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ORIGINAL PAPER

Comparison of an automated classification system with an empirical classification of circulation patterns over the Pannonian basin, Central Europe

Panagiotis Maheras[1] · Konstantia Tolika[1] · Ioannis Tegoulias[1] · Christina Anagnostopoulou[1] · Klicász Szpirosz[2] · Csaba Károssy[3] · László Makra[4]

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Abstract

The aim of the study is to compare the performance of the two classification methods, based on the atmospheric circulation types over the Pannonian basin in Central Europe. Moreover, relationships including seasonal occurrences and correlation coefficients, as well as comparative diagrams of the seasonal occurrences of the circulation types of the two classification systems are presented. When comparing of the automated (objective) and empirical (subjective) classification methods, it was found that the frequency of the empirical anticyclonic (cyclonic) types is much higher (lower) than that of the automated anticyclonic (cyclonic) types both on an annual and seasonal basis. The highest and statistically significant correlations between the circulation types of the two classification systems, as well as those between the cumulated seasonal anticyclonic and cyclonic types occur in winter for both classifications, since the weather-influencing effect of the atmospheric circulation in this season is the most prevalent. Precipitation amounts in Budapest display a decreasing trend in accordance with the decrease in the occurrence of the automated cyclonic types. In contrast, the occurrence of the empirical cyclonic types displays an increasing trend. There occur types in a given classification that are usually accompanied by high ratios of certain types in the other classification.

1 Introduction

Atmospheric circulation is a complex system of airflows with characteristic components in space and recurrent elements in time. To get a deeper insight into this phenomenon and to better understand this process, the classification of synoptic systems are usually performed (Huth et al. 2008). The classification of large-scale weather situations can be listed into three basic groups, namely (1) manual (subjective) (e.g., Péczely 1983), (2) automated (objective) (e.g., Maheras et al. 2000a), and (3) hybrid classifications (e.g., Frakes and Yarnal 1997; Sheridan 2002). However, we should add that (a) automated methods, which are often regarded as objective, always include subjective decisions, and (b) hybrid methods define types subjectively, but assign all observation patterns automatically (Philipp et al. 2010).

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✉ László Makra
makra@geo.u-szeged.hu

Panagiotis Maheras
maheras@geo.auth.gr

Konstantia Tolika
diatol@geo.auth.gr

Ioannis Tegoulias
tegoulia@auth.gr

Christina Anagnostopoulou
chanag@geo.auth.gr

Klicász Szpirosz
spiros@hwr.hu

Csaba Károssy
c.karossy@gmail.com

[1] Department of Meteorology and Climatology, Faculty of Sciences, School of Geology, Aristotle University of Thessaloniki, 54124 Thessaloníki, Greece

[2] Zrínyi Miklós Secondary School, Mádi u. 173, Budapest 1108, Hungary

[3] Savaria University Centre, Eötvös Loránd University, Károlyi Gáspár tér 4, Szombathely 9700, Hungary

[4] Faculty of Agriculture, Institute of Economics and Rural Development, University of Szeged, Andrássy út 15, Hódmezővásárhely 6800, Hungary

Before the advent of high-speed computers, subjective or manual methods were the most common methods for classifying atmospheric circulation. The 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 it can be difficult to export to other locations. Hence, these schemes cannot usually be replicated (Sheridan 2002). Some of the most important subjective weather classifications are as follows: the Vangengeim-Girs catalogue (Vangengeim 1935; Girs 1948), Hess-Brezowsky catalogue (Baur et al. 1944; Hess and Brezowsky 1952; Gerstengarbe et al. 1999), Péczely catalogue (1957b, 1983; Klicász 1990; Károssy 2016), Maheras catalogue (Maheras 1983, 1988), synoptic categories at the isobaric levels of 850 and 700 hPa (Kassomenos et al. 1998), and the Lamb catalogue (Lamb 1972; Perry and Mayes 1998).

