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Mean annual totals of precipitation during the period 1991–2015 with respect to cyclonic situations in Slovakia

Jakub Mészáros*[,1], **Martin Halaj**[2], **Norbert Polčák**[3], and **Milan Onderka**[4]

[1]*Institute of Hydrology*
Slovak Academy of Sciences
Dúbravská cesta 9, 841 04 Bratislava, Slovakia

[2] *Slovak Hydrometeorological Institute*
Zelená 5, 974 04 Banská Bystrica, Slovakia

[3] *Slovak Hydrometeorological Institute*
Jeséniova 17, 833 15 Bratislava, Slovakia

[4]*Earth Science Institute of the Slovak Academy of Sciences*
Dúbravská cesta 9, 840 05 Bratislava, Slovakia

** Corresponding Author e-mail: hydrjaku@savba.sk*

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Abstract— Atmospheric precipitation during cyclonic situations was analyzed using weather types classification. Based on data from the period 1991 to 2015, the observed cyclonic situations were analyzed in terms of their frequency of days with a given weather type. Cyclonic situations with airflow direction from the west and northwest, north and northeast, east and southeast, and south and southwest were analyzed. We identified a declining number of days that can be classified as cyclonic situations. The distributions of the mean annual precipitation totals for these cyclonic situations have been investigated. The highest mean annual precipitation totals occurred during the west cyclonic, northeast cyclonic, and east cyclonic weather types. The lowest mean annual precipitation totals were identified during the southwest cyclonic (with fronts moving from north to northeast) and north cyclonic weather types. The percentage of the individual cyclonic weather types and supertypes in the mean annual precipitation total was calculated. The directional supertype west + northwest with the west cyclonic type occurred with the highest percentage, although variations may arise due to windward and leeward effects.

Key-words: atmospheric precipitation, cyclonic situations, mean precipitation totals, Carpathian Mountains, Pannonian Plain

1. Introduction

The landscape can be supplied with water from the oceans and seas, glaciers, groundwater aquifers, or rivers. Central Europe is an inland region, and although glaciers have been more prevalent here in the past, the main source of water now are aquifers and rivers, which are formed by atmospheric precipitation. Because water is important for all forms of life, its resources require special attention. Here we focused on water from atmospheric precipitation and its distribution. Although the region of Central Europe is not physically surrounded by oceans, precipitation falls mostly during westerly and northwesterly cyclonic situations originating in the Atlantic Ocean, but occasionally also from cyclonic situations from the Mediterranean or the Black Sea.

Slovakia is a country with a wide range of altitudes varying from 94 m a.s.l. up to 2655 m a.s.l. The ridges of the Western and partly also the Eastern Carpathians stretch from west to east forming a significant barrier to the arriving air masses. The southwest and southeast parts of the country are mostly lowlands and are part of the Pannonian Basin (*Fig. 1*). In terms of the Köppen climate classification, the territory of Slovakia is a continental climate region with dry winters and warm summers. The climate is characterized by regular alternation of four seasons and variable weather, affected by pressure centers located in the Azores High and Icelandic Low. In Slovakia, the prevailing westerly winds and the relief enhance precipitation totals on windward slopes, causing the highest annual precipitation totals exceeding 1200 mm (occasionally even more than 1500 mm) in the mountainous northern region. The lowest precipitation totals of 550 mm per year are observed in lowlands and about 650 mm in depressions located in rain shadows of the surrounding mountains (*Fig. 2*). Precipitation is unevenly distributed throughout the year, some 40% of precipitation falls in summer, 25% in the spring, 20% in the autumn, and 15% in the winter (*SHMÚ*, 2009).

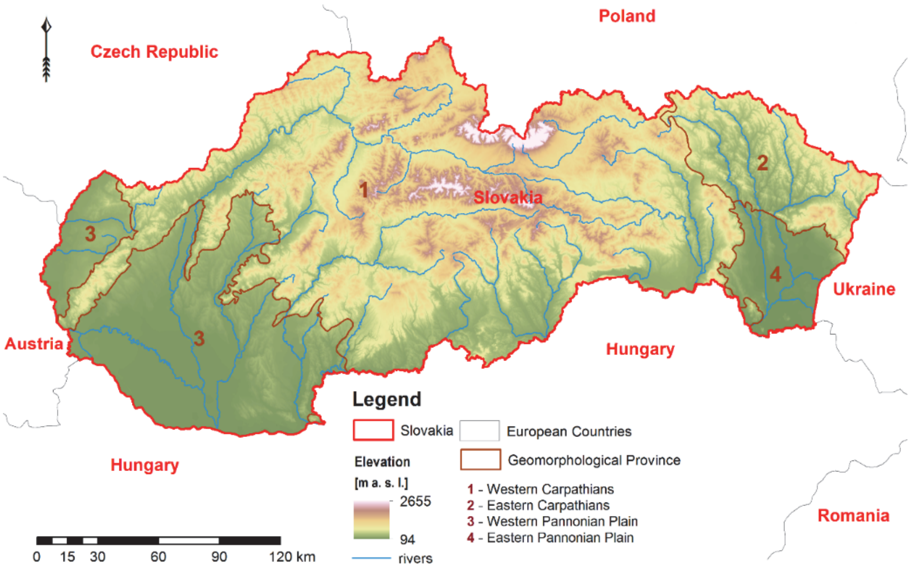

Fig. 1. Location and relief of Slovakia.

