The influence of circulation conditions on extreme precipitation totals over the territory of the Western Carpathians in the warm season

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Abstract: Based on data from a period of 72 years (1951–2022), the impact of atmospheric circulation on precipitation, which is usually the source of floods, was assessed for the area of the Western Carpathians. The analysis was performed for the season from April to October using daily rainfall totals originated from the E-OBS database and the calendar of circulation types according to Niedźwiedź's classification. A very significant influence of cyclonic circulation with the airflow from the north and northeast on the amount of daily rainfall was found. This impact is generally visible throughout the entire area of interest, but the most spectacular in the Tatra region (Tatra Mountains and Low Tatras) and on the Czech-Polish-Slovak border (White Carpathians, Maple Mountains, Silesian Beskid). Simultaneously, the analysis showed quite large spatial variations in rainfall, which results from very complex local conditions, especially the orography.

Key words: daily precipitation totals, precipitation extremes, circulation conditions, Western Carpathians

1. Introduction

The Western Carpathians occupy the north-western part of the longest mountain chain in Europe, the Carpathians. This area of typical medium-

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sized mountains with elements of high-mountain relief represents climatic conditions of Central Europe characterized by a temperate climate with transitional features. The location of the main mountain ranges is quite complicated (Fig. 1). In the northern part, it is usually latitudinal, in the southern part it is more meridional. Deep and sometimes wide river valleys emphasize the great orographic diversity. This diversity predisposes the considered area to the occurrence of precipitation with high spatial and temporal variability, which depends primarily on atmospheric circulation. It determines rainfall totals in this area, which can reach high values and which has been the issue of many considerations (e.g. *Lapin and Niedźwiedź, 1984; Cebulak, 1992; Cebulak et al., 2000; Niedźwiedź 2003; Sokol and Bližňák, 2009; Bičárová and Holko 2013; Niedźwiedź et al., 2015; Ustrnul et al., 2015*). Nevertheless, atmospheric circulation serves as the main determinant of intense rainfall in this region. This issue was discussed relatively extensively in the literature. Most publications concern circulation patterns with the dangerous effects of high rainfall totals highlighting that mountain areas are particularly prone to flooding, environmental damage, economic losses, and the loss of human life (e.g. *Cebulak, 1997; Ustrnul and Czekierda, 2001; Niedźwiedź, 2003; Brázdil et al., 2005; Cheval et al., 2014; Kundzewicz et al., 2014; Niedźwiedź et al., 2015; Łupikasza, 2016*). Sometimes high rainfall is local and is caused by convective phenomena (*Poreba at al., 2022*), causing dangerous but spatially limited flash floods.

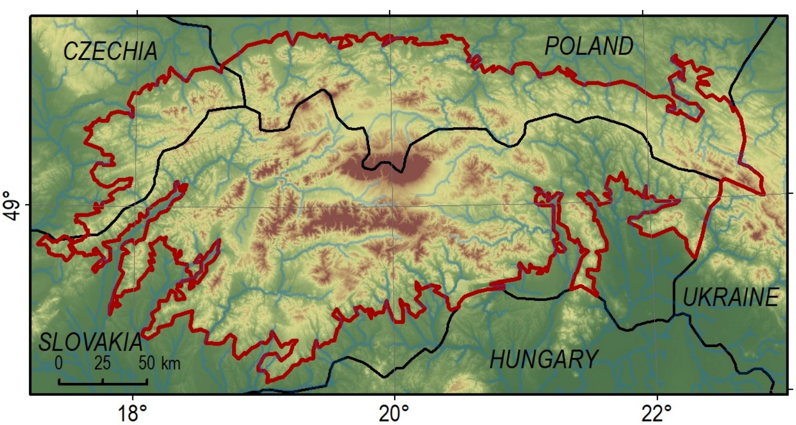

Fig. 1. The area of research (explanations: red line – Western Carpathians border, black line – country borders).

To sum up, the area of the Western Carpathians is therefore a source area for summer floods often covering southern Poland, northern Slovakia and the eastern part of the Czechia.

