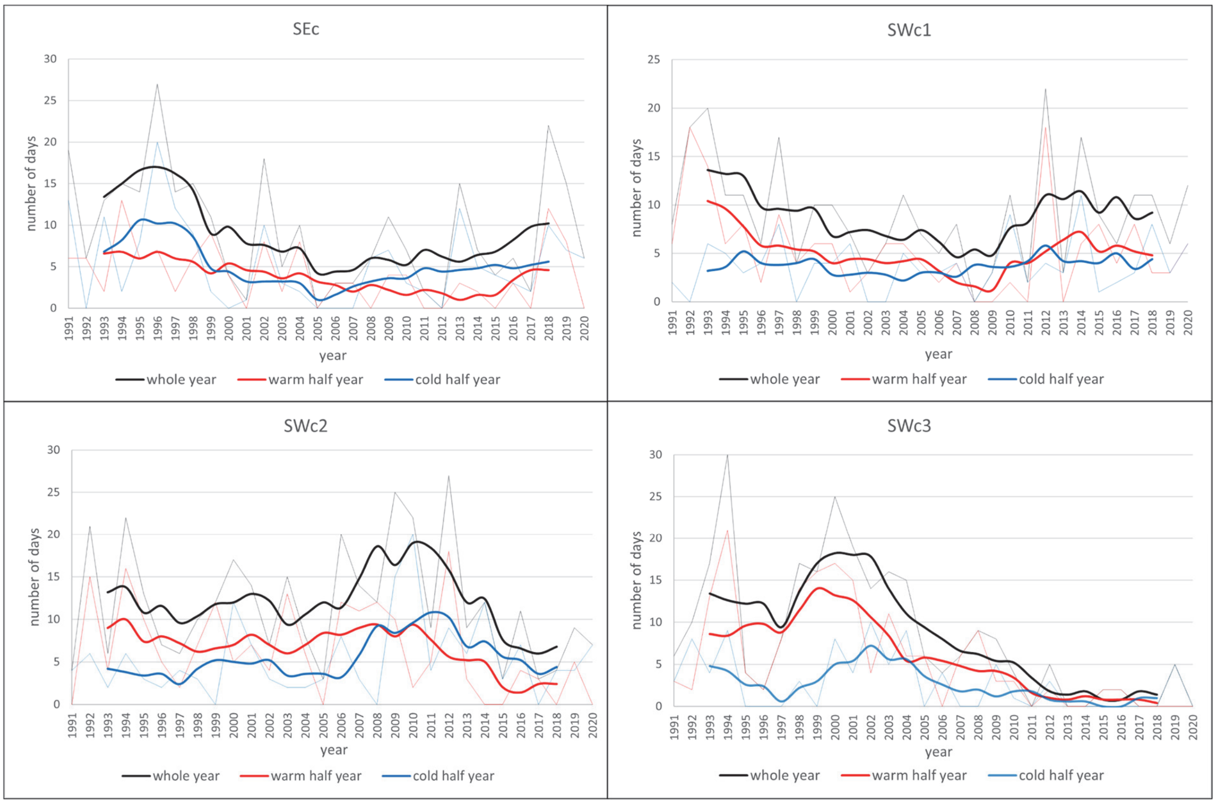

Fig. 9. Number of days with individual southern cyclonic situations between 1991–2020 (rough curves indicate 5-year moving averages) (Source: SHMI data, own processing).

The average annual precipitation for all northern cyclonic types between 1991–2020 ranged from about 68 mm at the boundary between the geomorphological units Podunajská pahorkatina and Podunajská rovina, to about 530 mm in the geomorphological unit Tatry (*Fig. 10*). The decade 1991–2000 (576 days of occurrence) was the driest in terms of average annual precipitation. In contrast, the decade 2001 to 2010 (589 days of occurrence) was the wettest decade for all northern cyclonic types. The last decade studied, 2011–2020 (471 days of occurrence), was the most similar to the average over the entire 30-year period studied.

