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RESEARCH ARTICLE

Relationship between mean and extreme precipitation and circulation types over Hungary

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In this paper we analyse the relationship between the mean and extreme precipitation for five stations in Hungary and the circulation types at the 500 hPa level, for a 52-year period, 1958–2010. We used daily rainfall data for each station and a calendar of the daily circulation types at the 500 hPa geopotential height for Hungary based on an automatic classification scheme. A trend analysis showed that, in general, the mean and extreme precipitation rarely exhibit significant trends, similarly to previous studies. The only exception was found for the number of annual and summer rainy days in Budapest with significant negative trends ($p = .05$), as well as the number of days with rainfall amounts greater than the 95% probability level for Debrecen with a significant positive trend. It was found that the circulation types that are mainly responsible for the largest precipitation amounts overall show (in some cases significant) negative trends, as well as the precipitation amounts that are associated with them (Cwsw, Cse, Cwnw). In most cases, the circulation types that are prevailing during the extreme precipitation events are associated with western or almost-western atmospheric circulations (Cwsw, Ase) and Mediterranean- or Atlantic-origin depressions.

KEYWORDS

circulation types, Hungary, mean and extreme precipitation, trends

1 | INTRODUCTION

Precipitation is, without any doubt, one of the most important meteorological parameters, and its extreme events have a significant impact on several human activities, especially agriculture. In order to mitigate or prevent the potential impacts of extreme precipitation events, it is essential to evaluate precipitation tendencies and associate rainfall extremes with the prevailing atmospheric circulation in order to improve their predictability.

The climate of Hungary is continental with warm humid summers and relatively cold winters. The largest part of the country can be classified as Cfb type according to the Köppen classification, while the northeastern part of the country is characterized as Dfb and southeast Hungary represents a Cfa climate (Köppen, 1900; Réthly, 1933; Szelepcsényi *et al.*, 2009).

The annual precipitation amount in Hungary varies from 500 to 750 mm, but there are important differences between different regions. The spatial distribution of the annual precipitation amount depends on the altitude, the distance from the Mediterranean and the distance from the Atlantic Ocean. A 100-m increase in altitude contributes approximately 35 mm to the annual amount, while increasing distance from the sea renders the climate drier. The southwestern area of the country and the mountains are the wettest, with an annual precipitation amount exceeding 700 mm, while the Hungarian Great Plain, east of the Danube River, receives the least precipitation, up to 500 mm/year. On the whole, the annual total decreases from southwest to northeast direction (Péczely, 1979).

Precipitation mainly falls during May–July, while the period from January to March is the driest one. Based on the precipitation pattern, a year can be classified as

Mediterranean or continental. If the amount of summer precipitation (May–July) exceeds the autumn (October–November), the year is of the continental type and vice versa. The secondary precipitation maximum in autumn can be associated with intense cyclone activity in the Mediterranean (Gulf of Genoa).

The high temporal uncertainty of precipitation is shown by the fact that in the wettest years three times as much precipitation may fall than in the driest years; in addition, zero precipitation may occur in any month (Okołowicz, 1977; Péczely, 1979).

The country-wide annual precipitation amount shows a decreasing tendency during the last century, to varying degrees according to different authors: Mersich *et al.* (2002) reported an overall decrease of approximately 10%, while Domonkos (2003) found it in the range of 15–20% for different stations. A more detailed analysis showed that the monthly rainfall totals in Hungary for the above-mentioned period presented a systematic decrease from 10% (March) to 40% (October), with the exception of June (Domonkos, 2003). While the overall decline was substantial in both halves of the century, it was mostly due to the precipitation decrease during the transitional seasons in the first 50 years, and also due to the decrease of the winter precipitation in the latest decades. The precipitation total for the period November–February declined significantly in the last 50 years. At the same time, the positions of the main pressure patterns over the Atlantic shifted northeastwards. Previous studies showed that regarding the examined period, there was an uncertainty in the frequency and intensity of the extreme precipitation in the Carpathian Basin. Namely, a decrease of extreme rainfall was observed during the period 1946–2001, while an increase was detected during the period 1976–2000 (Bartholy and Pongrácz, 2005; 2007). Moreover, important significant differences for the precipitation of different time periods for the Czech Republic were found by Beranová and Kyselý (2018). In addition, a decrease in the frequency and amounts of rainfall is observed over the Carpathian Basin while the ratio of heavy or extreme precipitation days increased considerably by the end of the 20th century (Bartholy and Pongrácz, 2005; 2007; 2010), especially in the case of the number of days with more than 20 mm (Mezősi, 2017). This observed precipitation decrease over central Europe is in general attributed to the increase of the North Atlantic Oscillation (NAO) values between the 1960s and early 1990s, which is accompanied with an increase of the anticyclonic types and a respected decrease of the cyclonic ones (Domonkos, 2003; Kyselý and Huth, 2006; Bartholy *et al.,* 2009).

Atmospheric circulation is a complex system of airflows with characteristic components in space and recurrent elements in time. In order to get a deeper insight into this phenomenon and to better understand this process, classification of synoptic systems is usually performed (Huth *et al.,* 2008). Before the advent of high-speed computers, subjective or manual methods were most common. Classification of circulation patterns or weather types from visual analyses of individual synoptic maps has several benefits. The researcher is in full control of the process and classification. However, the procedure is quite time-consuming and can be difficult to export to other locations. In addition, subjectivity can become excessive: Different researchers will not necessarily agree on classifications for a given day. Hence, these schemes cannot be replicated (Sheridan, 2002). Some of the most important subjective weather classifications, for Europe, are as follows: Hess-Brezowsky catalogue (Gerstengarbe *et al.,* 1999), Péczely catalogue (Péczely, 1983; Klicász, 1990; Károssy, 2016), Maheras catalogue (Maheras, 1979; 1988) and Lamb catalogue (Lamb, 1972; Perry and Mayes, 1998).

The objective or automated methods have come into use, such as the temporal synoptic index incorporating statistical or mathematical methods, such as principal component analysis (Maheras, 1988; Huth, 2000), a spatial method of geometry and topology (Maheras *et al.,* 2000; Anagnostopoulou *et al.,* 2009), a two-step cluster analysis–discriminant analysis (Michailidou *et al.,* 2009a; 2009b), an automated version of the Lamb weather-type classification (Putniković *et al.,* 2016; Putniković and Tošić, 2017) and the Jenkinson and Collison synoptic classification (Spellman, 2017). The paper of Yarnal *et al.* (2001) presents various classification techniques as manual typing, correlation-based analysis, eigenvector-based analysis and other new classification techniques. Moreover, Philipp *et al.* (2010) produced a new database of weather- and circulation-type catalogues comprising 17 automated classification methods. Finally, Maheras *et al.* (2017) presented the evolution of the analysis of weather-type methods, as well as circulation types for Greece over the last 60 years.

Concerning all objective methods, once initial thresholds are set, the methodology used then creates classification groups and assigns individual cases entirely based on statistical criteria. These systems are also useful and extend to a wide area of applications, such as daily mortality (Kalkstein, 1991), interpolating missing values in a data set (Huth and Nemešová, 1995), pollen concentrations (Makra *et al.,* 2006), extreme events (Maheras *et al.,* 2006), teleconnection patterns (e.g., Lorenzo *et al.,* 2008) and modelling daily rainfall amounts (Spellman, 2017). The use of circulation types can also be a useful tool for validating General Circulation Models (GCM) outputs (Anagnostopoulou *et al.,* 2008; Demuzere *et al.,* 2008).