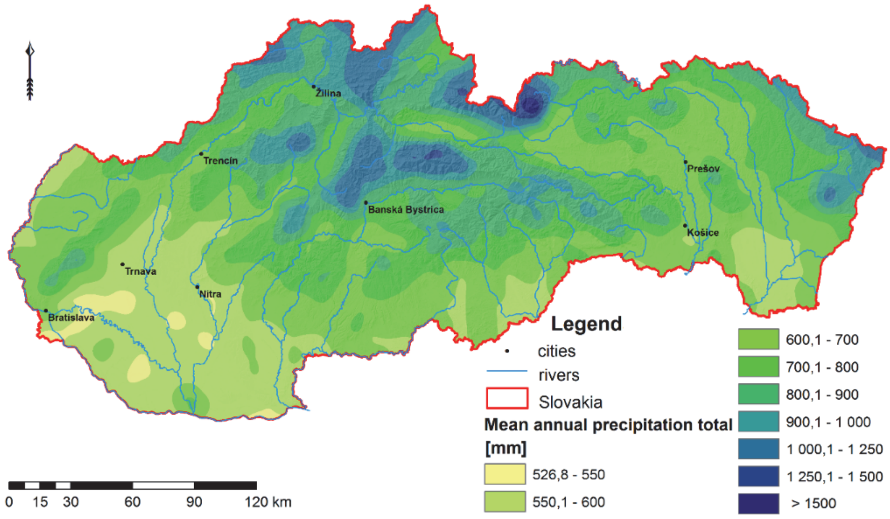

Fig. 2. Mean annual precipitation totals in Slovakia for the period 1991–2015.

In this paper, we deal with cyclonic situations that bring precipitation to the territory of Slovakia and are related to various directions of airflow. Our goal is to identify areas in Slovakia that are the most and the least affected by these cyclonic situations. These findings can improve our knowledge of the currently highly debated topic: the climate change. Although, it must be admitted that even a 25-year period may not be sufficiently long from climate change perspective, the analyses described herein can improve our knowledge about, e.g., circulation trends or intensity of precipitation. It is also important to know how the occurrence of weather types changes throughout the year. This can explain the temporal evolution of mean annual precipitation totals.

2. Materials and methods

Precipitation was measured within the network of precipitation gauges in Slovakia. Daily (24-hour) precipitation totals were registered only on days when precipitation exceeded 0.1 mm (the lowest total registered by the gauge). The analyzed precipitation data cover the period between 1991 and 2015. There are various schemes that can be applied in the classification of weather types in the region of Central Europe. The best known is the "Katalog der Grosswetterlagen Europas" (*Hess* and *Brezowsky*, 1977). In Germany, the "Objective weather types classification of the German Weather Service" is used (*Bissolli* and *Dittmann*, 2001). Poland uses the synoptic classification according to *Niedźwiedź* (2013) – known as the "Calendar of circulation types, air masses and fronts for Southern Poland". In Hungary, the classification according to *Péczely* (1983) is summarized in the “Catalog of the macro-synoptic types for Hungary”. In the Czech Republic and Slovakia, the first “Catalog of Weather Situations for the Territory of the Czechoslovak Socialist Republic” was published by the national hydrometeorological service in 1968 (*Brádka et al,* 1968). The first synoptic situations were classified for the year 1946. After bilateral discussions and consensus between meteorologists from both countries in 1991, the catalog summarizes weather types separately for Slovakia and the Czech Republic. Classification of weather types was carried out by the Slovak Hydrometeorological Institute (SHMI) between 1991 and 2015 from the calendar of weather type situations that is available on the SHMI website (*SHMÚ*, 2020) First, days with cyclonic situations related to different directions of the prevailing atmospheric airflow and different position of the low and high pressure areas were selected.

Records extracted from the calendar of weather type situations (*SHMÚ*, 2020) were used to select days with cyclonic weather situations. The duration of cyclonic situations in the analyzed period 1991–2015 ranged from 1 to more than 10 days. Using the Catalog of Weather Situations (*Brádka et al*., 1968), the synoptic situations were selected according to the nature of cyclonality and the predominant airflow direction. In order to increase the sample size, the weather types were grouped into ‘‘supertypes’’ according to their cyclonality and the dominant direction of airflow following the procedure of *Beranová* and *Huth* (2005) (*Table 1*). The synoptic situations with directions W + NW, N + NE, E + SE, S + SW (*Fig. 3*) were retained for further analysis. A list of cyclonic situations from the period 1991–2015 was created for the purposes of this paper; i.e., the number of days with a certain type of cyclonic situation during 5-year periods was extracted from the database.

Data from more than 600 precipitation gauges covering a period of 25 years were processed. The data contained information on the indicative of the precipitation gauge (station ID), location name, date, and the precipitation total measured in the rain gauge. The data were sorted into groups with given weather type of cyclonic situation. The precipitation totals were first processed for all cyclonic situations with certain airflow direction, and then they were interpolated in the ArcGIS 10. The interpolation procedure described in *Polčák* and *Mészáros* (2019) was adopted in this study. We used the Topo to Raster method, since according to *Šercl* (2008), the Topo to Raster method is suitable for interpolating point-measured precipitation. This method estimates interpolated values from four adjacent points using an iterative method of finite differences. The isolines created by this method resemble well the isolines that an expert would draw manually on a paper map. The greatest advantage of this interpolation tool is that it enables the user to define the boundary of the territory within which the interpolation is to be carried out and also to assign the lowest value used in interpolation. In this way, areas between stations with zero totals are not interpolated into physically unrealistic negative values, since precipitation total has to be always positive or equal to zero. This interpolation technique was used for each of the cyclonic situations. The individual precipitation fields were summed up for each type of cyclonic situation in the ArcGIS 10 by Raster Calculator. The sums were subsequently divided by the number of years to get precipitation fields of mean annual totals separately for each of the individual types of cyclonic situations.

Table 1. List of synoptic types and their merging into groups (supertypes) according to cyclonality and prevailing airflow. Source*: Beranová* and *Huth* (2005).