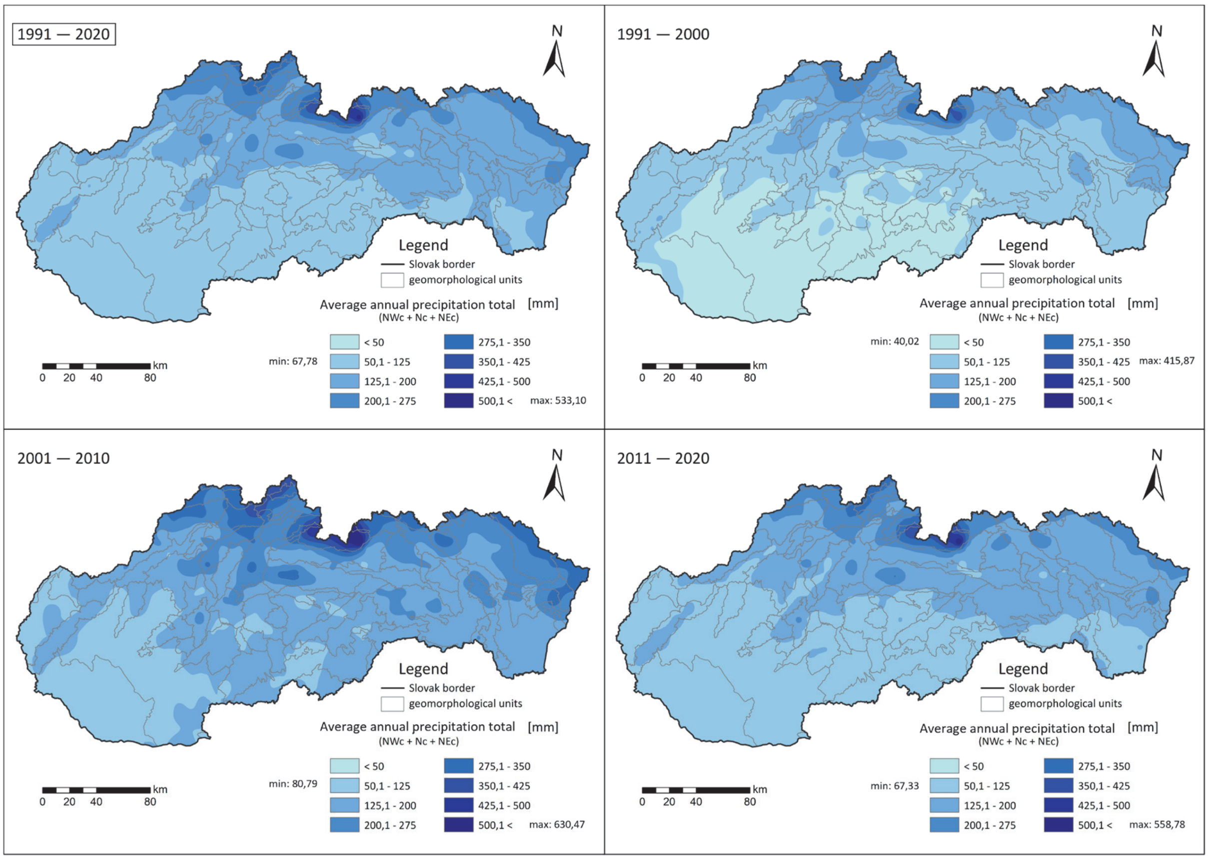

Fig. 10. Average annual precipitation total for all northern cyclonic types from 1991 – 2020 (full period and individual decades) (Source: SHMI data, own processing).

The average annual precipitation for all southern cyclonic types between 1991–2020 ranged from about 78 mm in the geomorphological unit Východoslovenská nížina to more than 200 mm in the geomorphological units Starohorské vrchy, Nízke Tatry, and Tatry (*Fig. 11*). The decade 1991–2000 (506 days of occurrence) was the wettest in terms of average annual precipitation for the southern types. In contrast, the driest decade for all southern cyclonic types was the last decade 2011–2020, when these situations occurred on only 286 days. The middle decade studied, 2001–2010 (366 days of occurrence), was the most similar to the average over the entire 30-year period studied.