The subjective classification of atmospheric circulation into distinct synoptic weather types is a useful tool for climate impact applications. They range from describing and analysing weather and climate conditions (Péczely 1957a, 1961; Kassomenos et al. 1998), analysing air pollution (Péczely 1959; Makra 2005; Makra et al. 2007a), to classifying airborne pollen grain concentrations (Makra et al. 2007b). More recently, objective or automated methods have come into use, such as the temporal synoptic index which incorporates principal component analysis and cluster analysis (Kalkstein and Corrigan 1986), principal component analysis by itself (Bartzokas and Metaxas 1996; Huth 2000), or combining it with cluster analysis (McGregor and Bamzelis 1995; Kassomenos et al. 2001, 2003, 2007; Casado et al. 2009), factor- and cluster analyses (Sindosi et al. 2003), neural networks (Hewitson and Crane 2002; Solman and Menéndez 2003), fuzzy (Bárdossy et al. 2002; Stehlík and Bárdossy 2003), optimisation algorithms (Demuzere et al. 2011), Lagrangian air trajectories (Ramos et al. 2014); 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). Moreover, Philipp et al. (2010) produced a new database of weather and circulation type catalogues that consists of 17 automated classification methods.

However, comparative analyses of different classifications methodologies of atmospheric circulation over the same region are to date quite rare. The study of Jones et al. (1993) compared Lamb circulation types with an objective classification scheme over the British Isles. Makra (2012) compared the performance of an objectively defined weather classification and the spatial synoptic classification (SSC) (Sheridan 2002) in classifying emergency department (ED) visits for acute asthma depending upon the weather, air pollutants, and airborne pollen variables. In addition, objective air mass types and the subjective Péczely weather types were compared in classifying both airborne pollen concentrations (Makra 2006) and chemical air pollutants (Makra et al. 2009).

This present study seeks to compare the performance of two classification methods, based on the atmospheric circulation types over the same area. The objective classification of Maheras et al. (2000a, b) and Anagnostopoulou et al. (2009) is compared with an empirical classification devised by Péczely (1983). The daily Péczely types have even been determined recently for the area of Hungary (Károssy 2016).

The main purpose of making a comparison between the two classifications is to analyse the characteristics of the circulation types, the relationship of the two classification schemes with the precipitation over Budapest, and a discussion of the advantages and drawbacks of the two classification schemes in order in a future work to study the mean precipitation amounts with the circulation types of the objective classification for Hungary using a denser station network. The overall aim of the study is to develop an empirical statistical downscaling model for the future projections of rainfall in Hungary.

2 Data and methods

In the present study we used daily grid point geopotential data at the 1000 hPa level for the time period (1958–2010) derived from the 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 that can be applied over any part of Europe (Anagnostopoulou et al. 2009). The spatial window that was selected extends from 20°N to 75°N and 25°W to 50°E, while the central point for the classification was the one over Budapest ($\varphi = 47.50°$N, $\lambda = 20.00°$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 1000 hPa for the time period 1971–2000. For the detection of the anticyclonic and the cyclonic types, we compared all the anomaly values of the field with the average anomalies of nine grid points with the central one included ($\varphi = 47.50°$N, $\lambda = 20.00°$E). A day was characterised as an anticyclonic one, when the mean value of the nine grid points was positive, while it was classified as a cyclonic one, if it was negative. Moreover, we checked the whole anomaly field, to find the centre of the anticyclone or cyclone that influenced the weather over Hungary. After computing the daily circulation type calendar over Hungary, we calculated several parameters on an annual and seasonal basis, such as the seasonal frequencies of the circulation types, their trends (both for the anticyclonic and cyclonic types) and the mean maps of the types. Finally, we calculated numerous parameters, with the aim of analysing the connection between the circulation types and the precipitation amounts over the domain of interest (Fig. 1).