Both subjective and objective types of classifications have shortcomings. Namely, manual methods are time-consuming and difficult to reproduce. Moreover, the type depends on the subjective judgement of the classifier. At the same time, automated methods are much easier to use and are generally reproducible (Yarnal, 1993). However, the main drawback of the objective classifications is the lack of comparability between locations. Most of these methods are applied to only one station (or one region) at a time, and the comparison of the results from station to station is difficult (El-Kadi and Smithson, 1992), as each station may have a different number of classification groups and, hence, the methods may not produce easily interpretable results (Sheridan, 2002). However, with the progress of computer technique on one hand and the development of methodologies on the other hand, the automated classification of synoptic types have become more refined and, hence, the types more distinct (Tolika *et al.,* 2007; Anagnostopoulou *et al.,* 2009).

The main scope of the present study is to examine and analyse the evolution of the average and extreme rainfalls, their statistical significance, as well as their relationship with the atmospheric circulation over central Europe. The novelty of this study in comparison to previous ones is the fact that (a) for the first time a more recent period is used, as well as (b) different extreme precipitation indices (the total rainfall amount of days with precipitation greater than 95th and 99th percentile, the maximum daily precipitation amount and others) are applied. Despite the high association identified from previous studies (Domonkos, 2003; Bartholy *et al.,* 2009) between the seasonal or annual circulation indices and seasonal or annual precipitation in Hungary, it would be however not reasonable to expect the daily precipitation regime in Hungary to be controlled only by one or two modes of the atmospheric circulation variability. Thus, in order to understand the mechanisms that govern the rainfall regime in Hungary, we undertook an analytical study of the circulation types focusing on the domain of interest. Moreover, for the first time, to the authors knowledge, the links between the atmospheric circulation and the rainfall in Hungary are being studied, namely the inter-annual variability as well as any long-term trend and extremes. We also investigated which types, at the geopotential level of 500 hPa, are the most frequent ones during the days of extreme rainfall, as well as if the atmospheric circulation changes can interpret these significant trends of precipitation amounts. Finally, we analyse the fields and patterns of the afore-mentioned circulation types.

2 | DATA AND METHODOLOGY

We utilized daily precipitation time series from five stations in Hungary (Budapest lat. = 47.50°N, lon. = 20.00°E; Szombathely, lat. = 47.23°N, lon. = 16.62°E; Pécs, lat. = 46.07°N, lon. = 18.23°E; Szeged, lat. = 46.25°N, lon. = 20.14°E and Debrecen, lat. = 47.53°N, lon. = 21.63°E) for a 53-year period (1958–2010). Their mean annual rainfall totals vary from 509.2 mm (Szeged) to 643.1 mm (Pécs), while for the rest of the stations have intermediate values, specifically 604.7 mm (Szombathely), 551.0 mm (Budapest) and 562.1 mm (Debrecen). Using the above data, we computed the following parameters:

1. The number of rainy days (one decimal resolution).
2. The annual and seasonal rainfall totals.
3. The daily precipitation values of the 95th and 99th percentiles.
4. The number of days with precipitation amounts greater than the 95th and 99th percentiles.
5. The total rainfall amount of days with precipitation amounts greater than 95th and 99th percentiles.
6. The maximum daily precipitation.
7. The ratio of the daily maximum and the 95th and 99th percentile values.

Furthermore, we calculated the trends of the time series of the (1)–(6) parameters and we checked their statistical significance using the Mann–Kendall test at a significance level of 95%.

Apart from the rainfall data, we also used daily grid point geopotential data at the 500 hPa level for the same time period (1958–2010) derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) database, with a spatial resolution of 2.5 × 2.5° (Kalnay *et al.,* 1996). With these data, we developed a daily circulation-type calendar using an updated automatic classification scheme which can be applied all over Europe (Anagnostopoulou *et al.,* 2009). The spatial window that was selected extends from 30.00°N to 75.00°N and from 22.50°W to 47.50°E, while the central point for the classification was the one over Budapest (lat. = 47.50°N, lon. = 20.00°E). This classification scheme was not applied directly to the geopotential values but to the anomalies of the geopotential fields. These anomalies were calculated on a daily basis using the mean monthly geopotential values at 500 hPa for the time period 1971–2000. For the detection of the anticyclonic and the cyclonic types, we considered the average anomalies of nine grid points including the central one (lat. = 47.50°N, lon. = 20.00°E). Apart from the central, the other eight grid points are the ones closer to the central grid point. Regarding the average anomalies of nine grid points a day with the positive (negative) anomaly is considered as an anticyclonic (cyclonic) day. Then we detected the highest positive (negative) anomaly over the whole field of study and we investigated if there is a continuous decrease (increase) of the anomaly values from this anomaly to the central grid point. If this criterion is not fulfilled, another trial is made this time for the grid point with the second highest positive (negative) anomaly, if not for the third and so on. However, the trials stop when the grid found performs according to the afore-mentioned terms. If more than one centre is detected, the one that is closer to the study region is chosen, and is identified as an anticyclonic or cyclonic centre that prevails over the domain of

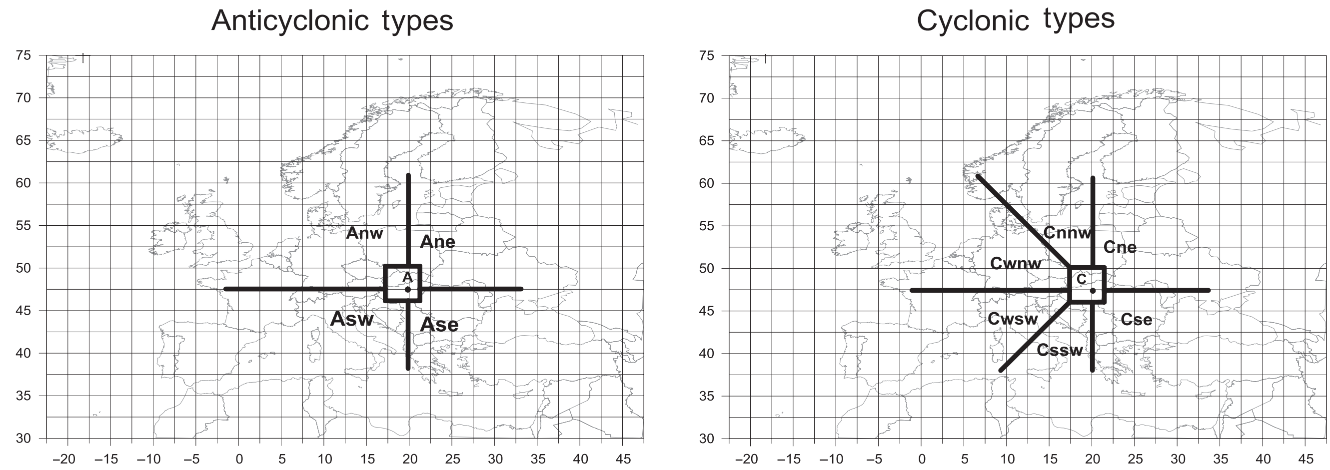

FIGURE 1 Geographical location of the centre of the classification and the position of the anticyclonic and cyclonic types

interest. Altogether 12 anticyclonic and cyclonic types are classified according to the location of the anomaly centre (Figure 1). Each type is named after the location its centre, which is observed in relation to the main central grid point and has a characteristic synoptic pattern based on the upper airflow and associated air masses. We finally calculated several parameters, with the aim of analysing the relationship between the circulation types and the precipitation amounts over the domain of interest.