Abbreviation	Short description	(Anti)cyclonic supertype	Directional supertype
Wc	west cyclonic	C	W+NW
Wcs	west cyclonic with southern track of cyclones	C	W+NW
Wa	west anticyclonic	A	W+NW
Wal	west anticyclonic of a summer type	A	W+NW
NWc	northwest cyclonic	C	W+NW
NWa	northwest anticyclonic	A	W+NW
Nc	north cyclonic	C	N+NE
NEc	northeast cyclonic	C	N+NE
NEa	northeast anticyclonic	A	N+NE
Ec	east cyclonic	C	E+SE
Ea	east anticyclonic	A	E+SE
SEc	southeast cyclonic	C	E+SE
SEa	southeast anticyclonic	A	E+SE
Sa	south anticyclonic	A	S+SW
SWc1	southwest cyclonic with fronts moving from north to northeastwards	C	S+SW
SWc2	southwest cyclonic with fronts moving from northeast to eastwards	C	S+SW
SWc3	southwest cyclonic with frontal zone shifted southward	C	S+SW
SWa	southwest anticyclonic	A	S+SW
A	stationary anticyclone over central Europe	A	-
C	cyclone over central Europe	C	-
Cv	upper-air cyclone	-	-
B	stationary trough over central Europe	C	-
Bp	eastward travelling through	C	-
Vfz	frontal zone entrance	-	-
Ap1	anticyclone travelling northeastward	A	-
Ap2	anticyclone travelling eastward	A	-
Ap3	anticyclone travelling southeastward	A	-
Ap4	anticyclone travelling southward	A	-

The mean annual precipitation total for the individual stations was calculated from the monthly mean precipitation totals. The mean annual totals were interpolated in ArcGIS 10. Using the precipitation fields created in this way, the percentage of individual types of cyclonic situations with respect to the total mean annual precipitation total was expressed for the period 1991–2015. The procedure is described in detail by *Mészáros* (2019).

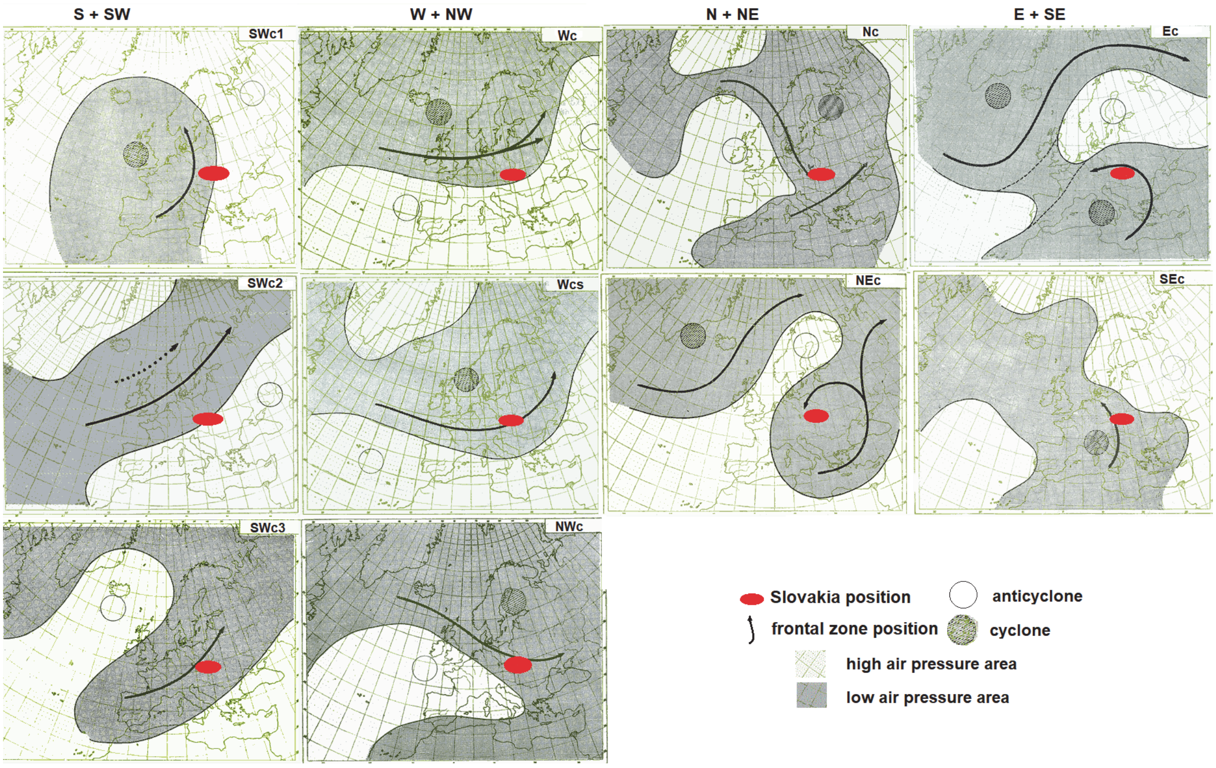

Fig. 3. Schematic layout of cyclonic situations. Types in each column create directional supertypes.

3. Results

The occurrence of individual cyclonic weather types based on their prevailing airflow direction was analyzed for the period 1991–2015. The number of days with all cyclonic weather types, the number of days with cyclonic weather types in 5-year periods and the mean precipitation total per day with cyclonic weather types in 5-year periods, are displayed in *Fig. 4.* The spatial distribution of the mean annual precipitation totals corresponding to the individual weather types of cyclonic situations is shown in *Fig. 5*. The precipitation fields for the cyclonic supertypes are shown in *Fig. 6*. The contribution of the individual weather types of cyclonic situations to the mean annual precipitation total is shown in *Fig. 7*, while the contribution of supertypes during the period 1991–2015 is shown in *Fig. 8*. Mean, minimum, and maximum values of mean annual precipitation totals during the individual weather types of cyclonic situations along with the contribution of the individual weather types and cyclonic supertypes to the mean annual precipitation total are summarized in *Table 2.* (In this table, mean total is the areal mean value of the average annual precipitation total, min total is the areal minimum value of the average annual precipitation total, max total is the areal maximum value of the average annual precipitation total, mean percentage is the areal mean value of the contribution to the mean annual precipitation total for all weather types, min percentage is the areal minimum value of the contribution to the mean annual precipitation total for all weather types, max percentage is the areal maximum value of the contribution to the mean annual precipitation total for all weather types. Values were obtained from precipitation fields calculated by interpolating precipitation data).

3.1. Occurrence of cyclonic situations (period 1991–2015)

From the selected weather types, the Wc type was the most frequent one, with 26 days per year, on average. This confirms that westerly cyclonic flow prevails in Slovakia. The second most frequent was the NEc type occurring 24 days per year. The NWc type occurred 18 days per year. The days with SWc3 and Wcs types occurred 10 times per year, while days with types SWc1 and SEc occurred only 9 times per year. All selected weather types had a declining trend, except for the types SWc2 and NWc. However, perhaps more important than the number of days per year is to identify the season of the year when the days with a given type occur. For example, during the winter 2012–2013 and the early spring of 2013, an anomalously large number of Mediterranean cyclones was observed in the Carpathian Basin *(Zsilinszki et al.*, 2019). These cyclonic situations led to floods in the southern half of Slovakia (*SHMÚ*, 2014).