The empirical classification of Péczely was based on the geographical location of cyclones and anticyclones over the Carpathian basin, which also considered the position of the cold and warm fronts. The 13 types were combined into five groups, namely; (1) meridional–northern, (2) meridional–southern, (3) zonal–western, (4) zonal–eastern, and (5) central types (Péczely 1961, 1983).

The precipitation datasets were based on data obtained from the Hungarian Meteorological Society. From our experience of over 40 years in processing empirical and objective classifications over the Greek domain (as well as in other parts of the European Region), the use of precipitation associated with the anticyclonic and cyclonic types is the most important criterion for the validation of an empirical or objective classification. The smaller the percentage of rainfall is associated with the anticyclonic types, the better the classification can be. Overall, it is concluded that the utilisation of geopotential heights at 1000 hPa and SLP data can greatly assist the validation of a scheme. And in our experience, the use of temperature or other meteorological data does not offer any added value to the validation.

The comparison between the two classification schemes is based on: (1) an analysis of the frequencies of occurrences of the circulation types on an annual and seasonal basis and the study of the equivalent trends; (2) the percentage of rainfall associated with the circulation types (anticyclonic and cyclonic) annually and seasonally and the study of their equivalent trends; (3) the computation of the monthly SLP values at the grid point closest to the station of Budapest; and (4) the calculation of the correlation coefficients as well as comparative diagrams of the seasonal occurrences of the circulation types of the two classification schemes.

3 Results

3.1 Annual and seasonal occurrence of the anticyclonic and cyclonic types in the two classifications

According to the objective methodology of Anagnostopoulou et al. (2009), the circulation types over Hungary were classified at a geopotential height with 1000 hPa (Fig. 2). Similarly, mean sea-level air pressure maps of the subjective empirical weather types for the North-Atlantic–European area were also produced (Fig. 3).

The frequency of both the cyclones and anticyclones differ substantially on an annual basis for the seasons. For the objective Maheras types, the occurrence of anticyclones (cyclones) on an annual basis is 49.6% (50.4%) (Table 1), while for Péczely types it is 66.1% (33.9%) (Table 2). Season-wise, the frequency ratio of the extreme pressure formations for the two classifications is as follows. For the automated (Maheras) classification, the occurrence of the cyclonic (anticyclonic) types is in winter 60.9% (39.1%), in spring 58.0% (42.0%), in summer 35.3% (64.7%) and in autumn 47.9% (52.1%) (Table 1). At the same time, for the empirical (Péczely) classification, the cyclonic (anticyclonic) types occur in the following ratios: winter 34.5% (65.5%), spring 40.7% (59.3%), summer 29.9% (70.1%), and autumn 30.5% (69.5%) (Table 2).