The aim of the work is to determine the role of atmospheric circulation in shaping precipitation in the Western Carpathians and to identify regions with the greatest susceptibility to high daily precipitation amounts causing unfavourable environmental phenomena. Such an analysis is possible using very rich research material covering a period of 72 years and a spatial resolution of 0.1°, which corresponds to points approximately every 10 km. In the study, special attention will be paid to high daily rainfall amounts which generally cause negative hydrological and sometimes environmental effects. It is worth noting here that the literature contains many analyses for individual regions of the Western Carpathians, but the analyses are usually limited only to the national dimension. It is therefore necessary to take a comprehensive look at this large and geographically diverse region without the limitations of national borders. Examples of such studies can be found earlier, but they were limited only to the Tatra Mountains (*Konček, 1974; Niedźwiedź, 1992; Ustrnul et al., 2015*).

2. Data and methods

At the beginning of the research standard (in-situ) data from several meteorological stations in Poland and Slovakia were used. However, the uneven location of the stations and sometimes incomplete data series prompted the authors to use data from the E-OBS database (v28.0e, `https://cds.climate.copernicus.eu`, *Cornes et al., 2018*) which is currently the best source of uniform, with the spatial resolution of $0.1° \times 0.1°$, rainfall data for the studied area. Its usefulness has been checked, among others, in the works of *Wypych et al. (2016)* and *Sulikowska and Wypych (2020).* However, daily data from this database were checked only for air temperature for the Carpathians. Precipitation totals were used only indicatively without detailed comparative analyses with station data. Daily precipitation totals from the E-OBS database were used for the entire domain covering the area of 48° – 50°N and 17° – 23°E (1281 grids in total). In the case of the study area, daily rainfall sums are calculated for 24-hour intervals from 6 UTC of the current day until 6 UTC the next day.

Another basic material concerned information about atmospheric circulation. At the beginning, the use of several well-known circulation type calendars (including Grosswetterlagen, by Lityński, by Osuchowska-Klein; *Ustrnul et al., 2012; 2013*) or their modifications or other automatic approaches were considered. However, the experience from many analyses prompted the application of a traditional, manual approach and taking into account the classification according to *Niedźwiedź (2023).* This mesoscale calendar of circulation types is available up-to-date and its application, among others, for the Western Carpathians has been positively verified many times (e.g. *Cebulak, 1983; Ustrnul and Czekierda, 2009; Twardosz et al., 2016; Wypych et al., 2018*). It was also successfully used for the southern (Slovak) part of the Western Carpathians (*Lapin and Niedźwiedź, 1984*). The classification is based on the distinguishing of 21 types of circulation based on the direction of advection and the dominant baric system. Its detailed description can be found in the work of *Niedźwiedź (2023).*

The study used a typical synoptic climatology method, which considered precipitation events in individual 21 types (see Table 1 for list of types) of circulation in the multiannual period 1951–2022. The analysis took into account the extended warm season, i.e. including also April, when sometimes the highest daily and monthly totals occur.

Due to the main goal, a special attention was paid to the daily rainfall totals in the individual analysed months from April to October in the entire domain. Particular attention was paid to the region where rainfall is the highest, i.e. the Tatra Mountains and the Low Tatras. The diversity of precipitation over the entire domain was presented on maps constructed for the circulation types with the highest daily totals.

3. Results and discussion

Initially, the frequency of circulation types was determined in individual months of the summer season throughout the period 1951–2022. The types with a high pressure wedge (Ka) and a cyclonic trough (Bc) were the most common, with an average frequency of 12% (Table 1). The latter type is of great importance for the purpose of this work as it is characterized by significant rainfall. It is worth noting that its frequency in June is the highest and reaches almost 16%. Types whose frequency on average throughout the

Table 1. Frequency (in %) of the particular circulation types according to Niedźwiedź classification (1951–2022) (explanations: colour shading indicates the intensity of the phenomenon).