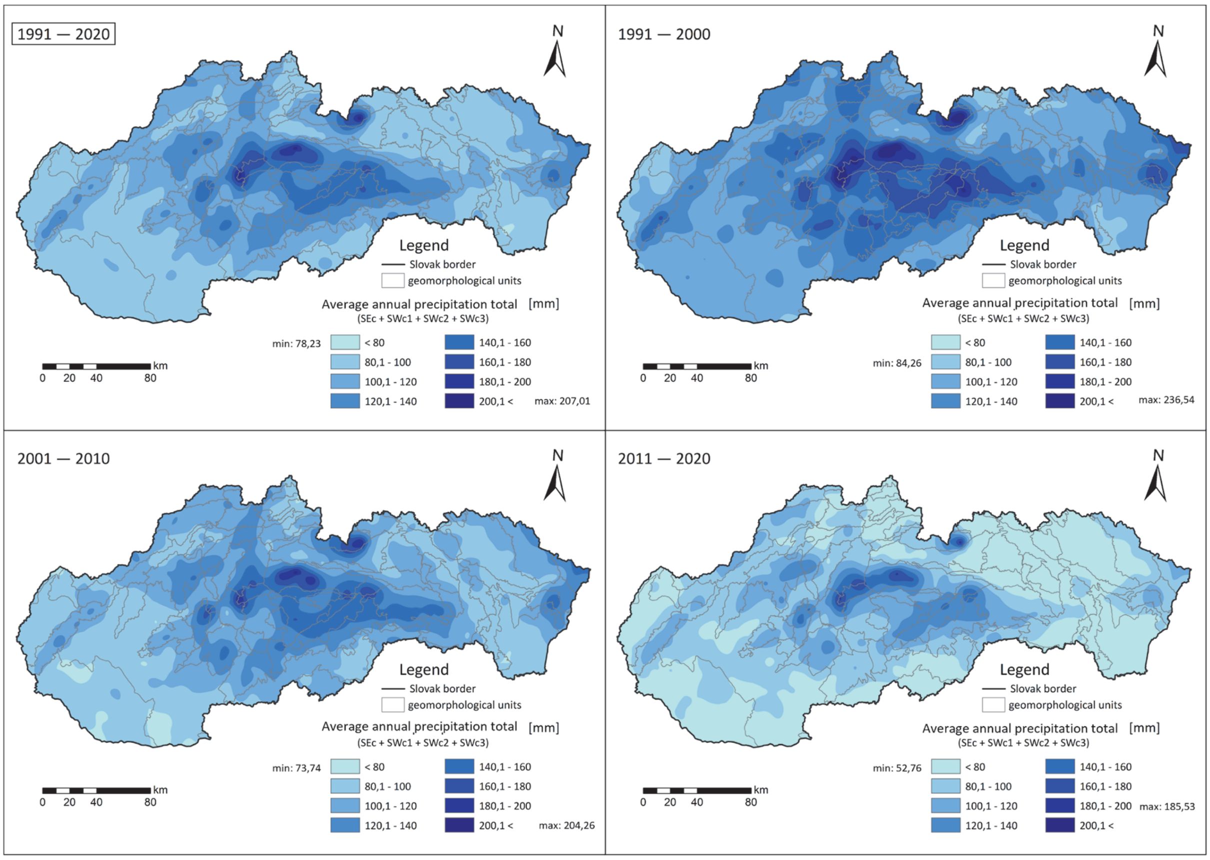

Fig. 11. Average annual precipitation for all southern cyclonic types from 1991–2020 (full period and individual decades) (Source: SHMI data, own processing).

The proportion of the average annual precipitation fallen during all northern cyclonic types out of the total average annual precipitation during the period 1991–2020 ranged from less than 12% in the geomorphological units Zvolenská kotlina and Horehronské podolie, to more than 32% in the geomorphological units Čergov and Busov (*Fig. 12*). In general, the highest proportion of average annual precipitation falling during all northern types of cyclonic situations out of the total average annual precipitation was in the second studied decade from 2001–2010, where it was also more than 40% in Čergov. In the geomorphological units in the north of the territory, especially in the border area with Poland, the significantly increased percentage of the average annual precipitation fallen during all northern types of cyclonic situations from the total average annual precipitation can be attributed to the enhanced windward effect of the individual mountain ranges.

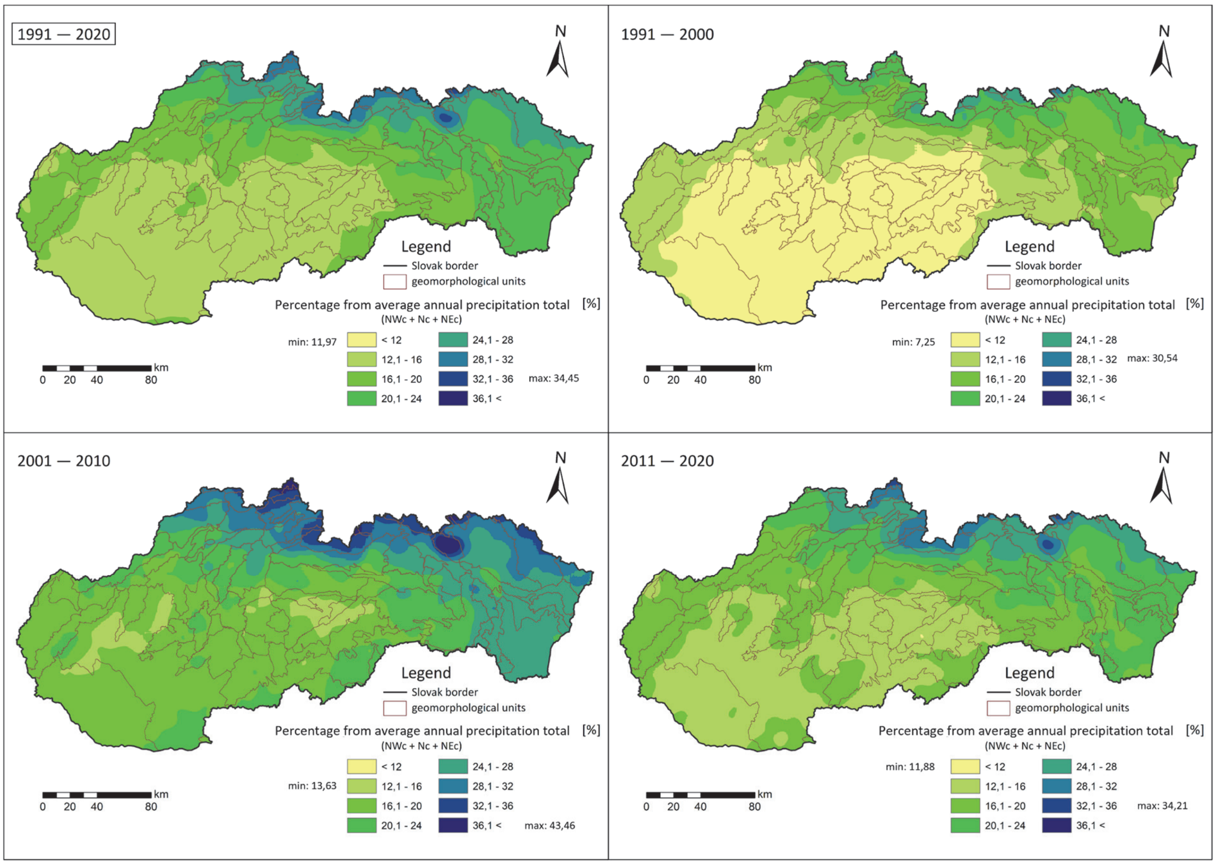

Fig. 12. Percentage of average annual precipitation fallen during all northern cyclonic types out of the total average annual precipitation for the whole period (1991–2020) or for each decade (1991–2000, 2001–2010, 2011–2020). (Source: SHMI data, own processing).