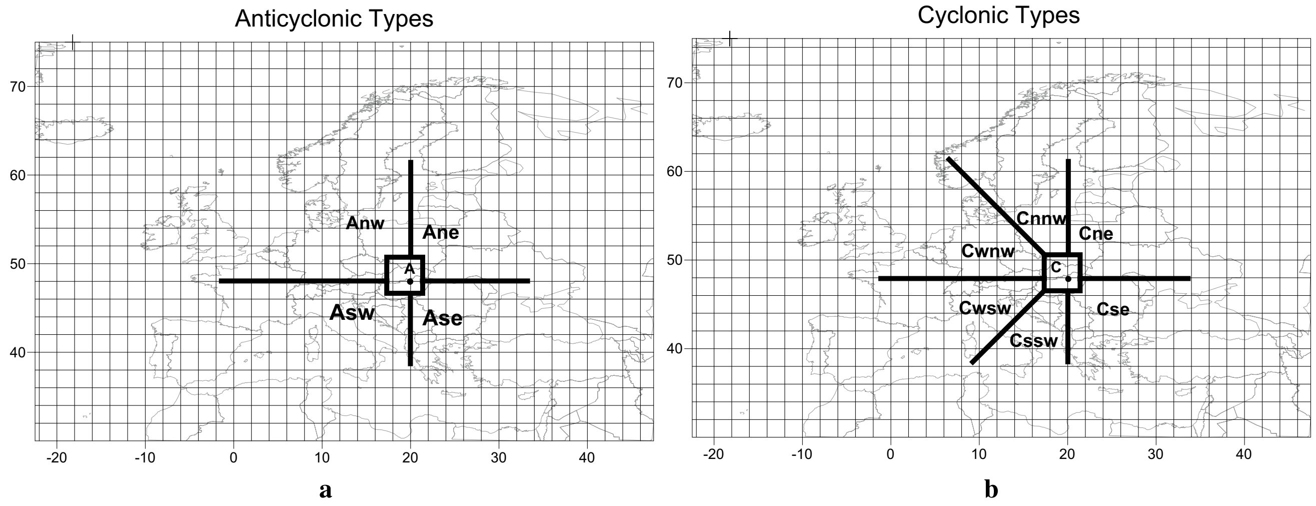


Fig. 1 Geographical location of the centre of the classification and the position of the anticyclonic and cyclonic types (objective Maheras types)

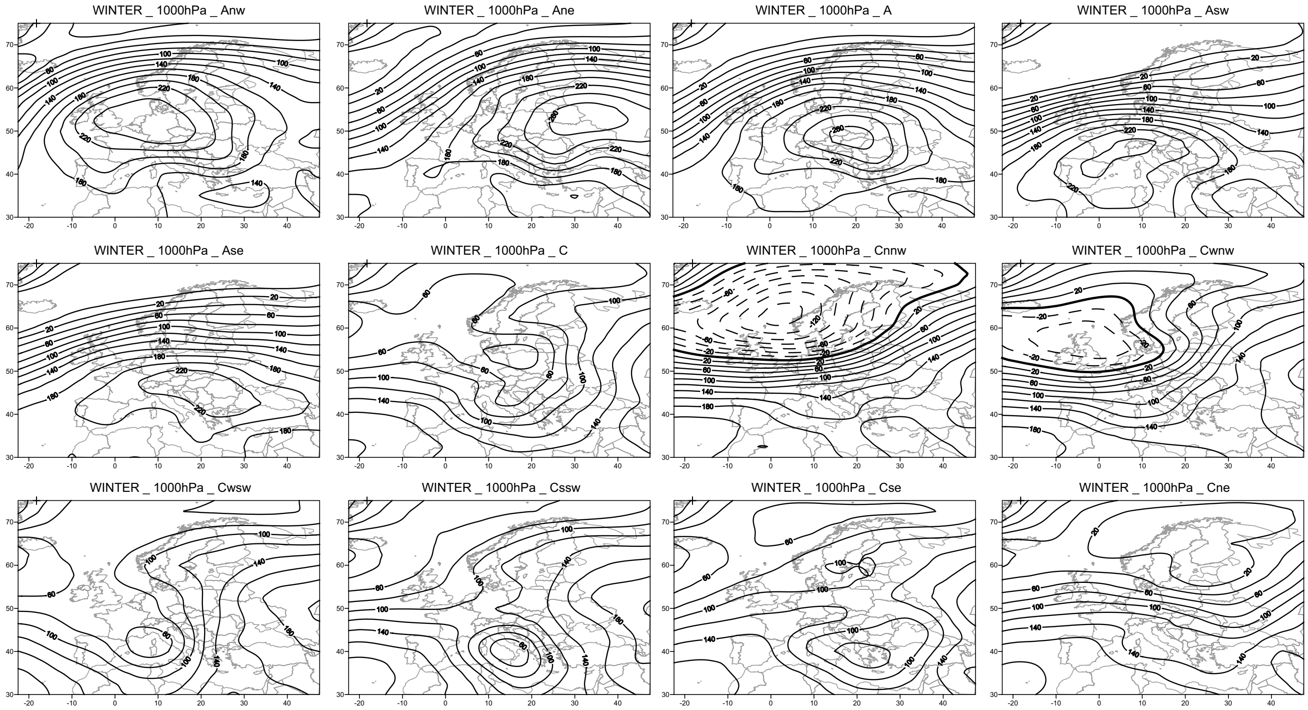


Fig. 2 Mean 1000 hPa absolute topography maps of the objective (Maheras) circulation types (in metres) for winter