One of the indicators of the activity of cyclonic situations is their frequency of occurrence during the period of observation. This allows us to investigate the annual fluctuations in cyclonic situations. The 1990s were rich in the number of days with cyclonic situations. In the early 2000s, the number of days with a cyclonic situation fluctuated considerably. There were years with less than 200 days (e.g., the dry year of 2003) but also with almost 250 days with a cyclonic situation (e.g., the wet year of 2010). During the last years of the observation period, the absolute number of days with cyclonic situations did not exceed 200. The general trend in the form of a 5-year moving average clearly indicates a slight decrease in the activity of cyclonic situations in the investigated territory. The frequency of occurrence of days with cyclonic situation declined in most weather types (*Fig. 4* top and middle). However, this decline is not observed in the precipitation amount. The total amount of precipitation per year in Slovakia did not decrease significantly (*Markovič et al.*, 2016) despite the facts that there have been fewer days with cyclonic situations. This means that precipitation totals during cyclonic situations increased (*Fig. 4* down), and convective precipitation has increased during days with other weather situations. The investigation of *Markovič et al*. (2016) confirms a higher proportion of storm showers in the mean annual total precipitation in the recent years.

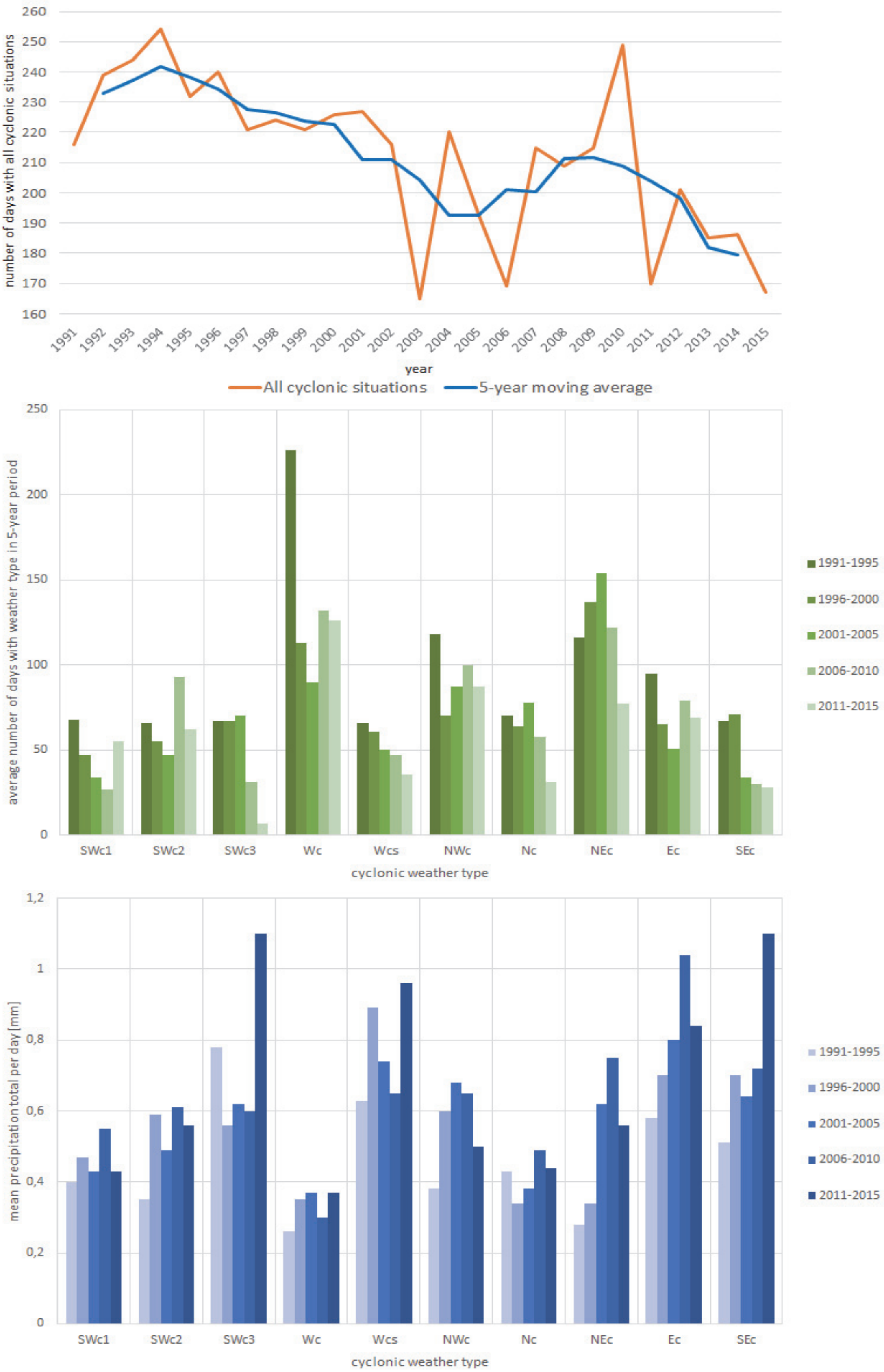

Fig. 4. Top: The number of days with all cyclonic situations in the period 1991–2015 and the 5-year moving average. Middle: The number of days with cyclonic weather types in 5-year periods. Bottom: Mean precipitation total per day with cyclonic weather type in 5-year periods.