Circulation type	APR	MAY	JUN	JUL	AUG	SEP	OCT	Seasonal mean (APR-OCT)
Na	3.7	4.6	5.6	5.1	3.3	3.5	2.8	4.1
NEa	4.0	7.0	4.1	5.2	4.6	2.9	1.3	4.2
Ea	6.0	6.1	4.4	4.4	5.8	3.6	4.1	4.9
SEa	3.6	4.3	2.5	1.3	3.8	5.2	6.2	3.9
Sa	3.7	2.9	2.4	2.2	4.0	5.0	6.1	3.7
SWa	3.0	2.0	2.3	2.0	3.4	4.9	8.2	3.7
Wa	3.1	3.1	4.5	7.7	8.0	8.4	10.7	6.5
NWa	3.3	3.9	5.7	7.5	5.6	6.3	5.0	5.3
Ca	1.8	2.2	2.8	2.4	4.4	5.1	5.0	3.4
Ka	10.8	10.6	13.4	14.3	13.9	11.1	10.3	12.1
Nc	4.5	4.3	4.6	4.3	2.7	2.9	1.8	3.6
NEc	3.9	3.8	3.9	2.9	2.3	2.0	1.2	2.8
Ec	4.4	3.3	3.1	1.7	1.3	2.3	1.5	2.5
SEc	4.3	3.5	1.7	1.3	2.3	1.9	2.0	2.4
Sc	4.9	4.3	2.5	2.2	2.1	3.0	3.7	3.2
SWc	5.8	4.7	2.8	2.7	3.3	4.8	6.5	4.4
Wc	7.3	5.8	6.8	9.7	7.7	9.4	9.8	8.1
NWc	5.6	4.9	7.0	7.0	5.2	5.7	4.0	5.6
Cc	2.4	2.0	1.9	1.0	1.2	0.6	1.0	1.4
Bc	11.7	14.4	15.8	13.1	13.6	9.1	7.1	12.1
X	2.4	2.2	1.9	1.8	1.7	2.2	1.7	2.0

Anticyclonic ‘a’ situations:
1 – Na — North (direction of air masses advection)
2 – NEa — North–East
3 – Ea — East
4 – SEa — South–East
5 – Sa — South
6 – SWa — South–West
7 – Wa — West
8 – NW — North–West
9 – Ca — central anticyclone situation (high center)
10 – Ka — anticyclonic wedge or ridge of high pressure

Cyclonic ‘c’ situations:
11 – Nc — North
12 – NEc — North–East
13 – Ec — East
14 – SEc — South–East
15 – Sc — South
16 – SWc — South–West
17 – Wc — West
18 – NWc — North–West
19 – Cc — central cyclonic, center of low
20 – Bc — through of low pressure (different directions of air flow and frontal system in the axis of through)

21 – X — unclassified situations or pressure col.

season exceeds 5% are situations with advection from the west (Wc – 8.1% and Wa – 6.5%) and types with the airflow from the NW direction (NWc – 5.6% and NWa – 5.3%).

In the following step, the average daily rainfall values in individual circulation types were considered. Throughout the entire analysed area, they reached relatively small values, approximately 1–2 mm. Of course, in many situations, especially anticyclonic ones, they were close to 0 mm. Spatial distributions made for all circulation types generally show little spatial variation and are not presented. Slightly higher values exceeding the average sums of 1–2 mm were found for all cyclonic situations. However, also in this case, the spatial variation of these values was small. The largest ones were found in the Tatra Mountains and in several other regions of the study area (Fig. 2). These were the Silesian and Żywiecki Beskids and the Gorce Mountains in the north and the Slovak-Czech border in the west. Due to such differences, in the next stage the influence of circulation was considered in detail on the example of the so-called the Tatra region including the Tatra Mountains and the Low Tatras with adjacent areas included between the coordinates 48° 50′ – 49° 30′ N and 19° 30′ – 20° 30′ E.