3 | RESULTS

3.1 | Analysis of the annual and seasonal precipitations

On an annual basis, the station of Pécs is found to be the rainiest one with 643.1 mm followed by the station of Szombathely (604.7 mm) and Debrecen (562.1 mm). The two remaining stations with smaller annual totals are located at the south (Szeged: 509.2 mm) and at the north (Budapest: 551.0 mm) of the country. The range of the annual precipitation amounts is relatively similar to the one found by Matyasovszky *et al*. (1999) and Mezősi (2017). The highest average annual rainfall amount is observed at the station of Kőszeg (807 mm), whereas the lowest annual precipitation total is observed at the station of Szeged (203 mm) during the year 2000 (Bartholy and Pongrácz, 2013). Regarding the seasonal analysis, it was found that during winter, the two wettest stations are Pécs (116.9 mm) and Budapest (116.8 mm) and the two driest ones are Szeged (95.6 mm) and Szombathely (82.1 mm). In spring, the stations with the highest precipitation amounts are Pécs (153.1 mm) and Szombathely (138.4 mm), while Budapest and Szeged present smaller values, namely 130.1 and 119.3 mm, respectively. For summer, as it was expected, the wettest stations are Szombathely (231.5 mm) and Pécs (211.5 mm), while the driest ones are Budapest (170.0 mm) and Szeged (179.2 mm). Finally, during autumn, the same stations show the highest seasonal totals (Pécs: 161.6 mm and Szombathely: 152.6 mm) and the station of Szeged represents the lowest rainfall amount (115.1 mm). For all the stations, the wettest season is summer, while the driest one is winter. On the other hand, the maximum number of rainy days is observed either in winter (Budapest: 33.6 days, Szeged: 33.4 days, Debrecen: 35.8 days) or in spring (Pécs: 36.8 days) and summer (Szombathely: 37.5 days). The minimum number of rainy days is found in general in autumn, with the only exception of Szombathely, where the minimum is observed in winter (Table 1).

The annual precipitation trends differ for the study stations. Szombathely and Budapest present negative, statistically non-significant trends, while the rest of the stations show positive, though negligible trends. The seasonal analysis showed that Szombathely indicates negative negligible trends for all seasons. The rest of the stations have either positive or negative trends, depending on the season, but all are non-significant. It is worth mentioning that all the stations present negative trends during winter and the majority of them (apart from Szombathely and Budapest) display non-significant positive trends in autumn (Table 1).

On the other hand, the trends of rainy days slightly differ in comparison to the rainfall totals. On an annual basis, two stations (Szombathely and Szeged) show positive, though non-significant trends, while the remaining three stations indicate negative trends (for Budapest only, this negative trend is statistically significant). Szinell *et al*. (1998) studied drought tendencies in Hungary and their analysis for the station of Budapest showed that the occurrence of dry years is more frequent after the 1960s which is reflected by the disappearance of the wet years during the same period. On a seasonal basis, the only station displaying significant trend is again Budapest, with a negative trend for summer. In winter, all stations present negative, though non-significant trends (Table 1). Anders *et al*. (2014) found that in Hungary precipitation has decreased up to 10% during the period 1901–2009 and this decrease is more pronounced especially since the 1970s mainly during spring. According to the same

TABLE 1 Mean precipitation amounts (mm) and trends, as well as mean number of rainy days and trends for the five examined stations for the 52-year period, 1958–2010. The asterisk signs show significant trends at the .05 probability level

Stations	Parameters	Winter	Spring	Summer	Autumn	Year
Szombathely	Mean precipitation	82.1	138.4	231.5	152.6	604.7
	Trend	–	–	–	–	–
	Mean number of rainy days	31.5	34.9	37.5	32.5	136.4
	Trend	–	+	–	+	–
Pécs	Mean precipitation	116.9	153.1	211.5	161.6	643.1
	Trend	–	+	+	+	+
	Number of rainy days	35.4	36.8	33.2	31.1	136.5
	Trend	–	–	–	+	+
Budapest	Mean precipitation	116.8	130.1	170.0	134.1	551.0
	Trend	–	+	–	–	–
	Mean number of rainy days	33.6	32.3	29.3	27.6	122.9
	Trend	–	–	–*	+	–*
Szeged	Mean precipitation	95.6	119.3	179.2	115.1	509.2
	Trend	–	+	+	+	+
	Mean number of rainy days	33.4	33.3	30.6	27.8	125.0
	Trend	–	–	+	+	+
Debrecen	Mean precipitation	106.9	136.3	196.2	122.5	562.1
	Trend	–	+	+	+	+
	Mean number of rainy days	35.8	33.4	32.1	29.6	130.9
	Trend	–	–	–	+	–

authors, summer precipitation does not show a significant negative trend. The Hungarian plains are most affected with drought, particularly during late spring and early summer.

3.2 | Analysis of the extreme precipitations

It was found that the values of the 95th and the 99th percentiles of daily rainfall are relatively low (Table 2). The highest values of these two extreme indices are observed for the two rainiest stations Pécs (17.7 and 33.7 mm) and Szombathely (17.5 and 31.6 mm). For the remaining study stations the respective extreme values are 16.0 and 29.3 mm for Szeged, furthermore 16.0 and 31.2 mm for Debrecen, as well as 17.1 and 30.1 mm for Budapest. Regarding the absolute maxima of the daily totals, the highest one is also observed in Pécs (97.4 mm), while the smallest one in Szombathely (71.6 mm). According to Munzar and Ondráček (2013), the record 1-day rainfall for central Europe exceeded 300 mm but in Hungary and in Slovakia this extreme daily amount has never been recorded. According to Bartholy and Pongrácz (2013) the highest daily extreme precipitation amount was recoded at the station of Dad on June 9, 1953 (260 mm). The comparison of the extreme and absolute values for the stations in Hungary with the equivalent ones over western Europe and especially in Belgium, with higher annual totals, shows that the Hungarian extremes are significantly higher (Maheras *et al.*, 2008), while in comparison with the respective extreme values in the Mediterranean, they are much lower (Tolika *et al.*, 2007). Nevertheless, the values of the ratios Abs.max/95th and Abs.max/99th of the

TABLE 2 Extreme precipitation values for the five examined stations. The asterisk sign shows a significant trend at the .05 probability level

Stations	95%	99%	Abs.max.	Mean number of days >95%	Mean number of days >99%	Ratio Abs.max./95%	Ratio Abs.max./99%
Szombathely	17.5	31.6	71.6	6.9	1.4	4.1	2.3
	–	–		–	–		
Pécs	17.7	33.7	97.4	6.9	1.4	5.5	2.9
	+	+		+	+		
Budapest	17.1	30.1	75.1	6.2	1.2	4.4	2.5
	–	–		–	–		
Szeged	16.0	29.3	92.3	6.3	1.3	5.8	3.2
	+	+		+	+		
Debrecen	16.0	31.2	80.3	6.6	1.3	5.0	2.6
	+	–		+*	–		

Abs.max. = absolute maximum

Hungarian stations, furthermore those of Belgium and the Mediterranean are very similar (Abs.max. = absolute maximum). More specifically, the values of the first ratio vary from 4.1 (Szombathely) to 5.8 (Szeged) and for the second one from 2.3 (Szombathely) to 3.2 (Szeged). Regarding the indices values of the rainy days >95th and >99th for the five stations in Hungary, they are from 6.2 to 6.9 for the first index and from 1.2 to 1.4 for the second one. The trends of the extreme indices for the 95th and 99th percentiles both for the actual totals, as well as for the rainy days with values greater than these two percentiles, differ from station to station, being either positive or negative, but in most cases they are non-significant. Kyselý (2009) found spatially coherent and statistically significant positive trends for heavy rainfall for the western parts of Czech Republic during winter. On the other hand, for the eastern parts of the country, these changes are not so clear due to the Mediterranean influence. The only station that indicates significant positive trend is Debrecen in the case of the number of rainy days with amounts greater than the 95th percentile (Table 2). Recent studies for the Carpathian Basin showed that the observed trends of extreme precipitation are not significant (Bartholy and Pongrácz, 2005; 2007; Bartholy *et al.,* 2015).