3.2. *Mean annual precipitation totals during individual weather types of cyclonic situations and cyclonic supertypes with different airflow direction (period 1991–2015)*

Directional cyclonic supertype S + SW

During this supertype, the mean annual totals ranged from 52 to 174 mm. The mean precipitation total was 87 mm. The highest totals (> 150 mm) were observed on the windward southern slopes of the Western Carpathians in the central part of the territory, on the highest summits of the Western Carpathians in the northern part of the territory, and in the Eastern Carpathians in the eastern part of the territory. The lowest totals (< 70 mm) were observed in the Western Pannonian and Eastern Pannonian Plain. In general, precipitation totals increase with altitude, and therefore, the totals in the lowlands were lower. The Western Pannonian Plain lies in the rain shadow of the Alps, and the Eastern Pannonian Plain is located in the rain shadow of the North Hungarian Mountains. Also, low precipitation totals (< 80 mm) were observed in the basins in the northern part of the territory, which are located in the lee of the Carpathian arch, and in the basins located in the southern part of the territory, which are in the lee of the North Hungarian Mountains. Precipitation fields were similar in all types belonging to this directional supertype (SWc1, SWc2, SWc3). Only the type SWc1 differed from types SWc2 and SWc3 in that there were no higher totals in the Eastern Carpathians. Maximum of the mean annual total was investigated for the SWc2 type (74 mm) and minimum for the SWc1 type (12 mm).

Directional cyclonic supertype W + NW

This supertype was characterized by the widest range of mean annual totals from 65 to 518 mm. The mean value of the total was 159 mm. The windward effect was very strong here, thus the highest precipitation (> 400 mm) fell in the Western Carpathians in the northwestern part of the territory. The lowest precipitation (< 100 mm) fell in the southern and eastern parts of the territory in a significant rain shadow. Types from this supertype (Wc, Wcs, NWc) had a similar territorial distribution of precipitation. The difference was in the amount of the precipitation total. Maximum was for the Wc type (200 mm) and minimum for the Wcs type (40 mm). The Wc type (prevailing in Slovakia) had the highest mean annual precipitation total (69 mm) from all selected weather types.

Directional cyclonic supertype N + NE

During this supertype, the average precipitation total was 38 to 323 mm per year. The mean value of the precipitation total was 87 mm. The highest precipitation totals (> 200 mm) were observed on the windward northern slopes of the Western Carpathians in the northernmost part of the territory and the Eastern Carpathians in the northeasternmost. The lowest totals (< 60 mm) were observed in the western third of the territory and in the southern half of the central part of the territory.

This part was protected by the Carpathian Mountains from precipitation arriving from the north and northeast. In both types belonging to this directional supertype (Nc, NEc), high precipitation totals (> 150 mm) occurred mainly in the north during the NEc type, and partially also in the east. Low precipitation totals (< 20 mm) occurred in the southern half of the territory and a rain shadow was observed in the south of the highest summits of the Carpathians during the Nc type and in almost the entire western half of the territory during the NEc type.

Directional cyclonic supertype E + SE

This supertype was characterized by the smallest range of mean annual precipitation totals ranging from 49 to 155 mm. The mean precipitation total was 89 mm. A great contrast was discernible between the southern and northern parts of the territory induced by the windward effect on the southern slopes of the Western Carpathians. The maximum precipitation totals (> 150 mm) were observed in the highest elevations of the Western Carpathians. A rain shadow was observed in the northern and eastern parts of the territory. The Ec type had higher characteristics of precipitation totals (mean 53 mm, maximum 103 mm, minimum 26 mm) than the SEc type (mean 33 mm, maximum 69 mm, minimum 16 mm). Very interesting is the precipitation field in the eastern part of the territory during the Ec type due to the rain shadow of the Ukrainian Eastern Carpathians from the east and rain shadow in the north of the territory during the SEc type, while further northern part the height of the mean annual precipitation total decreased. The only exceptions were the highest summits of the Western Carpathians.