As a result, the highest difference between the two classification systems can be experienced in winter (26.4%), while the smallest in summer (5.4%) (Tables 1, 2).

When performing the objective classification, among the anticyclonic types the A_{SE} type is the most frequent (11.9%), which is followed by the type A_{SW} (10.6%), on an annual basis. While among the cyclonic types, the C_{NE} and C_{SE} types occur most with ratios 12.3 and 10.7%, respectively (Table 1; Fig. 1). As regards the empirical (Péczely) classification, the Aw type is the most frequent (14.6%), followed by the Ae type (12.6%) on an annual basis. At the same time, among the cyclonic types mCc and mCw occur most with ratios (9.7%) and (7.9%), respectively (Table 2).

In winter, for the objective classification the anticyclonic A_{NW} type is the most frequent (9.1%), followed by the A_{SW} and A_{SE} types with 8.3 and 8.1%, respectively. Among the cyclonic types C_{NE} occurs the most (16.1%), at almost double the frequency of the A_{NW} type, while the C_{SE} type is ranked second (13.4%) (Table 1; Fig. 1). As regards the empirical classification, among the anticyclonic types Ae (14.2%) and Aw (13.1%) are the most frequent, while among the cyclonic types mCw (9.2%) and CMw (8.9%) are the most frequent (Table 2; Fig. 3). In spring, for the automated classification, there is a change in the occurrence ratio of the types compared to winter. Among the anticyclonic types, A_{NE} (9.3%) is ranked first, followed by the A_{NW} type (9.0%), while for the cyclonic types C_{NE} (15.1%) and C_{SE} (11.9%) are the most frequent (Table 1; Figs. 1, 2). According to the empirical classification the anticyclonic types An (12.8%) and Ae (11.3%) occur most often (Table 2; Fig. 3). In summer, according to the objective classification, in decreasing order the anticyclonic types A_{NE} (15.7%), A_{SW} (15.4%) and A_{SE} (15.4%) (Figs. 1a, 2), as well as the cyclonic types C_{NE} (8.3%) and C_{WSW} (6.6%) are the most frequent (Table 1; Figs. 1b, 2). For the empirical classification, the anticyclonic types Aw (20.8%) and A (13.3%) occur most. At the same time the most frequent cyclonic types are mCc (12.1%) and mCw (5.7%) (Table 2; Fig. 3). In autumn, according to the automated classification the anticyclonic types A_{SE} (16.7%) and A_{SW} (10.3%) (Figs. 1a, 2) are the most frequent, while for the cyclonic types C_{SE} (11.0%) and C_{NE} (9.1%) are the most frequent (Table 1; Figs. 1b, 2). The empirical classification provides the majority of anticyclonic Ae (17.6%) and A (13.3%), as well as the cyclonic CMw (8.3%) and mCc (8.0%) (Table 2; Fig. 3).