3.3 | Circulation types: Description, frequencies and trends

The classification scheme that was used in the study consists of five anticyclonic types and seven cyclonic ones (Figures 1 and 2). The classification of each type is based mainly on the location of the anomaly centre, a positive centre for the anticyclonic types and a negative one for the cyclonic types at the 500-hPa absolute topography. Any classification is valuable if each type corresponds to a characteristic geopotential pattern, optically distinct from the other types, if it can reproduce the wind directions in different heights and at the surface, as well as the weather conditions that are expected over the domain of interest. In order to certify all the above conditions, we computed the mean seasonal maps (called as composites) of the anomalies of the 12 circulation types (Figure 2). For all the types and each season we applied the one sample t test at the whole range of values of the positive and negative anomalies, as well as for their maximum values. The results of these calculations showed that all the anomaly fields are significant at the $p \geq .05$ probability level. The comparison of the anticyclonic and cyclonic types showed that they represent the reverse atmospheric circulation conditions. The mean annual relative frequencies of the circulation types (Table 3) show that 48.7% of them belong to anticyclonic types and the rest (51.3%) are of cyclonic ones. The most frequent anticyclonic type is Ase (13.2%), while the cyclonic ones are Cse (11.9%) and Cne (11.2%). Finally, the two cyclonic types that are associated with the largest rainfall percentages (Cwsw = 9.7% and Cwnw = 4.9%) have much smaller frequencies compared to the above-mentioned cyclonic types.

The frequencies of the circulation types on a seasonal basis differ compared to the annual ones. In winter, the frequencies of the anticyclonic types are substantially smaller (34.8%), compared to those of the cyclonic ones (65.2%). The cyclonic types with the highest frequencies are Cse (18.7%), Cne (14.6%) and Cwsw (12.1%). Regarding spring, the total frequencies of the anticyclonic types and cyclonic types is 41.0 and 59.0%, respectively. As in winter, the most frequent cyclonic types are Cne (15.3%), Cse (13.0%) and Cwsw (10.1%). The summer anticyclonic frequency increases significantly (65.8%), while this season is far less cyclonic (34.2%). The discrepancies in the frequency of occurrence of the anticyclonic and the cyclonic circulation types between the seasons of winter and summer are mentioned by Bartholy *et al.* (2009). According to their results during the negative (positive) phase of the NAO index, the cyclonic types are more (less) frequent during all seasons but the greatest differences are observed between summer (13 and −10%) and winter (7 and −7%). The greatest frequencies are observed for Asw (17.7%), Ase (16.2%), Ane (14.6%) and Csw (7.3%) followed by C (6.8%). Finally, during autumn the anticyclonic types are prevailing against cyclonic ones with 53.2 and 46.8%, respectively. In this season, type Ase (17.7%) is the most frequent. From the cyclonic types Cse (9.8%) and Cwsw (9.3%) show the highest frequencies.

On the whole, both on an annual and seasonal range, the anticyclonic types displayed positive, non-significant trends. Conversely, the cyclonic types showed negative (non-significant) trends. This finding is in agreement with results from other studies regarding both Europe (Kyselý and Huth, 2006) and eastern Europe (Bartoszek, 2017). Nevertheless, the analysis of the trends of each type separately indicated a different pattern (Table 3). From the anticyclonic types, Ase presented significant positive trends both on an annual and seasonal basis. This is the case for Asw type (except from autumn), however with non-significant positive trends. Moreover, type Cwsw showed significant negative trends both for the year and summer. Type Cse represented also negative trends; however, they were significant during the year, spring and summer.

3.4 | Relationship between the circulation types and precipitation

On an annual scale, the percentage of rainfall during the occurrence of the anticyclonic types, averaged for the five study stations, equals to 27.2%, which is higher compared to that found for Belgium (23.2%) (Maheras *et al.,* 2008) (Table 4), and even much higher than the corresponding value over several stations in the Mediterranean (<10%, Tolika *et al.,* 2007). This high percentage of precipitation is probably associated with the higher air mass instability in

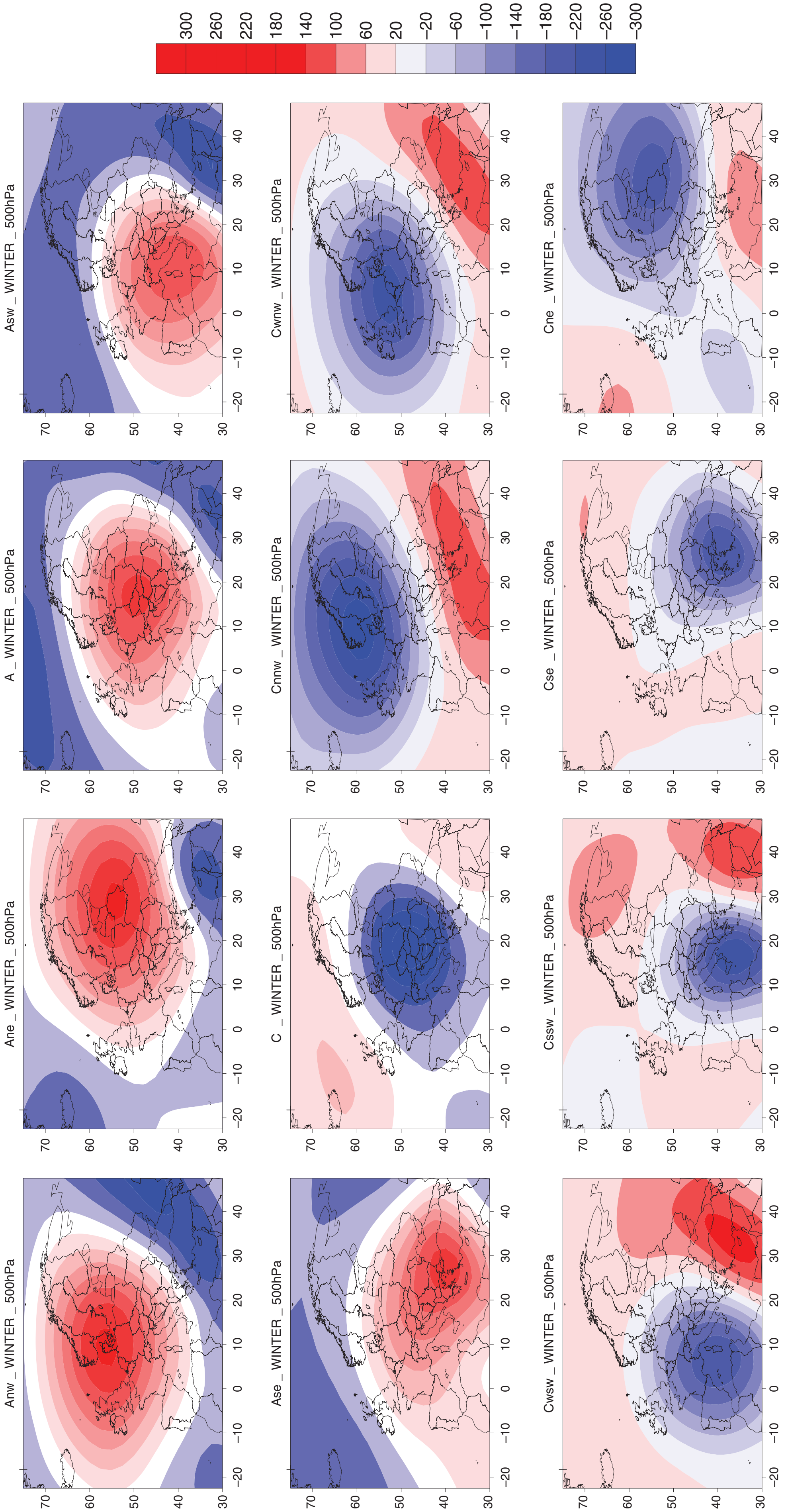

FIGURE 2 Composites of the 12 circulation types, 500 hPa level, winter [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Description, frequency and trends (*F*/*T*) of the circulation types at the 500 hPa. The asterisk trends are statistically significant