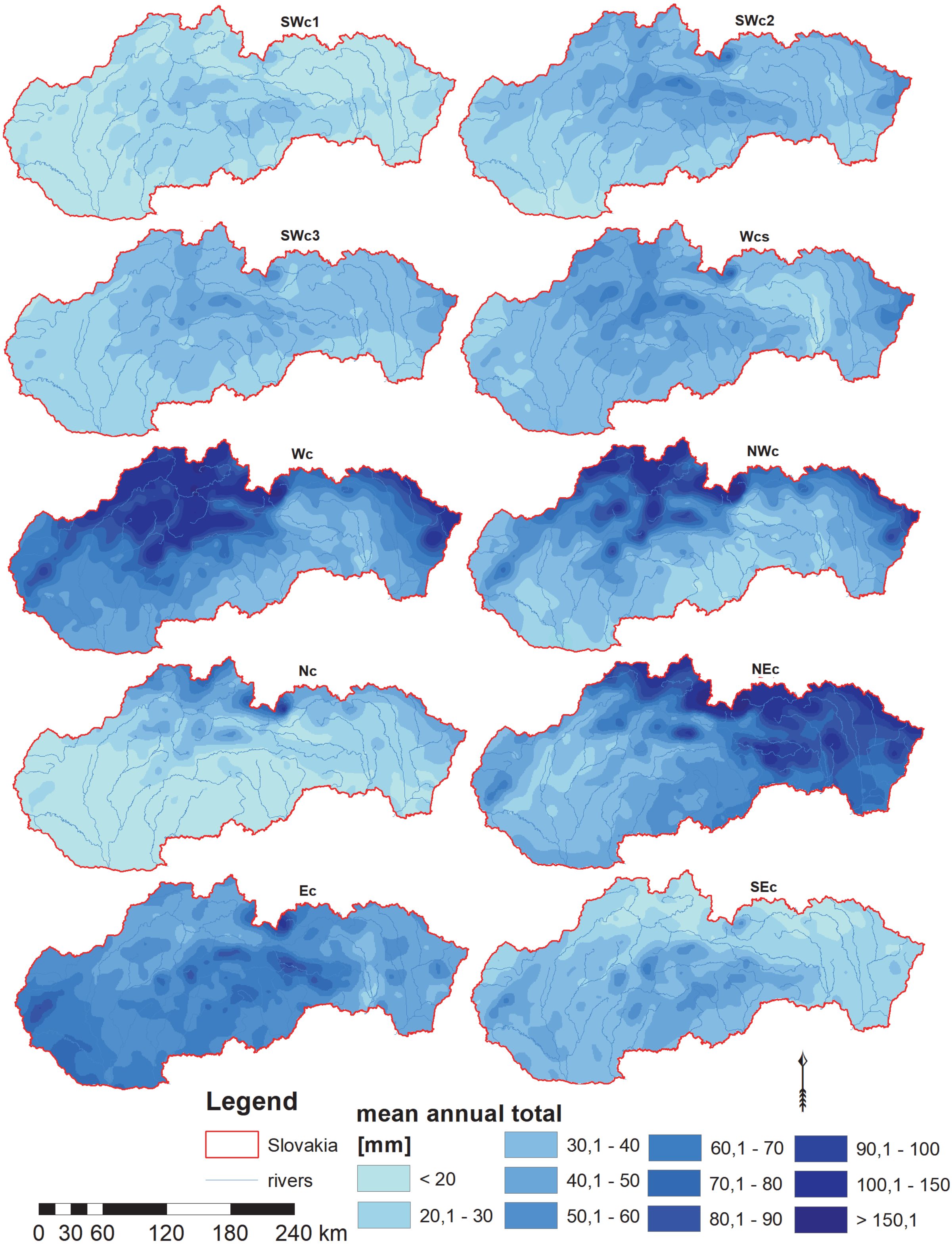

Fig. 5. Mean annual precipitation total in Slovakia during individual types of cyclonic situations for the period 1991–2015.

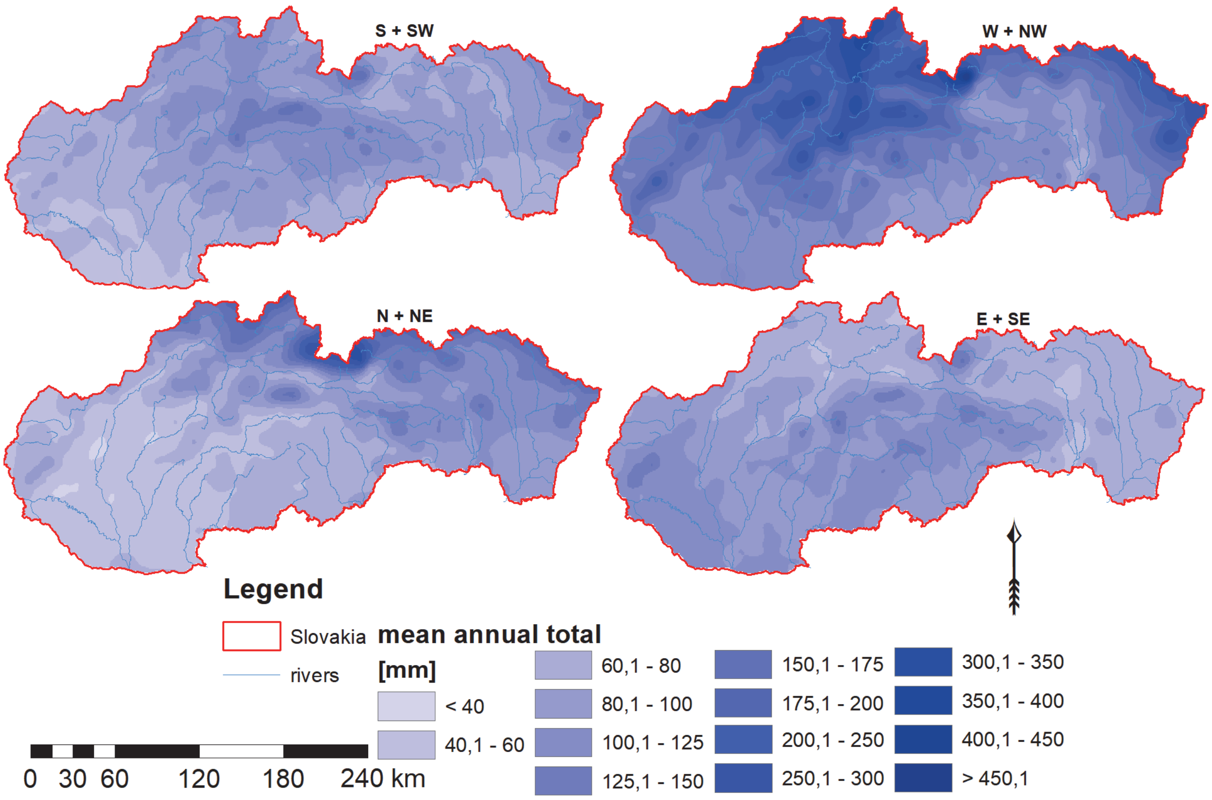

Fig. 6. Mean annual precipitation total in Slovakia during cyclonic supertypes from the mean annual precipitation total for the period 1991–2015.

3.3. *Percentage of the mean precipitation total fallen during individual weather types of cyclonic situations and cyclonic supertypes with different airflow directions from the mean annual precipitation total (period 1991–2015)*

The spatial expression of the percentage contribution of precipitation in individual parts of the territory is important from the point of view, that we can identify in which part which cyclonic type (or supertype) had the largest or smallest share in the mean annual precipitation total.

Directional cyclonic supertype S + SW

This supertype was represented in the mean annual total by 9 to 15%, with an average 12%. Above 14%, it was in the southern half of the central part of the territory. Up to 10% were totals in the northernmost, but also in the southwestern part of the territory. The individual types SWc1, SWc2 and SWc3 had little significant contribution, with maximum 6% during the SWc3 type.

Directional cyclonic supertype W + NW

This supertype was characterized by the highest percentage (from 11 to 36%) with an overall mean of 21%. The largest percentage (> 30%) was observed in the mountains located in the northwestern part of the territory. The smallest percentage (approx. 14%) was observed in the eastern part of the territory. The Wc type is the most significant direction for the Western Carpathians in the northwestern part of the territory (> 30%). The NWc type had a high contribution in northern part of the territory.

Directional cyclonic supertype N + NE

Precipitation from this supertype contributed to the mean annual total by 6 to 24% (12% on average). They had the largest percentage in the northern and northeastern parts of the territory, over 20%. Up to 8% was in the southern half of the western and central parts of the territory. The Nc type had over 6% in the northernmost part of the territory, and the NEc type had above 16% in the very north of the territory in the highest locations of the Western Carpathians and above 10% in a large area in the eastern part of the territory.