Trends in the occurrence of the objective (Maheras) and manual (Péczely) circulation types display significant differences both on an annual and seasonal basis (Table 3). The trends were calculated using the Mann–Kendall test at a significance level of 95%. For the objective classification, except for autumn, the frequency of the anticyclonic (cyclonic) types has a statistically significant increasing (decreasing) trend (with a 5% probability level). In the autumn, though the sign of the trends is the same, they are not significant. As for the empirical classification on an annual basis, the anticyclonic (cyclonic) types have

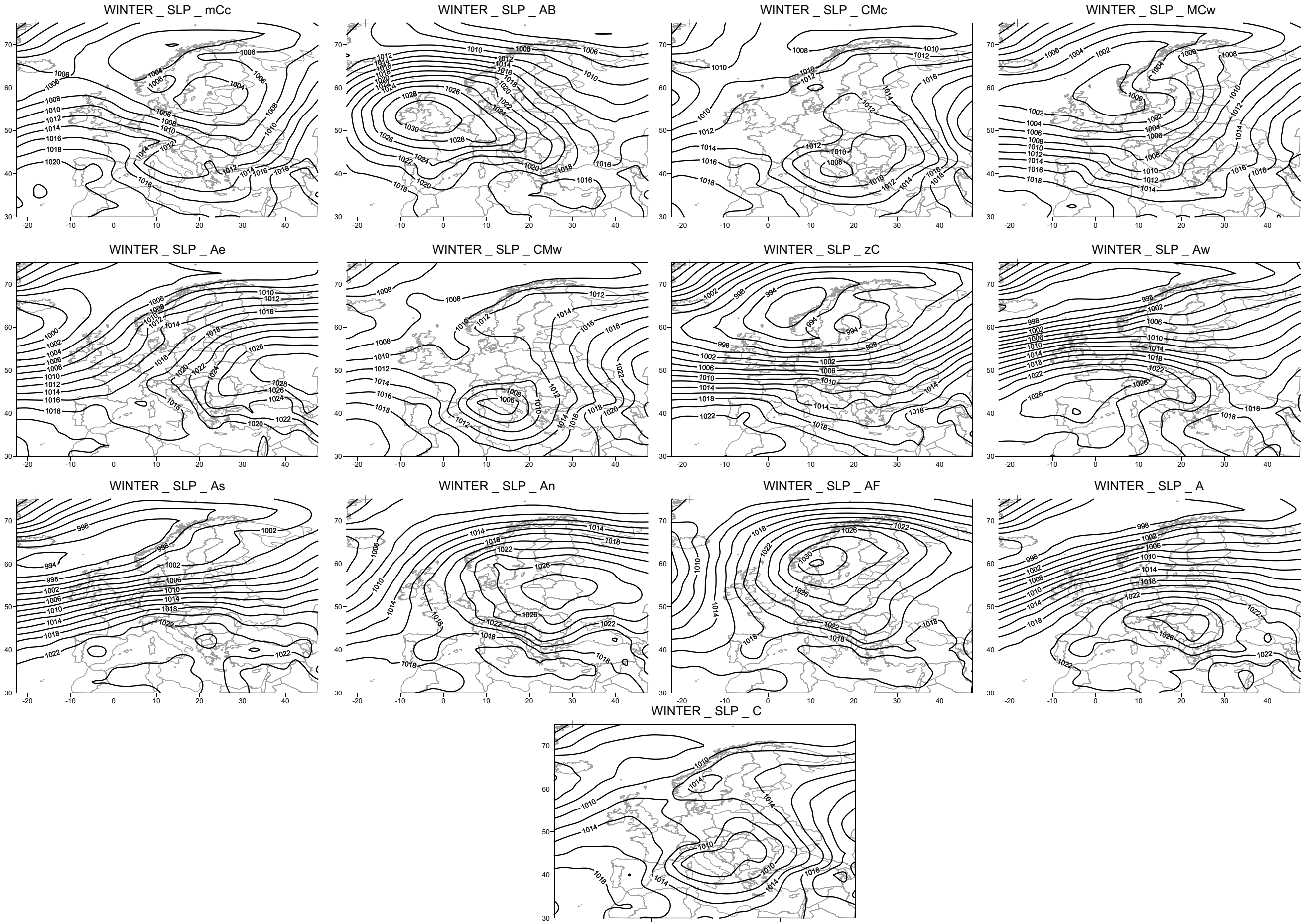


Fig. 3 Mean sea-level pressure maps of the empirical (Péczely) types (in millibars) for winter