	Type acronym	Description	W	S	Sum.	A	Y
1	Anw	The anticyclonic centre is located in the northwest of the study region. The wind over the study region, in the surface of the 500 hPa prevails from the northerly sector	7.4 +	9.9 +*	8.6 –	9.5 –*	8.8 –
2	Ane	The anticyclonic centre is located in the northeast of the study region, over eastern Europe. The winds are principally from the northerly sector	6.2 +	8.2 +	14.6 +	8.9 –	9.5 +
3	A	The anticyclonic centre is located over the study region producing weak variable winds during the warm period and relatively strong wind	2.5 +	4.9 +*	8.7 +	4.0 +	5.0 +*
4	Asw	The anticyclonic centre is located in the west or southwest of the study region. This type is characterized, in 500 hPa surface, mainly by westerly or northwesterly flow	7.3 +*	10.6 +*	17.7 +*	13.0 +	12.2 +*
5	Ase	The anticyclonic centre is located over the southeastern of the study region. The wind over the area blow mainly from the southerly sector	11.4 +*	7.4 +*	16.2 +*	17.7 +*	13.2 +*
6	C	The cyclonic centre is located over the study region. The wind over the area blow mainly from different sectors	4.4 –	7.3 –*	6.8 –	6.5 +	6.3 –
7	Cnnw	The cyclonic centre is located in the NNW of the study region. The prevailing wind has a westerly–southwesterly flow over the study region	5.0 –	3.9 +	1.2 +	3.0 –	3.3 –
8	Cwnw	The cyclonic centre is located in the WNW of the study region producing intense westerly–southwesterly flow over the study region	5.4 –	5.5 +	3.6 –	5.3 –	4.9 –
9	Cwsw	The cyclonic centre is located in the WSW of the study region producing intense westerly–southwesterly flow over the study region	12.1 –	10.1 –	7.3 –*	9.3 –	9.7 –*
10	Cssw	The cyclonic centre is found in the SSW of the study region. The wind blows from the southwesterly sector	5.0 –	3.9 –*	2.4 –	4.7 –	4.0 –*
11	Cse	The cyclonic centre is located in the southeast of the study region. The wind has a pronounced northerly sector	18.7 –	13.0 –*	6.3 –*	9.8 –	11.9 –*
12	Cne	The cyclonic centre is located in the northeast of Greece. The wind blows mainly from the northerly, northwesterly sector	14.6 –	15.3 –	6.6 –*	8.3 –	11.2 –

high altitudes over Hungary, central Europe, compared to the Mediterranean. This is the case especially for summer, when the percentage of rainfall of the anticyclonic types reaches 46.5%. In all cases and with a different circulation in altitude, the surface is characterized by high pressure, generally with slack pressure field.

Obviously, the percentage of rainfall that is associated with the cyclonic types is much higher (72.8%). For central Europe the observed annual precipitation characterized as cyclone precipitation, varies from 57 to 73% (Hofstätter *et al.,* 2018). On annual scale, the rainiest type is Cwsw (22.4%), followed by the types Cwnw (11.3%) and Cne (10.7%). From the seasonal analysis the greatest precipitation percentage attributed to cyclonic types is found in winter (91.7%) and the lowest one in summer (53.5%). According to Hawcroft *et al*. (2012) these percentages vary between 80 and 70% for winter and summer, respectively, in the storm track regions of parts of Europe. Spring and autumn show almost the same percentages: 79 and 80.5%, respectively (Table 4).

During all seasons, the cyclonic type with the highest rainfall percentage is Cwsw, with a value varying from 24.8% during winter to 18.3% during summer. The second wettest type is Cne ranging from 19.1% in winter and 14.7% in spring; while the third one is Cwnw, the frequency of which is high, mainly during winter (15.8%) and autumn (15.1%). Finally, it is characteristic that type C, which is one of the wettest type in the Mediterranean and Belgium, is only the fifth wettest type in decreasing order over Hungary (8.2% on an annual scale) (Table 4).

In general, on an annual basis, the trends of the rainy days for the anticyclonic types were significantly positive in all stations, while for the cyclonic types significant negative trends occur in all stations apart from Szeged. Seasonally, the behaviour of the trends for the rainy days remains the same, with positive (negative) trends for the anticyclonic

TABLE 4 Percentage of precipitation (%) per circulation types for the five examined stations

Period	Anw	Ane	A	Asw	Ase	C	Cnnw	Cwnw	Cwsw	Cssw	Cse	Cne	Anticyclonic	Cyclonic
Year	2.5	6.6	1.1	6.4	10.6	8.2	5.6	11.3	22.4	6.4	8.3	10.7	27.2	72.8
Winter	0.9	1.3	0.1	2.7	3.4	4.2	10.0	15.8	24.8	4.7	13.0	19.1	8.3	91.7
Spring	3.7	4.7	1.2	4.8	6.6	8.5	6.3	10.7	24.1	6.1	8.5	14.7	21.0	79.0
Summer	3.0	13.1	2.2	10.6	17.6	8.9	2.1	6.8	18.3	5.5	6.0	5.8	46.5	53.5
Autumn	1.7	3.2	0.1	4.8	9.8	9.8	6.5	15.1	24.6	9.2	7.7	7.5	19.5	80.5

TABLE 5 Trends of the rainy days according to the circulation types. The asterisks show significant trends at the .05 probability level

Stations	Circulation type	Year	Winter	Spring	Summer	Autumn
Szombathely	Anticyclonic	+*	+	+*	+*	+
	Cyclonic	−*	−*	−	−*	−
Pécs	Anticyclonic	+*	+*	+*	+*	+*
	Cyclonic	−*	−	−	−*	−
Budapest	Anticyclonic	+*	+	+	+	+*
	Cyclonic	−*	−*	−*	−*	−
Debrecen	Anticyclonic	+*	+	+*	+*	+
	Cyclonic	−	−*	−	−*	+
Szeged	Anticyclonic	+*	+*	+*	+*	+
	Cyclonic	−	−	−	−	+

(cyclonic) types that are significant in some stations (Table 5).

On an annual basis, significant positive trends of the precipitation amounts can be experienced for the anticyclonic types for all stations except for Budapest. On the other hand, the trends of the rainfall totals for the cyclonic types are negative (except for Szeged, where they are positive) (Table 6).

The results of the trend analysis of the precipitation amounts per type for all the ensemble of the stations are as follows. On an annual scale, the circulation types Anw, Asw and Ase showed significant positive trends (Table 7). Conversely, the rainfall amounts of the cyclonic types Cwsw and Cse displayed significant negative trends (Table 7). Note that these are the rainiest types. The seasonal results revealed significant positive trends for the rainfall amounts of the summer anticyclonic types Anw and Ase and for the autumn type Asw. In the case of the cyclonic precipitation amounts, significant negative trends were found for type Cse during winter and summer, while type Cwsw presented negative trends that were negligible for all seasons, except for spring. It is worth mentioning that the rainfall of type C in autumn presented significant positive trends (Table 7).