The obtained results showed that in the NEc and Nc circulation types,

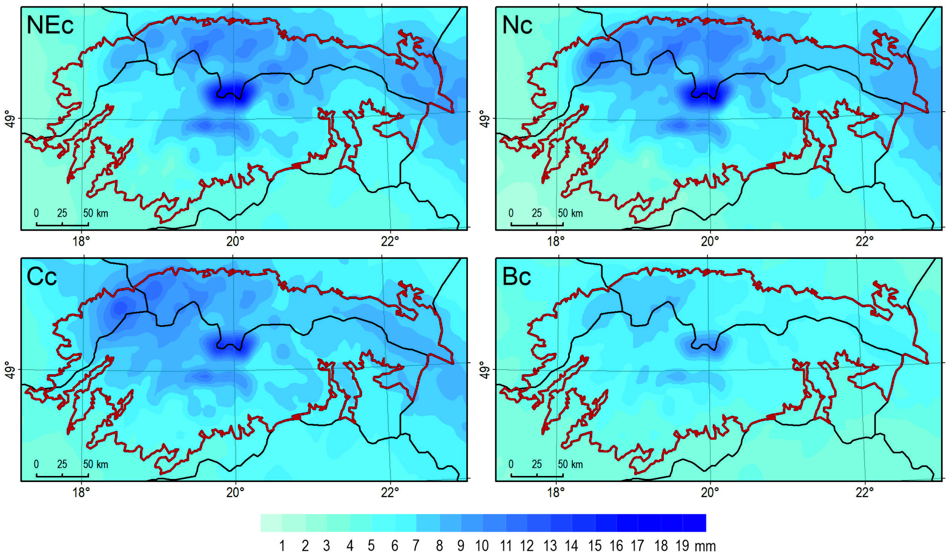

Fig. 2. Mean daily precipitation totals in circulations types NEc, Nc, Cc, Bc.

the average daily precipitation in this area exceeds 10 mm in the period from June to August (Table 2). Sums exceeding 10 mm occurred in the NEc type in September and October and also in the Cc type in June and July. So these types are key in triggering heavy rainfall episodes. It should be remembered that the obtained values are averages for a field of approximately 100 km^2 determined from daily values for 72 years. The actual average rainfall amounts calculated for individual meteorological stations may be higher. When analysing Table 2 it should be noted that the average precipitation amount in all months and all circulation types exceeds 0 mm. This means that rainfall can occur in each synoptic situation without exception.

Table 2. Mean precipitation daily totals (in mm) in particular circulation types according to Niedźwiedź classification (1951-2022) – 'Tatra region' (see explanations in the text; other explanations as for Table 1).

Circulation type	APR	MAY	JUN	JUL	AUG	SEP	OCT	Seasonal mean (APR-OCT)
Na	1.6	1.6	2.0	2.2	2.5	1.7	1.8	1.9
NEa	1.2	2.8	3.2	2.2	3.1	1.3	1.0	2.1
Ea	0.5	1.5	2.9	2.6	1.1	1.1	0.6	1.5
SEa	0.4	0.8	1.6	1.6	1.2	0.4	0.4	0.9
Sa	0.3	1.4	2.4	2.5	1.4	0.4	0.6	1.3
SWa	0.2	0.8	1.0	1.4	0.3	0.4	0.4	0.6
Wa	0.7	1.1	1.7	1.4	1.3	0.8	0.8	1.1
NWa	1.3	2.1	1.8	2.3	1.4	1.5	2.0	1.8
Ca	0.5	0.4	0.2	1.1	0.5	0.5	0.2	0.5
Ka	0.5	0.8	1.3	1.4	1.1	0.6	0.6	0.9
Nc	5.5	7.6	10.7	14.4	12.1	8.9	5.8	9.3
NEc	4.8	8.6	10.3	13.7	11.7	10.6	11.6	10.2
Ec	4.5	4.7	8.4	8.0	7.1	4.5	4.7	6.0
SEc	3.3	4.2	5.9	8.8	5.8	6.8	5.0	5.7
Sc	1.6	4.3	6.2	5.0	4.2	4.7	2.9	4.1
SWc	1.7	3.3	5.0	3.1	3.7	2.9	2.6	3.2
Wc	2.7	3.8	5.1	4.8	3.6	4.2	2.5	3.8
NWc	3.1	3.9	5.0	5.9	4.7	5.0	4.7	4.6
Cc	6.8	8.9	11.6	11.4	9.2	9.7	4.9	8.9
Bc	3.9	6.1	6.7	8.3	8.7	7.8	7.2	7.0
X	3.1	3.2	4.9	3.4	2.1	2.1	3.2	3.1

The next stage involved assessing the impact of atmospheric circulation on the highest daily rainfall totals. Table 3 shows the calculated maximum amounts for individual circulation types. As expected, the highest values exceeding 100 mm occurred in 4 circulation types. These were Nc, NEc, Ec and Cc. Particularly noteworthy here are the totals that occurred in

Table 3. Maximum precipitation daily totals (in mm) in particular circulation types according to Niedźwiedź classification (1951–2022) – 'Tatra region' (see explanations in the text; other explanations as for Table 1).