Directional cyclonic supertype E + SE

This supertype was characterized by a range of percentage from 6 to 21%, with an average of 13%. The lowest percentage (< 8%) was observed in the northern and northeastern parts of the territory. The largest percentage (> 18%) was observed in the southwestern and southern parts of the territory. The Ec type had the highest percentage in the Western Pannonian Plain and the southwestern part of the territory. The same holds for the SEc type, but in this case the percentage was lower.

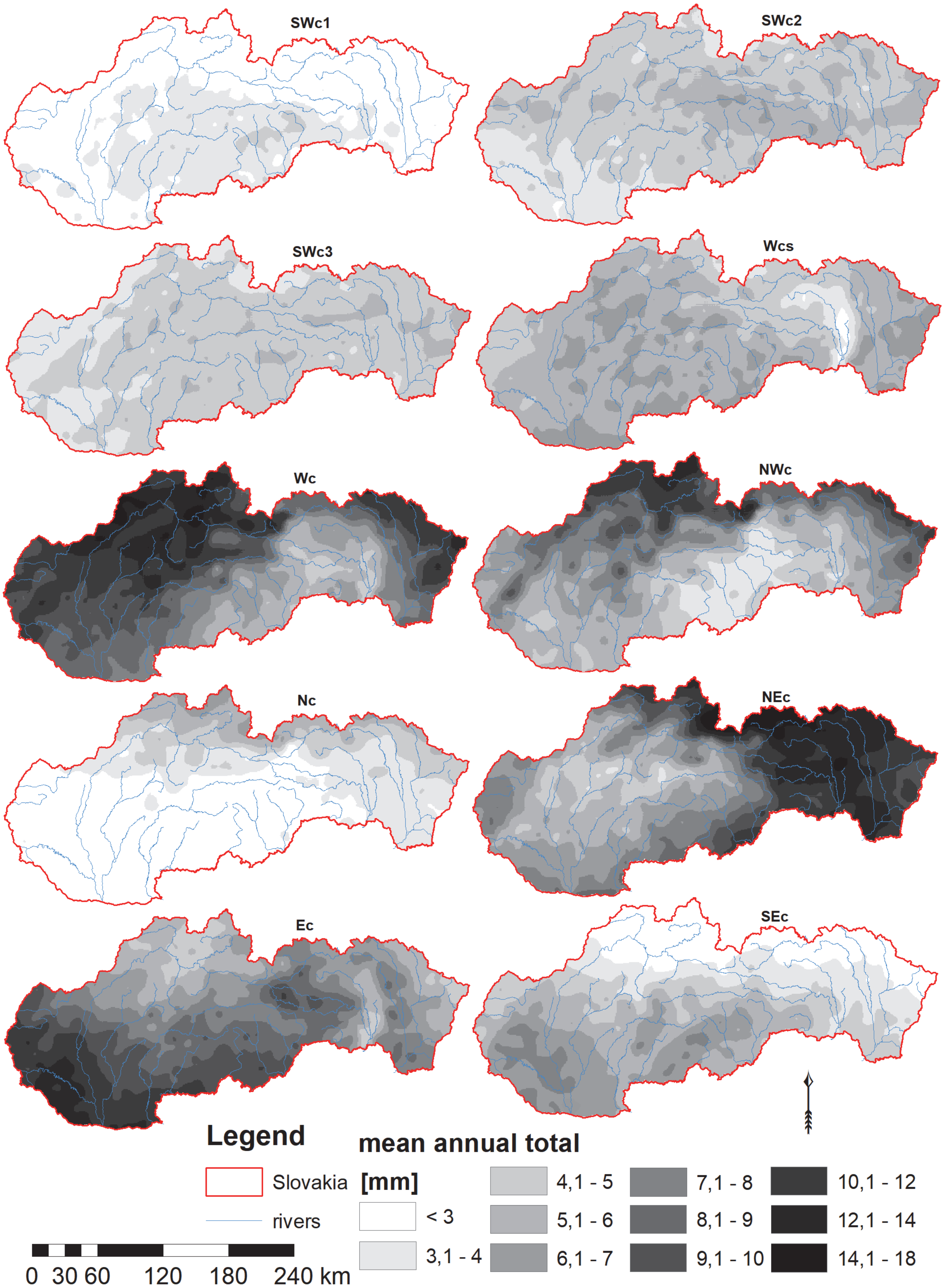

Fig. 7. Percentage of the mean annual precipitation fallen during individual types of cyclonic situations to the mean annual total precipitation in Slovakia for the period 1991–2015.