Cwsw is the cyclonic type indicating the highest frequency for extreme precipitation days (for both indices, 95th and 99th percentiles) for all the stations (Table 8). This circulation type, the centre of which is located at the west southwest of Hungary, has a Mediterranean origin (this has been checked for all the extreme precipitation cases). Analogous results were found by Hofstätter *et al*. (2018) for central Europe. More specifically, they mention that the depressions that follow the trajectory Vb (they pass through the western part of Hungary), are the ones that are mainly associated with heavy cyclone rainfall for all seasons and have a significant impact over a far larger part of central Europe than the isobars of the cyclone delimit. The greatest frequency of this type for rainfall ≥95th percentile occurs for Budapest (31.0%), while the lowest one for Debrecen (20.1%) (Table 8). Furthermore, the highest percentage of rainfall for this index in type Cwsw is also observed for Budapest (29.8%), while the lowest one for Debrecen (19.9%). For the second extreme index (99th percentile), the highest frequency is found for Szeged (28.4%) and the lowest one (17.8%) for Szombathely. Analogous results were found for the percentage of rainfall for this index, with the highest (lowest) one 29.0% (18.0%) for Szeged (Szombathely). The second type with the highest frequency of occurrence for extreme precipitation is the anticyclonic type Ase. For three stations (Szombathely, Szeged and Debrecen), this type shows the second highest frequency for both extreme indices. For the other two stations (Pécs and Budapest), and for the index 95th percentile, the second highest frequency of occurrence happens for the cyclonic type Cwnw, while for the index 99th percentile it is found for type Ase (Ane) in the case of Pécs (Budapest). Obviously, both the frequencies as well as the rainfall amounts of the second most

TABLE 6 Precipitation trends according to the circulation types. The asterisks show significant trends at the .05 probability level

Stations	Circulation type	Year	Winter	Spring	Summer	Autumn
Szombathely	Anticyclonic	+*	−	+	+*	+
	Cyclonic	−*	−	−	−	−
Pécs	Anticyclonic	+*	+	+	+*	+*
	Cyclonic	−	−	−	−	+
Budapest	Anticyclonic	+	+	+	+	+
	Cyclonic	−*	−	−	−	−
Debrecen	Anticyclonic	+*	+	+*	+	−
	Cyclonic	−	−	+	−	+
Szeged	Anticyclonic	+*	+	+	+*	+
	Cyclonic	+	−	+	−	+

TABLE 7 Precipitation trends according to the circulation types for all examined stations. The asterisks show significant trends at the .05 probability level

Circulation types	Year	Winter	Spring	Summer	Autumn
Anw	+*	+	+	+*	+
Ane	+	+	+	+	−
A	+	+	+	+	−
Asw	+*	+	+	+	+*
Ase	+*	+	+	+*	+
C	+	−	−	−	+*
Cnnw	+	−	+	+	+
Cwnw	−	+	−	−	−
Cwsw	−*	−	+	−	−
Cssw	+	+	−	+	−
Cse	−*	−*	−	−*	+
Cne	−	−	−	−	+
Anticyclonic	+*	+	+*	+*	+
Cyclonic	−	−	−	−	+

frequent types are much smaller, compared to the equivalent ones of the first circulation type (Table 8).

3.5 | Analysis of the geopotential fields of the circulation types that are associated with extreme precipitation events

We computed the mean maps (composites) of all the circulation types under study and the composites of the two most frequent types that are associated with the extreme rainfall episodes for the days that the precipitation amount is equal or greater than the two percentiles (95th and 99th). Moreover, we computed the difference—composites derived from the other two sets of maps (general mean field of the type—mean field of the type for the extreme rainfall). Figures 3–6 illustrate the results of these computations for the stations that present the greatest frequencies of the two indices (Budapest, ≥95th and Szeged, ≥99th) and for Debrecen for both indices. This latter station presents significant positive trends for the 95th index.

The first examined case refers to Budapest for the 95th index, which shows the greatest frequency in comparison to the remaining stations. As mentioned before, the prevailing circulation type is the cyclonic Cwsw. The analysis of the composites shows an extended zone of negative anomalies that covers almost the whole Europe, except for the Scandinavian Peninsula (Figure 3). The centre of these anomalies is located in northern Italy. On the other hand, positive anomalies are found over the eastern Mediterranean and Turkey. The composite of the difference is also quite interesting (Figure 3b). An extended zone of positive differences over central Italy covers the area from 55°E to north−northwest from central Mediterranean to the North Sea, covering almost the whole area as previously, apart from the western Iberian Peninsula. The extreme precipitation is the result of a perturbation associated with fronts, with the main trajectory of this pressure system from southwest to northeast, conducted by the circulation in altitude (Figure 3b). The general pattern of the anomaly field for Budapest, but for the 99th index is very similar to the previous one, regarding the

TABLE 8 Extreme cases and precipitation amounts according to the circulation types for each station

Stations	Circulation types (CTs)	Indices	Frequency (days)	Frequency of the CTs (%)	Precipitation frequency of the CTs (%)
Szombathely	Cwsw	95th	94	25.8	25.0
	Cwsw	99th	13	17.8	18.0
	Ase	95th	62	17.0	17.8
	Ase	99th	15	20.5	21.4
Pécs	Cwsw	95th	79	21.6	21.5
	Cwsw	99th	17	23.3	21.9
	Cwnw	95th	49	13.4	13.7
	Ase	99th	15	20.5	22.0
Budapest	Cwsw	95th	102	31.0	29.8
	Cwsw	99th	17	25.8	24.8
	Cnnw	95th	35	10.6	9.6
	Ane	99th	11	16.7	18.3
Szeged	Cwsw	95th	75	22.5	23.6
	Cwsw	99th	19	28.4	29.0
	Ase	95th	40	12.0	12.5
	Ase	99th	9	13.4	13.3
Debrecen	Cwsw	95th	70	20.1	19.9
	Cwsw	99th	18	25.7	23.4
	Ase	95th	46	13.2	14.6
	Ase	99th	15	21.4	21.5

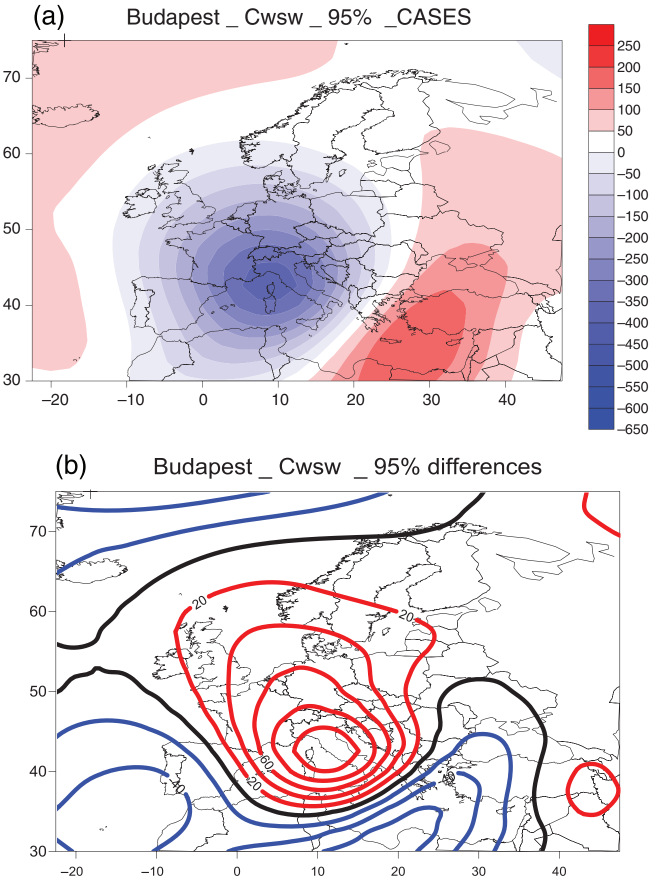

FIGURE 3 The mean anomaly field of the Cwsw type during the days of extreme rainfall (95th percentile). (a) The differences of the general mean field of the type—mean field of the type for the extreme rainfall; (b) for the station of Budapest [Colour figure can be viewed at wileyonlinelibrary.com]

location of the negative and positive anomalies, as well as their intensity (Figure 4a). The difference of the 99th index can be explained by the fact that the negative and positive anomalies are even more intense (Figure 4b).