Circulation type	APR	MAY	JUN	JUL	AUG	SEP	OCT
Na	28.4	42.0	56.9	72.4	37.1	33.0	23.5
NEa	19.6	66.1	96.2	63.9	54.0	38.0	18.0
Ea	23.9	38.5	91.0	48.5	38.9	43.4	19.7
SEa	17.0	23.2	37.6	18.1	23.3	16.1	23.3
Sa	11.1	30.9	51.9	50.3	29.5	35.6	26.9
SWa	10.6	31.6	14.7	40.8	12.5	24.6	42.2
Wa	15.4	21.2	33.0	46.0	35.4	51.2	45.0
NWa	20.6	42.3	41.0	38.1	40.6	30.1	44.0
Ca	33.6	9.6	13.0	36.6	28.9	19.5	18.6
Ka	34.0	35.9	49.2	58.4	30.8	39.4	23.0
Nc	51.5	93.2	195.7	212.3	108.8	106.5	43.2
NEc	79.3	155.5	121.1	140.7	91.4	89.0	50.2
Ec	68.8	44.4	106.5	86.5	63.9	51.6	44.3
SEc	44.3	39.2	51.7	76.9	81.4	57.3	45.7
Sc	23.1	82.2	50.5	41.5	50.3	44.6	41.4
SWc	29.9	62.2	53.2	39.7	53.7	43.9	52.0
Wc	38.2	48.2	62.1	59.0	60.6	44.3	44.4
NWc	36.4	48.0	81.7	75.0	89.8	59.7	42.1
Cc	76.9	54.3	93.7	125.1	55.2	53.1	38.9
Bc	62.2	74.7	95.8	87.6	95.2	65.1	82.7
X	36.5	35.7	48.2	47.0	38.1	40.4	56.8

the Nc type in June and July, when they reached values of approximately 200 mm. These values were the highest in the entire considered area of the Western Carpathians and caused catastrophic floods (*Łupikasza et al., 2011; Woźniak, 2013; Stoffel et al., 2016*). The distribution of these highest daily sums for the entire studied area and the mentioned 4 types of circulation is presented in Fig. 3. Outside the Tatras, the above-mentioned regions are visible, and additionally in the case of the cyclonic trough (Bc) one can notice the Štiavnica Mountains, constituting the western part of the Slovak Ore Mountains, which are located in the central-southern part of Slovakia.

The results obtained in the current analysis based on gridded data fully confirm the relationship between atmospheric circulation and precipitation data taken from meteorological stations (e.g. *Ustrnul and Czekierda 2009; Wypych et al. 2018*). When studying synoptic situations causing high, even extreme, rainfall it is almost always visible on the sea level pressure charts they are related to the flow of moist and usually cold air from the northern sector. They are the result of a shallow low-pressure system hovering over

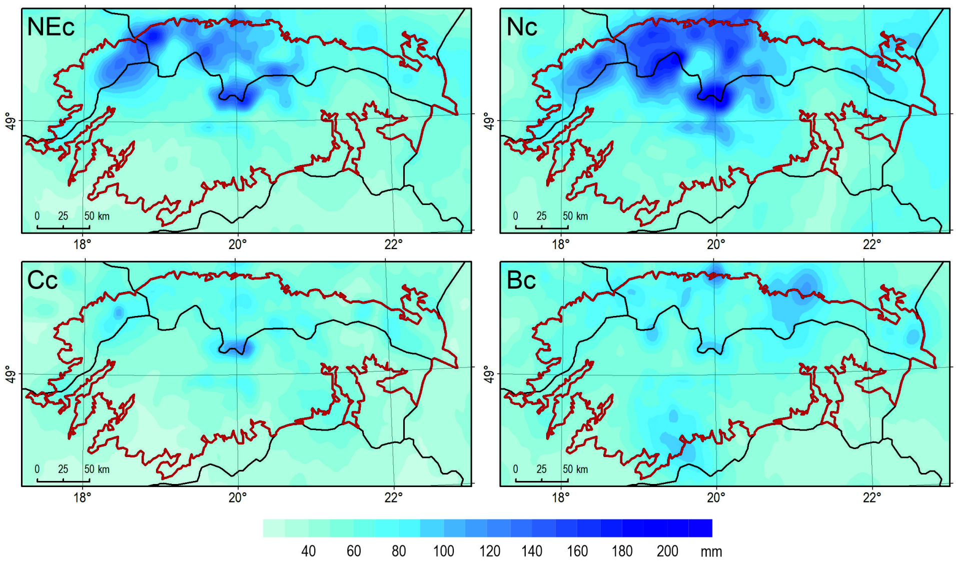

Fig. 3. Maximum daily precipitation totals in circulations types NEc, Nc, Cc, Bc.