The percentage of the average annual precipitation fallen during all southern cyclonic types out of the total average annual precipitation in the period 1991–2020 ranged from less than 10% in the geomorphological units Oravské Beskydy, Podbeskydská brázda, Podtatranská brázda, Skorušinské vrchy, Spišská Magura, and Pieniny, to more than 18.5% in the geomorphological units Revúcka vrchovina, Stolické vrchy, and Zvolenská kotlina (*Fig. 13*). The highest percentage of the average annual precipitation fallen during all southern cyclonic types out of the total average annual precipitation of cyclonic situations was during the first studied decade in the period 1991–2000, where in most of the geomorphological units of the southern half of Slovakia the mentioned percentage was more than 20%. This was due to the very frequent occurrence of southern cyclonic types in this decade (506 days of occurrence). On the contrary, in the following decades, a significant decrease in the studied situations was recorded, which was also reflected in the actual decrease of the percentage of the average annual precipitation falling during all southern types out of the total average annual precipitation.

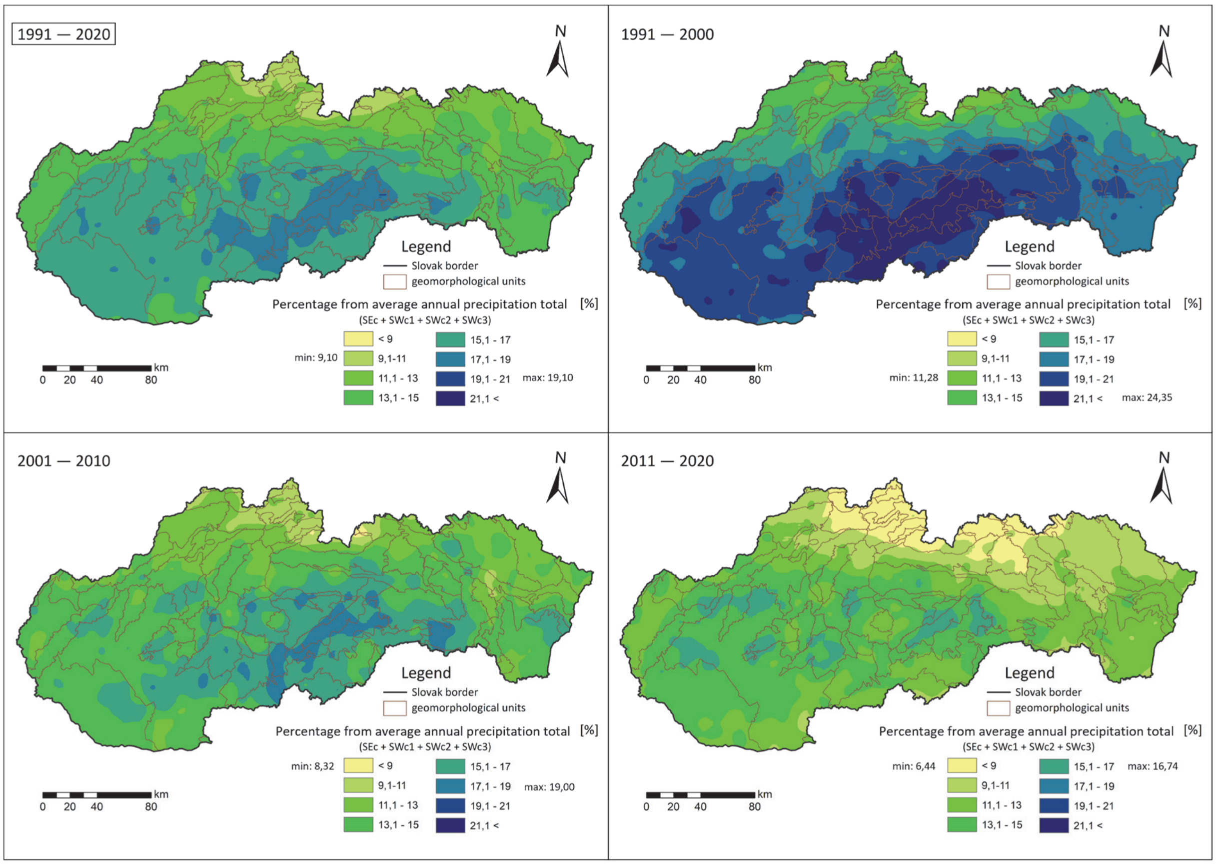

Fig. 13. Percentage of average annual precipitation fallen during all southern cyclonic types out of the total average annual precipitation for the whole period (1991–2020) or for each decade (1991–2000, 2001–2010, 2011–2020). (Source: SHMI data, own processing).

5. Discussion and conclusion

In terms of statistical processing, we can conclude that all northern cyclonic types (NWc, Nc and, NEc) occurred in 1636 days between 1991–2020, while all southern types (SEc, SWc1, SWc2, and SWc3) occurred in 1158 days. In both cases, there was a decrease in the occurrence of weather events over the study period, but the decrease is more pronounced for the southern types (*Fig. 8*). Such results confirm the changes in the general circulation of the atmosphere in our area and help to capture trends or predictions of the future climate on the territory of Slovakia. The North Atlantic Oscillation (NAO) may be one of the reasons for the decrease in days with the occurrence of the studied situations, especially meridional types. In recent decades, its positive phase prevails over the negative phase, as confirmed by *Lešková et al.* (2012), and even the frequency of the extremely positive phase could increase in the winter months in the future, according to *McKenna* and *Maycock* (2022). When the NAO is in the negative phase, the flow is more meridional. On the contrary, when the phase is positive, the flow is more zonal (*Labudová et al*., 2013).