The second case concerns the station of Szeged and the 99th index. The prevailing type, as mentioned before, is the cyclonic type Cwsw and in this case the centre of the negative anomalies is located over northern Italy. The whole zone of the negative anomalies covers a much larger area, extending to northeast, to eastern Europe, compared to the equivalent one for the station of Budapest (Figure 5a). The mean difference composite (Figure 5b) shows that the extended positive anomaly zone covers almost the whole Europe, from southwest to northeast, except for the Iberian Peninsula, the British Isles and a part of the Balkans. Once again, the intense rainfall conditions are associated with the perturbation current, which moves from the southwest to the northeast, due to the atmospheric circulation in altitude. The general pattern of the anomaly field for Szeged, but in the case of the 95th index does not differ much from the 99th one. Both the area covered by the negative and positive anomalies, as well as their intensity are very similar. The only critical difference is the location of the centre of the anomalies, which is observed closer to the station than for the 95th index.

For Debrecen, the prevailing circulation type for the two indices is the cyclonic Cwsw with 70 and 18 cases (days) for the 95th and the 99th indices, respectively (Table 8). For both indices, the mean anomaly field and the difference field do not differ much from those described before for the other two stations, for the same circulation type (Figure 6). For Debrecen, the circulation type with the second highest occurrence during the days of extreme rainfall (46 and 15 cases for the 95th and the 99th indices, respectively), is Ase. This is an anticyclonic type, anomaly centre of which is located at the southeastern part of Hungary. The study of the anomalies (not shown) for the two indices displayed a zone of positive anomalies, centred over the southern Balkans, covering the largest part of eastern Europe and eastern Mediterranean. The limits of this positive anomaly zone are extended to eastern Hungary, the largest part of which is covered by almost zero anomaly values. Furthermore, a weaker negative anomaly zone covers western Europe. The analysis of the difference pattern for both extreme indices showed that they are quite different. Namely, two positive anomaly poles are found, where the first one occurs over the

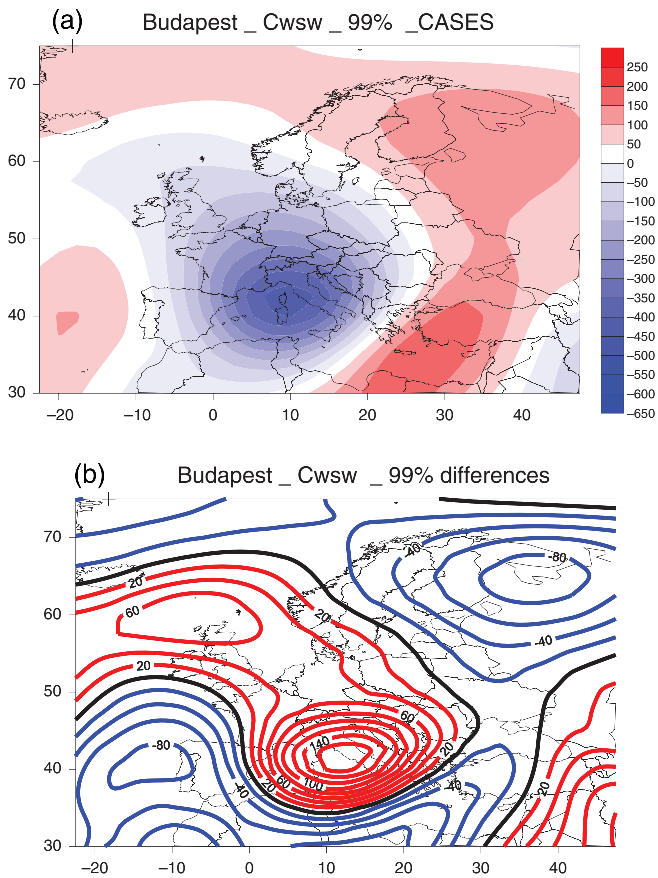

FIGURE 4 The mean anomaly field of the Cwsw type during the days of extreme rainfall (99th percentile). (a) The differences of the general mean field of the type—mean field of the type for the extreme rainfall; (b) for the station of Budapest [Colour figure can be viewed at wileyonlinelibrary.com]

southwestern part of Hungary, centred over northern Italy, while the second one is quite far from Hungary: at southeast with its centre over the eastern Mediterranean. Obviously, the positive anomalies are more intense for the 99th index, especially for the first pole over Italy. Furthermore, the analysis of the season in which the extreme rainfall type Ase occurs, shows that these extreme precipitation episodes—for all cases and for both indices—occurred during summer. All the above lead to the conclusion that it regards of a slack pressure field over Hungary, with a frontal passage (these has been a check for all the extreme precipitation cases for this type), most of the times with a depression centre located at higher latitudes. In the case of cold fronts the circulation in higher altitude (at 500 hPa) is generally zonal, while for warm fronts it is southwestern. In each case and only in summer, the occurrence of intense/extreme rainfall during Ase type (not shown) is mainly due to the instability of air masses induced by meteorological and geographical factors. It is worth mentioning that for the remaining stations in Hungary (Szombathely, Pécs, Szeged), in the majority of the cases extreme precipitation episodes during days of anticyclonic circulation are associated with the occurrence of type Ase (except for Budapest) and approximately 100 of these days happen in summer. Moreover, the physical mechanism that is responsible for these extreme episodes does not differ from the one described for Debrecen.

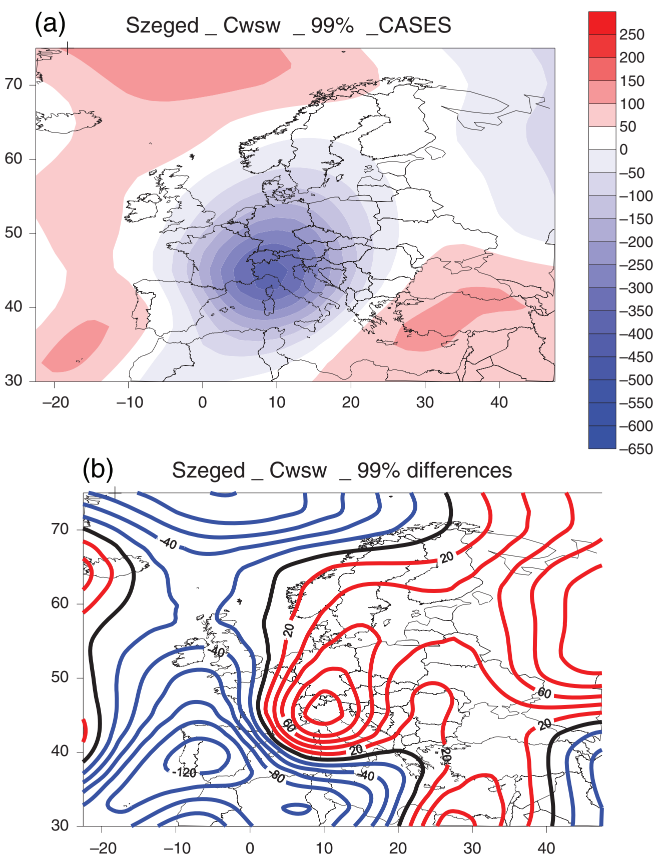

FIGURE 5 The mean anomaly field of the Cwsw type during the days of extreme rainfall (99th percentile). (a) The differences of the general mean field of the type—mean field of the type for the extreme rainfall; (b) for the station of Szeged [Colour figure can be viewed at wileyonlinelibrary.com]