Ukraine (north and north-easterly cyclonic types and trough over Central Europe), often with a front system causing cyclone-type airflow from the north and northeast. During these situations, cool air masses coming in from the north and northeast cause heavy precipitation events (dynamic rise of air over the mountain barrier increases the amount of precipitation). The analysis confirmed the meaning of the Vb cyclone track described by van Bebber over one hundred years ago and confirmed many times recently for Central Europe as well as for Western Carpathians (e.g. *Mudelsee et al., 2004; Seibert et al., 2007; Niedźwiedź et al., 2015*). The synoptic situations of these phenomena were neither thoroughly analysed in this study, nor was atmospheric circulation at higher levels taken into account. This issue requires additional data, although such attempts have already been made for the Polish part of the Western Carpathians (*Wypych et al., 2018*).

4. Conclusions

The results showed the dominant influence of atmospheric circulation on daily rainfall totals in the entire study area. This applies to both northern and southern parts of the area, which was not clear from previous studies. By far the highest rainfall amounts occur in the area of the Tatra Mountains and the Low Tatras and the Czech-Polish-Slovak border. Of course, it was found that the further south of the study area from the Tatra region, the rainfall amounts are smaller, but still generally significant. A similar pattern, but much weaker, is visible in the north of the domain. The analysis clearly showed that the greatest rainfall occurs in cyclonic situations with airflow from the N and NE directions. Daily totals may then exceed 200 mm. High, although slightly lower, rainfall was also recorded when the centre of the low pressure was located over the Western Carpathians and when a trough of low pressure occurred.

Data analysis showed that sometimes high totals may occur with other types of circulation, but their distribution is quite diverse. As selected case studies have shown they may be the result not only of specific circulation conditions but also of convective processes determined by orography or other local conditions.

The use of precipitation data from the E-OBS database confirmed their high applicability for the analysis performed. These data correspond quite well with the data from available station series. This fact was found when comparing daily rainfall totals above 30 mm.

The analysis of the results obtained and the knowledge from the literature allow us to conclude that the relationships between atmospheric circulation, most often considered in the form of circulation types, and precipitation are not as clear and simple as in the case of other climatic elements, e.g. air temperature or wind speed and direction (*Ustrnul and Czekierda, 2009; Onderka and Pecho, 2023*). The influence of circulation, although the most important, is only one of the factors shaping favorable conditions for the rainfall. Other factors include e.g. orographic features cause very different conditions for their occurrence (e.g. orographic forcing or precipitation shadows). The physical characteristics of the incoming air masses are also important – as they may differ slightly for the same circulation type.

All these factors mean that in areas with complex terrain, such as in the Western Carpathians, there is a very large variation in rainfall amounts. This is especially true in the case of extreme rainfall, which can be completely different even in the same small catchment. It is therefore not surprising that forecasting rainfall at a local scale is extremely difficult and even sophisticated mesoscale models sometimes fail in such situations.

The results of the conducted research allow one more conclusion to be drawn. Thanks to a coherent analysis based on a uniform rainfall database, it was not found that the Western Carpathians constitute a significant climatic barrier. Such an opinion can sometimes be found both in the scientific community and in some educational materials (e.g. *Romer, 1947*). Of course, this conclusion is based only on the diversity of precipitation totals and requires verification taking into account other climatic elements.

Determining the influence of atmospheric circulation and other factors on the variability of precipitation in areas with complex relief is still a serious scientific challenge. Even though many basic relationships have already been explained, knowledge of the processes of precipitation formation is still not sufficient. One can hope that the coming years will bring significant progress in this area thanks to the large-scale use of radar data, numerical modelling and machine learning.

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