Noting the resulting maps of mean annual precipitation for all northern and southern types of cyclonic situations from the total average annual precipitation, respectively, we see only small areas of intervals for the highest precipitation totals for the northern types of cyclonic situations (NWc + Nc + NEc) compared to large areas of intervals for the lowest precipitation totals (mainly the southern half of Slovakia). In contrast, there was almost no difference between the size of the areas representing the areas of the intervals for the highest and lowest precipitation totals for the southern types of cyclonic situations (SEc + SWc1 + SWc2 + SWc3). This is probably due to the absence of significant vertically and horizontally massive mountain ranges in the southern part of Slovakia. Because of this, from the southern directions, these types of situations are not weakened by mountain ranges further north and are even often precipitation amplified by outflow movements in the central part of Slovakia (suitably located mountain ranges with respect to the flow direction) and are thus not weakened as in the case of the northern types, which "crash" into higher geomorphological units already at the border with Poland.

In the next part of the results, we investigated the percentage of the mean annual precipitation fallen during all northern and southern cyclonic situations, respectively, out of the total average annual precipitation. Noting the result maps of this part of the results alone, we see higher differences between the maximum and minimum percentages for the northern types of cyclonic situations (NWc + Nc + NEc) than for the southern types (SEc + SWc1 + SWc2 + SWc3). One reason for this may be the more pronounced windward and leeward effect for the northern types of cyclonic situations partly mentioned in the previous paragraph. Another cause is the more frequent occurrence of northern types of cyclonic situations. For the southern types, there was a significant decrease in the proportion of total precipitation out of the total mean precipitation over the decades, which correlated with a rapid decline in the number of days with southern types of cyclonic situations. For the northern types, we also observed a decrease in the number of days between the first (1991–2000) and the last decade (2011–2020), but the percentage of total precipitation increased for these types in the last decade studied. This suggests to us that the average daily precipitation for the northern cyclonic types was higher than in the first decade under study (if we consider a minimal change in the total average annual precipitation). This may be due to the higher air temperature in the near-surface layer of the atmosphere caused by global warming, which directly affects the ability of the air to take up water vapour (there is an increase in water vapour content of about 6–7% per 1 °C for the same relative humidity) (*Pecho* and *Faško*, 2010). However, as *Lapin et al.* (2010) point out, higher average air temperature does not only cause a higher risk of heavy precipitation under cyclonic weather conditions or intense convection but also a higher risk of drought under anticyclonic weather conditions. Droughts are particularly accentuated by increasing evapotranspiration due to rising temperatures and increasing frequency of heat waves in central Europe (*Lapin et al.,* 2015; *Tomczyk* and *Bednorz,* 2016).

Climate change has resulted in a change in the occurrence of more extreme weather events (Ministry of the Environment of the Slovak Republic, 2018). For example, the period 1980–2016 was characterized by high variability in rainfall (152% of normal in 2010, 74% of normal in 2003), which caused episodes of severe drought on the one hand and local or regional floods on the other (*Gnida et al.*, 2017). One of the adverse consequences of this change is that it can cause changes in hydrological processes, thereby increasing the likelihood of extreme events such as droughts and floods (*De Sá Silva et al*., 2022). Therefore, we also consider it very important to study changes in precipitation ratios for different types of cyclonic situations in an attempt to understand, prepare for, or adapt to ongoing and also incoming climate change.

Although works of similar focus in Slovakia can be found in the earlier past (*Brázdil* and *Faško*, 1993). *Hoy et al*. (2014) investigated large-scale synoptic types in relation to precipitation in Europe and concluded that changes in precipitation totals are related to changes in the frequency of synoptic types, but predominantly during the winter half-year. However, similar work can also be found in neighboring Poland where the variability of precipitation in relation to individual situations was addressed in the area of the High Tatras and they identified 3 types of cyclonic situations (namely 2 of them are Nc and NEc), which are responsible for the most extreme precipitation in the mentioned area (*Niedźwiedź et al*., 2015). However, the first work in Slovakia that set up a systematic treatment of precipitation totals in different types of cyclonic situations was by *Mészáros* (2015), focusing on situations from southerly directions. In addition, *Mészáros* (2019) developed this work with results for windward and leeward positions and the occurrence of different types of southern cyclonic situations. A similar methodology has been developed in the works by *Kasza* (2018) - northern directions and *Halaj* (2019) - western directions. The subject of the work was mainly the average annual rainfall totals during the different situations studied. The identified precipitation total and the cumulative precipitation total forecast from the ECMWF model (European Centre for Medium-Range Weather Forecasts) were confronted by *Polčák* and *Mészáros* (2018) on the example of a specific cyclonic situation. The aforementioned work was followed by *Zaujec* (2020), where the influence of georelief on the precipitation totals of the Podunajská nížina under NWc and SEc situations was investigated in detail. Based on a 40-year period, windward, leeward and neutral positions were identified for all northern and southern cyclonic situation types using an innovative methodology (*Zaujec*, 2022). A partially new output was the grouping of cyclonic situations based on their prevailing flow (*Mészáros et al.,* 2022). As the methodological approach was adopted in the then work and encountered its limitations, it had to be modified. This occurred in the comprehensive treatment of all classified types of cyclonic situations, including those with ambiguous trajectories (*Halaj* and *Zaujec*, 2023). Based on the chronological arrangement of all published works, one may consider the issue closed, but the opposite is true. The topic of the spatiotemporal distribution of precipitation under different weather situations can be further developed by applying the findings so far and searching for new connections in further works and related fields – in conjunction with synoptic meteorology, operational hydrology but also still in climatology. In conclusion these and other results will help to improve climate projections for the region and inform the development of water management policies. This is important because atmospheric circulation is a major source of uncertainty in climate change projections (*Shepherd*, 2014; *Oudar et al*., 2020).