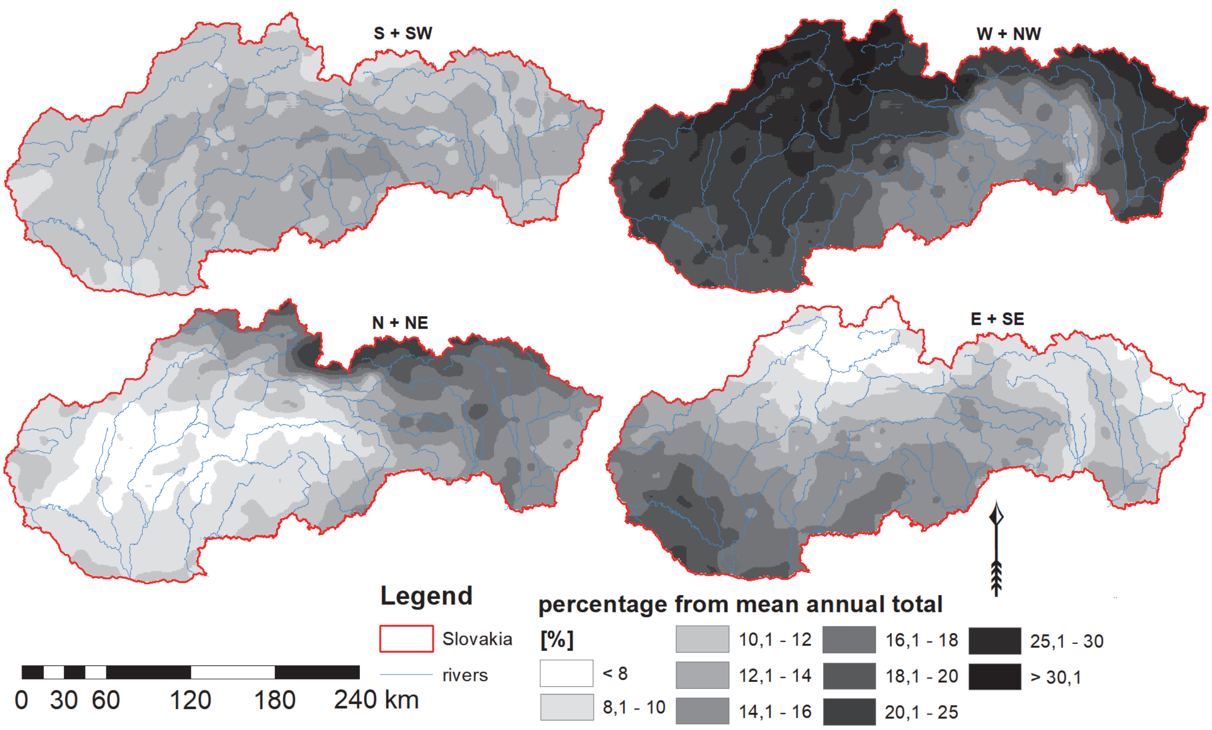

Fig. 8. Percentage of the mean annual precipitation fallen during individual cyclonic supertypes to the mean annual total precipitation in Slovakia for the period 1991–2015.

Table 2. Statistical values of mean annual precipitation totals for individual types of cyclonic situations and cyclonic supertypes for the period 1995–2015, and their contribution to the mean annual precipitation total for all weather types.

Type	Total [mm]			Percentage [%]		
	Mean	Min	Max	Mean	Min	Max
SWc1	21	12	40	3	1	4
SWc2	30	17	74	5	3	6
SWc3	32	18	63	4	3	6
Wc	69	24	200	9	4	17
Wcs	40	17	82	5	3	7
NWc	51	19	236	7	3	14
Nc	25	10	111	3	2	7
NEc	62	24	239	8	4	18
Ec	53	26	103	8	4	13
SEc	33	16	69	5	2	8

Supertype	Total [mm]			Percentage [%]		
	Mean	Min	Max	Mean	Min	Max
S + SW	87	52	174	12	9	15
W + NW	159	65	518	21	11	36
N + NE	87	38	323	12	6	24
E + SE	89	49	155	13	6	21
All directional cyclonic types	422	277	1150	57	46	72
All weather types	733	527	1757	-	-	-

4. Conclusion

During the period 1991–2015, the most frequent weather type in Slovakia was the Wc, followed by the NEc and NWc types. Days with SWc1, SEc, SWc3, and Wcs types were less frequent. During the analyzed period, a decrease in the incidence of days with cyclonal synoptic situation was observed. Nevertheless, the mean annual precipitation did not decrease. As the surface runoff is inherently linked to the precipitation (*Petrow et al*., 2009), it would be interesting to carry out an additional research in the future and focus on changes in runoff due to the altered occurrence of weather types.

This study showed that the mean annual precipitation totals were highest during the types Wc (69 mm), NEc (62 mm), and Ec (53 mm). The lowest mean annual precipitation totals were observed during the types SWc1 (21 mm) and Nc (25 mm). These types of cyclonic situations were accompanied with the lowest overall annual mean precipitation totals. Up to 15 mm of precipitation fell in the south of the territory during the Nc type, and up to 15 mm during the SWc1 type in the Western Pannonian and Eastern Pannonian Plains and in the basins in the northern part of the territory. The maximum annual totals occurred during the NEc type with almost 240 mm on the windward northern slopes of the Western and Eastern Carpathians in the northernmost and northeastern parts of the territory, and during the NWc type in the highest locations of the Western Carpathians in the very north. Regarding cyclonic supertypes, i.e., considering airflow directions, the highest mean annual precipitation totals fell during situations from the directional supertype W + NW and the lowest from the directional supertype N + NE, although maximum annual totals were observed during the NEc type (supertype S + SW had a mean annual total higher by only 0.3 mm). As the most common cyclonic situation type is not always responsible for the greatest floods (*Bednorz et al.,* 2019), it would be interesting to study which type, or supertype, of cyclonic situations is responsible for major floods. On the other hand, it has been shown that a deficiency of some cyclonic weather types can cause drought (*Stahl* and *Demuth,* 1999).

In terms of the contribution of the precipitation total associated with a certain type of cyclonic situation and airflow direction on the mean annual precipitation total, types with the highest percentages were: Wc with 9%, NEc with 8%, and Ec with 8%. The least significant ones, were the SWc1 and Nc types, both with 3% contribution. In terms of locations with the highest contribution to annual precipitation totals, locations in the highest parts of the Western Carpathians contributed with 18% during the NEc type, in the northwestern part of the territory with 17% during the Wc type, and in the northwestern and northern parts of the territory with 14% during the NWc type. The SWc1 type contributed only with 1% in the northernmost part of the territory. The Nc type contributed with 2% in the western and central part of the southern half of the territory, and the SEc type contributed with 2% in the northern part of the territory.

Our analyses allowed us to identify the most and the least affected regions by precipitation arising from a given type of cyclonic situation (supertype). Windward and leeward locations were identified as well. In general, it can be concluded that the investigated territory of Slovakia had its maximum precipitation mainly during the supertype W + NW (mean percentage for the area is 21%). In the northern and eastern parts of the territory, precipitation from supertype N + NE was significant. An important agricultural area and the most densely populated part of the territory in the Western Pannonian Plain received high percentage of precipitation totals originating in the E + SE supertype situations.

In this paper, we analyzed atmospheric precipitation, which is the main source of water in our country. The presented results are beneficial for the country's agriculture, tourism, industry, but they will be most appreciated by experts in climatology, meteorology, and hydrology. The frequency of weather types occurrence is influenced by the North Atlantic Oscillation (*Fernández-González et al.*, 2012). Therefore, our research avenue for the near future is to investigate the dependence of weather types on the positive or negative values of the NAO index. It will be necessary to process a longer period. Then, we will be able to predict which locations will be above or below average in terms of precipitation during the next season.

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