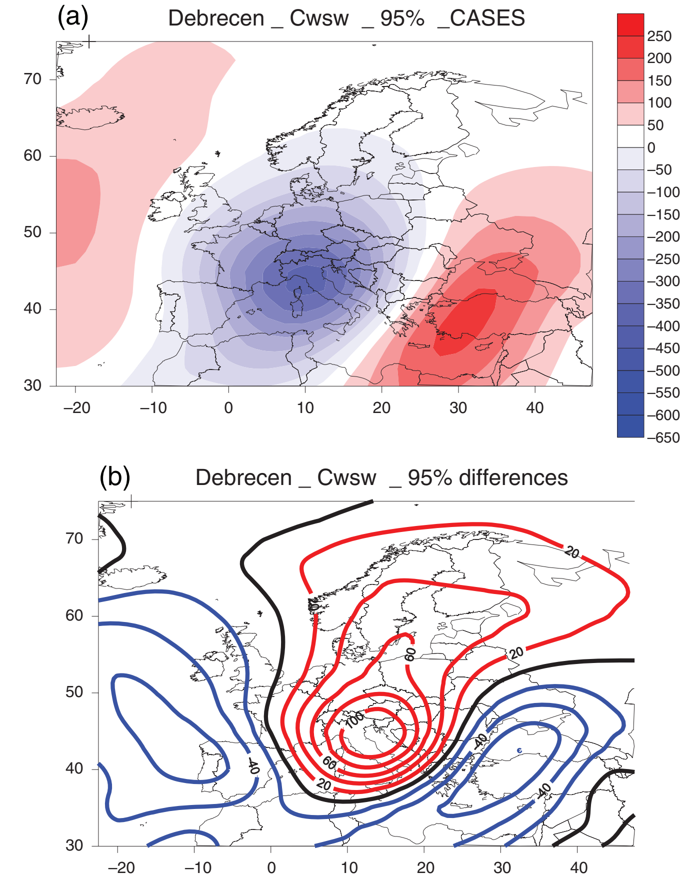

FIGURE 6 The mean anomaly field of the Cwsw type during the days of extreme rainfall (95th percentile). (a) The differences of the general mean field of the type—mean field of the type for the extreme rainfall; (b) for the station of Debrecen [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION AND CONCLUSIONS

In the present paper, an attempt is made to investigate the annual and seasonal precipitation trends, as well as the number of rainy days for five representative stations, uniformly distributed over Hungary. The trends of the extreme rainfall for the selected stations are also analysed. Moreover, an objective circulation-type classification scheme, which contains five anticyclonic and seven cyclonic types is utilized, in order to examine the links between the atmospheric circulation and the mean and extreme rainfall amounts over the domain of study.

In general, no significant trends were detected either on an annual or seasonal basis for the precipitation data sets in the selected stations. The annual rainfall totals of Szombathely in west Hungary and Budapest in north Hungary show negative trends, while Pécs and Szeged in south Hungary, as well as Debrecen in east Hungary indicate positive trends.

Overall, the number of rainy days shows the same behaviour in the five study stations as the rainfall totals, except for Budapest, where it displays significant negative trends both on an annual scale and summer.

Finally, the trends of the extreme rainfall (95th and 99th percentiles) are in general non-significant. An exception is found for Debrecen indicating positive significant trend for the number of days with rainfall amount higher than the 95th percentile. Thus, neither the general decrease of the annual rainfall, nor the systematic decrease (increase) of the summer rainfall (winter rainfall) can be proven for the selected stations and the study period in Hungary (Bartholy and Pongrácz, 2010). The same conclusion can be drawn for the frequency and intensity of the extreme precipitation, as well. A systematic increase or decrease is observed only in some stations and it cannot be characterized as a general phenomenon.

On an annual basis, the frequency of the anticyclonic types is 48.7%, while that of the cyclonic ones is 51.3%. The anticyclonic (cyclonic) types show positive (negative) trends in agreement with previous studies in central Europe (Domonkos, 2003; Kyselý and Huth, 2006); however, they are not significant in either cases. The percentage of precipitation for the cyclonic types equals to 72.8% on an annual basis. This percentage is among the highest in comparison to other regions over central Europe (Hofstätter *et al.,* 2018), similarly to other recent studies (Hawcroft *et al.,* 2012; Rulfová and Kyselý, 2014). Furthermore, winter is the season indicating the highest percentage of rainfall associated with the cyclonic types (91.7%). Conversely, summer showed the lowest precipitation percentage connected to the cyclonic circulation (53.5%) and, in this way, displayed the largest one associated with the anticyclonic types (46.5%). According to Plavcová *et al*. (2014) in summer about 50% of the total precipitation is due to convection developed under cyclonic conditions.

The significant negative trends for the rainy days and precipitation totals for several cyclonic types for Budapest (Cwsw, Cse: annually; and Cwnw, Cwsw, Cse: summer) could partially interpret the critical decrease of precipitation in this station during the year and for all seasons, as well as the significant decrease of rainy days annually and during summer. A major finding is that the wettest type, which is in general responsible for the occurrence of extreme rainfall episodes, shows significant negative trends (Cwsw, for the year). At the same time, for winter and summer its trends are also negative but non-significant. Thus, the general absence of significant trends of extreme rainfall could also be interpreted by the combination of two factors: (a) the negative trend of the precipitation of the circulation type Cwsw and (b) the positive rainfall trend of the anticyclonic types, especially of the Ase type which compensates the aforementioned negative trend. This latter type (Ase) shows significant precipitation increase mainly in summer, resulting in non-significant trend for the extreme rainfall. It should be mentioned that Debrecen is the exception, because the number of days with rainfall greater than 95th percentile shows significant positive trends.

In most cases the circulation types linked with extreme precipitation are associated with zonal or western−southwestern circulation, where the depressions are generally originated over the Mediterranean. Using an objective scheme to observe depression on a Vb track from the Mediterranean to central Europe, Nissen *et al*. (2014) found that over 40% of the depressions of the Vb track are responsible for rainfall exceeding the 95th percentile of the daily values over central Europe and about 15% of all extreme precipitation days (99th percentile) (Messmer *et al.,* 2015). According to Hofstätter *et al*. (2018) the reasons for this are (a) the deep depressions along the Vb trajectory during all seasons over central Europe, (b) the fact that the depressions remain longer over this area due to the cyclonic trajectory of their centre at the surface moving to the NE and (c) the intensity of rainfall is in average much stronger in comparison to the depressions of the Atlantic. The influence of this circulation to precipitation is related to both with frontal passing and the deepening of the pressure system, as well as with the effect of positive vorticity of the perturbation current. This fact was certified by the anomaly fields of the circulation types: the anomalies of type Cwsw at 500-hPa geopotential height are more intense for the 99th index than for the 95th index. Also, the anomaly centre is located closer to the reference station in agreement with the finding of Nowosad and Stach (2014) who mention that individual circulation types do not only cause the extreme precipitation episodes but they determine the amount of rainfall. In addition, Jacobeit *et al*. (2009) noted that during extreme precipitation events over a flat terrain (as in our study), a cyclone centre often prevails highlighting the importance of the lifting mechanisms that are related to the cyclone dynamics. Overall, it is considered that the study of the rainfall in relation to the circulation types offers great potentials. It provides information about rainfall regime changes and in several cases in extreme event rainfall regime changes in a way that their interpretation is possible in terms of physical mechanisms.

As a future work, the authors aim at analysing further the relationships between the circulation types and precipitation over Hungary, using data derived from Regional Climate Models (RCMs), both for the present and future time periods in order to investigate climate change over the domain of interest.

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