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References

ArcGIS, 2024: How Topo to Raster works [online]. [cit. 2024-05-10]. Available at: https://pro.arcgis.com/en/pro-app/latest/tool-reference/3d-analyst/how-topo-to-rasteworks.htm

Arora, M., Singh, P., Goel, N.K., and *R.D.* and *Singh,* 2006: Spatial Distribution and Seasonal Variability of Rainfall in a Mountainous Basin in the Himalayan Region. *Water Resour. Manage. 20*, 489–508. https://doi.org/10.1007/s11269-006-8773-4

Beck, Ch. and *Philipp, A.*, 2010: Evaluation and comparison of circulation type classifications for the European domain. *Phys. Chemist. Earth, Parts A/B/C*, *35*(9-12), 374–387.

Benco, M., 2009: Typy poveternostných situácií a tok vlhkosti v Čechách. Prague. Diploma thesis. Charles University in Prague, Faculty of Natural Sciences. 68 p. [online]. [cit. 2023-10-10]. Available at: https://dspace.cuni.cz/handle/20.500.11956/20716 (in Czech)

Brádka, J., Dřevikovský, A., Gregor, Z., and *Kolesár, J.,* 1961: Počasí na území Čech a Moravy v typických povětrnostních situacích. Prague: Hydrometeorological Institute. (in Czech)

Brádka, J. and *collective of authors*, 1968: Katalog povětrnostních situací pro území ČSSR. Prague. 94 p. (in Czech)

Brázdil, R. and *Faško, P.,* 1993: Orographic effects on precipitation distribution on the territory of the Slovak Republic. In Sixteenth International Conference on Carpathian Meteorology 1, 86–91.

Bochníček, O., Borsányi, P., Čepčeková, E., Faško, P., Chmelík, M., Jančovičová, Ľ., Kapolková, H., Labudová, L., Mikulová, K., Mišaga, O., Nejedlík, P., Pribullová, A., Snopková, Z., Šťastný, P., Švec, M., and *Turňa, M.,* 2015: Average annual rainfall totals. In Climate atlas of Slovakia. Slovak Hydrometeorological Institute. Bratislava. 132 p. ISBN 978-80-88907-90-9.

Casanueva, A., Rodríguez-Puebla, C., Frías, M. D., and *González-Reviriego, N.*, 2014: Variability of extreme precipitation over Europe and its relationships with teleconnection patterns. *Hydrol. Earth Syst. Sci. 18*, 709-725, https://doi.org/10.5194/hess-18-709-2014

Červený, J., 1965: Typizace povětrnostních situací. *Meteorologické zprávy 18*(4), 101–103. (in Czech)

Czech Meteorological Society, 2023: Czech electronic meteorological dictionary [online]. [cit. 2023-10-10]. Available at: http://slovnik.cmes.cz/fulltext/typizace%20pov%C4%9Btrnostn%C3%ADch%20situac%C3%AD%20HM%C3%9A (in Czech)

De Sá Silva, A.C.R., Bimbato, A.M., Balestieri, J.A.P., and *Vilanova, M.R.N.,* 2022: Exploring environmental, economic and social aspects of rainwater harvesting systems: A review. *Sustain. Cities Soc.76*(23), 103475. https://doi.org/10.1016/j.scs.2021.103475
Faško, P. and *Šťastný, P.,* 2002: Average annual rainfall totals. In Atlas of the landscape of the Slovak Republic. Bratislava: Ministry of the Environment of the Slovak Republic, Banská Bystrica: Slovak Environmental Agency. 344 p. ISBN 80-88833-27-2.
Freeworldmaps, 2023: Europe physical map. [online]. [cit. 2024-01-10]. Available on the internet: https://www.freeworldmaps.net/europe/
Gnida, M., Grajciar, M., Chocholová, L., Košovský, P., Malatinská, L., ... and *Hlásny, T.*, 2017: The Seventh National Communication of the Slovak Republic on Climate Change. Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Ministry of Environment of the Slovak Republic and Slovak Hydrometeorological Institute, Bratislava. [online]. [cit. 2024-01-10]. Available at: https://unfccc.int/sites/default/files/resource/976840315_Slovakia-NC7-17NC_SVK.pdf
Halaj, M., 2019: Effect of relief on the distribution of precipitation in Slovakia in western cyclonic situations. Bratislava. Diploma thesis. Comenius University in Bratislava. Faculty of Natural Sciences, 83 p. [online]. (in Slovak) [cit. 2023-10-10]. Available at: https://opac.crzp.sk/?fn=detailBiblioForm&sid=BCA102CB6C4CA54D4BE6A175C35B
Halaj, M., and *Zaujec, P.,* 2023: Priestorové rozloženie atmosférických zrážok na Slovensku počas rôznych typov synoptických situácií v období 1991–2020. *Meteorologický časopis 26(1)*, 15–25. (in Slovak)
Hansen, M., and *Belusić, D.,* 2021: Tailoring circulation type classification outcomes. *Int. J. Climatol. 41,* 6145–6161. https://doi.org/10.1002/joc.7171
Hess P. and Brezowsky H., 1952: Katalog der grosswetterlagen europas. Deutscher Wetterdienst. 39 p. (in German)
Hoy, A., Schucknecht, A., Sepp, M., and *Matschullat, J.,* 2014: Large-scale synoptic types and their impact on European precipitation. *Theor. Appl. Climatol. 116*, 19–35. https://doi.org/10.1007/s00704-013-0897-x
Iqbal, Z., Shahid, S., Ahmed, K., Termizi I., and *Nadeem N.,* 2019: Spatial distribution of the trends in precipitation and precipitation extremes in the sub-Himalayan region of Pakistan. *Theor. Appl. Climatol. 137*, 2755–2769. https://doi.org/10.1007/s00704-019-02773-4
Kasza, R., 2018: Effect of relief on the distribution of precipitation in Slovakia in northern cyclonic situations. Diploma thesis. Comenius University in Bratislava. Faculty of Natural Sciences. 67 p. (in Slovak) [online]. [cit. 2023-10-10]. Available at: https://opac.crzp.sk/?fn=detailBiblioForm&sid=EEE57057A47611A7EF7ACC4E9AC3
Labudová, L., Šťastný, P. and *Trizna, M.,* 2013: The north atlantic oscillation and winter precipitation totals in Slovakia. *Moravian Geographical Reports 21*(4), 38–49. https://doi.org/10.2478/mgr-2013-0019
Lapin, M., Damborská, I., Gera, M., Hrvol, J., and *Melo, M.*, 2015: Trends of evapotranspiration in Slovakia, including scenarios up to 2100. In: International Bioclimatological Conference: Toward Climatic Services. Slovak Bioclimatological Society SAS, Nitra, 5 p. http://www.sbks.sk/doc/papers/Lapin%20Trends%20of%20evapotranspiration.pdf
Lapin, M., Gera, M., and *Kremler, M.,* 2010: Temperature and Air Humidity Scenarios for Slovakia and Possible Impacts in the Cities. *Život. Prostr. 44*(3), 227–231. (in Slovak) http://publikacie.uke.sav.sk/sites/default/files/2010_5_227_231_lapin.pdf
Lešková, L., Šťastný, P., and *Trizna, M.,* 2012: Analýza vplyvu Severoatlantickej oscilácie na sezónne úhrny zrážok v zrážkových oblastiach Slovenska. *Meteorologický časopis 15*(2), 75–80. (in Slovak) https://www.shmu.sk/File/ExtraFiles/MET_CASOPIS/2012-2_MC.pdf
Lukniš, M. 1972: Slovakia 2. Nature. Bratislava: Obzor. ISBN 65-043-72-I (in Slovak)
Markovič L., Faško P., and *Pecho J.,* 2021: Climatology of the extreme heavy precipitation events in Slovakia in the 1951–2020 period. *Acta Hydrologica Slovaca 22*(2), 294–303. https://doi.org/10.31577/ahs-2021-0022.02.0033
Mazúr E. and *Lukniš M.,* 1978: Regional Geomorphological Division of the SSR. *Geografický časopis, 30*(2), 101–125. (in Slovak) https://www.sav.sk/journals/uploads/10251027GC_1978_2_1_Mazur%20et%20al.pdf

McKenna, CH., and *Maycock, A.,* 2022: The Role of the North Atlantic Oscillation for Projections of Winter Mean Precipitation in Europe. *Geophys. Res. Lett. 49*(19). e2022GL099083. https://doi.org/10.1029/2022GL099083

Meseguer-Ruiz, O., Ponce-Philimon, P.I., Guijarro, J.A., and *Sarricolea, P.,* 2019: Spatial distribution and trends of different precipitation variability indices based on daily data in Northern Chile between 1966 and 2015. *Int. J. Climatol. 39,* 4595–4610. https://doi.org/10.1002/joc.6089

Mészáros, J., 2015: Effect of relief on the distribution of precipitation in Slovakia in southern cyclonic situations. Bratislava. Diploma thesis. Comenius University in Bratislava, Faculty of Natural Sciences. (in Slovak) [online]. [cit. 2024-01-17]. Available at: https://opac.crzp.sk/?fn=detailBiblioFormChildI103R7&sid=4A220BA9C567A84919003CD1351D&seo=CRZP-detail-kniha

Mészáros, J., 2019: Spatial patterns of distribution of atmospheric precipitation in Slovakia in southern cyclonic situations during the period 1991–2015. Bratislava. Rigorous thesis. Comenius University in Bratislava, Faculty of Natural Sciences. (in Slovak) [online]. [cit. 2024-01-17]. Available at: https://opac.crzp.sk/?fn=detailBiblioForm&sid=5379D0B7E3C25FE39D32B84ABF03

Mészáros, J., Halaj M., Polčák N., and *Onderka M.,* 2022: Mean annual totals of precipitation during the period 1991–2015 with respect to cyclonic situations in Slovakia. *Időjárás 126,* 267–284. https://doi.org/10.28974/idojaras.2022.2.6

Ministry of the Environment of the Slovak Republic, 2018: Stratégia adaptácie Slovenskej republiky na zmenu klímy. (in Slovak) [online]. [cit. 2024-02-25]. Available at: https://www.minzp.sk/files/odbor-politiky-zmeny-klimy/strategia-adaptacie-sr-zmenu-klimy-aktualizacia.pdf

Niedźwiedź, T., Łupikasza, E., Pińskwar, I., Kundzewicz, Z., and *Małarzewski, L.,* 2015: Variability of high rainfalls and related synoptic situations causing heavy floods at the northern foothills of the Tatra Mountains. *Theor. Appl. Climatol. 119,* 273–284. https://doi.org/10.1007/s00704-014-1108-0

Nikolova, N., Faško, P., Lapin, M., and *Švec, M.,* 2013: Changes in snowfall/precipitation-day ratio in Slovakia and their linkages with air temperature and precipitation. *Contribut. Geophys. Geodesy 43(2),* 141–155. https://doi.org/10.2478/congeo-2013-0009

Oudar, T., Cattiaux, J. and *Douville, H.*, 2020: Drivers of the northern extratropical eddy-driven jet change in CMIP5 and CMIP6 models. *Geophys. Res. Lett. 47(8).* e2019GL086695 https://doi.org/10.1029/2019GL086695

Pecho, J. and *Faško, P.,* 2010: Hazards of extreme summer rainfall. Slovak Hydrometeorological Institute. [online]. [cit. 2024-01-10]. Available at: https://www.shmu.sk/sk/?page=2049andid=142

Phillip, A., Dekka-Marta, P.M., Jacobeit, J., Fereday, D.R., Jones, P.D., Moberg, A., and *Wanner, H.,* 2007: Long-term variability of daily North Atlantic–European pressure patterns since 1850 classified by simulated annealing clustering. *J. Climate 20*, 4065–4095. https://doi.org/10.1175/JCLI4175.1

Polčák, N., and *Mészáros, J.,* 2018: The effect of relief on the distribution of atmospheric precipitation in Slovakia in the southern cyclonic situations. *Geografický časopis 70*(3), 259–272. (in Slovak) https://doi.org/10.31577/geogrcas.2018.70.3.14

Rein, F., 1959: Weather typing with regard to dynamic climatology. *Studia Geophysica et Geodaetica 3*, 177–194. (in Russian) https://doi.org/10.1007/BF02585561

Řehoř, J., Brázdil, R., Trnka, M., Řezníčková, L., Balek, J., and *Možný, M., 2*020: Regional effects of synoptic situations on soil drought in the Czech Republic. *Theor. Appl. Climatol. 141*, 1383–1401. https://doi.org/10.1007/s00704-020-03275-4

Řehoř, J., Brázdil, R., Lhotka, O., Trnka, M., Balek, J., Štěpánek, P., and *Zahradníček, P.,* 2021: Precipitation in the Czech Republic in light of subjective and objective classifications of circulation types. *Atmosphere 11*, 1536. https://doi.org/10.3390/atmos12111536

Šercl, P., 2008: Assessment of methods for area precipitation estimates. *Meteorologické zprávy 61(2),* 33–43. (in Czech) https://www.chmi.cz/files/portal/docs/reditel/SIS/casmz/assets/2008/Meteo-2008-02.pdf

Shepherd, T.G., 2014: Atmospheric circulation as a source of uncertainty in climate change projections. *Nat. Geosci. 7,* 703–708. https://doi.org/10.1038/NGEO2253

SHMIa, 2023: Climatic conditions of Slovakia. (in Slovak) [online]. [cit. 2024-02-26]. Available on the internet: https://www.shmu.sk/sk/?page=1064

SHMIb., 2023: Types of weather situations. (in Slovak) [online]. [cit. 2024-02-26]. Available on the internet: https://www.shmu.sk/sk/?page=8androk=2020

Sobíšek, B., 1993: Meteorologický slovník výkladový & terminologický. Praha: Ministerstvo životního prostředí České republiky. 594 p. ISBN 80-85368-45-5. (in Czech)

Tomczyk, A. M., and *Bednorz, E.,* 2016: Heat waves in Central Europe and their circulation conditions. *Int. J. Climatol. 36,* 770–782. https://doi.org/10.1002/joc.4381

Zaujec, P., 2020: Influence of the relief on the precipitation conditions of the Podunajská nížina during the period 1991 – 2018. Bratislava. Bachelor thesis. Comenius University in Bratislava, Faculty of Natural Sciences. 55 p. (in Slovak) [online]. [cit. 2024-01-10]. Available at: https://opac.crzp.sk/?fn=detailBiblioForm&sid=C4B2143D4F9CE1498D0864B8E130

Zaujec, P., 2022: Precipitation conditions of Slovakia in northern and southern cyclonic situations. Bratislava. Diploma thesis. Comenius University in Bratislava, Faculty of Natural Sciences. [online]. [cit. 2024-01-10]. Available at: https://opac.crzp.sk/?fn=detailBiblioForm&sid=2F8FD603D177BA679134FA795407 (in Slovak)