Table 1 Seasonal occurrences of the objective (Maheras) circulation types over Hungary and the annual precipitation (%) in Budapest, according to the types, 1958–2010

Code	Type	Description	Occurrence, %				Annual frequency	Annual precipitation, %[a]
			Winter	Spring	Summer	Autumn		
1	A_{NW}	Anticyclone centre over Northwest Hungary	9.1	9.0	8.6	10.2	9.3	4.1
2	A_{NE}	Anticyclone centre over Northeast Hungary	6.2	9.3	15.7	8.4	9.9	7.0
3	A	Anticyclone centre over Hungary	7.4	7.9	9.6	6.5	7.9	1.8
4	A_{SW}	Anticyclone centre over Southwest Hungary	8.3	8.2	15.4	10.3	10.6	4.1
5	A_{SE}	Anticyclone centre over Southeast Hungary	8.1	7.6	15.4	16.7	11.9	5.6
6	C	Cyclone centre over Hungary	5.9	8.6	5.6	6.2	6.5	16.5
7	C_{NNW}	Cyclone centre over North, Northwest Hungary	5.0	3.6	1.9	3.9	3.5	3.6
8	C_{WNW}	Cyclone centre over West-, Northwest Hungary	7.0	6.2	4.0	4.7	5.4	9.9
9	C_{WSW}	Cyclone centre over West, Southwest Hungary	10.3	8.0	6.6	8.9	8.4	16.7
10	C_{SSW}	Cyclone centre over South, Southwest Hungary	3.2	4.6	3.1	4.1	3.6	8.7
11	C_{SE}	Cyclone centre over Southeast Hungary	13.4	11.9	6.0	11.0	10.7	11.4
12	C_{NE}	Cyclone centre over Northeast Hungary	16.1	15.1	8.3	9.1	12.3	10.6

[a] See last row in Table 5

Table 2 Seasonal occurrences of the empirical (Péczely) circulation types over Hungary and the annual precipitation (%) in Budapest, according to the types, 1958–2010

Code	Type	Description	Occurrence, %				Annual frequency	Annual precipitation, %[a]
			Winter	Spring	Summer	Autumn		
1	mCc	A cyclone with a cold front over Northeast Europe, northern wind	7.3	11.3	12.1	8.0	9.7	12.5
2	AB	An anticyclone over the British Isles, northern wind	5.6	7.1	8.6	6.4	6.9	4.3
3	CMc	A Mediterranean cyclone with a cold front over Southern Europe, northern wind	2.5	3.5	1.8	1.9	2.4	3.3
4	mCw	A Mediterranean cyclone with a warm front over Northeast Europe, southern wind	9.2	9.7	5.7	7.2	7.9	16.4
5	Ae	An anticyclone over Eastern Europe, southern wind	14.2	11.3	7.3	17.6	12.6	8.2
6	CMw	A Mediterranean cyclone with a warm front over Southern Europe, southern wind	8.9	8.7	3.7	8.3	7.4	19.9
7	zC	A highly developed cyclone over Northern Europe, western wind	5.0	3.2	2.7	2.9	3.5	4.0
8	Aw	An anticyclone over Western Europe, western wind	13.1	11.2	20.8	12.8	14.6	6.9
9	As	An anticyclone over Southern Europe, western wind	7.0	4.4	2.9	5.6	4.9	2.4
10	An	An anticyclone over Northern Europe, eastern wind	10.9	12.8	11.3	10.1	11.3	7.7
11	AF	An anticyclone over Fennoscandia, eastern wind	2.8	5.2	5.9	3.7	4.4	2.9
12	A	An anticyclone over the Pannonian Basin, changing wind direction	11.8	7.3	13.3	13.3	11.4	3.0
13	C	A cyclone over the Pannonian Basin, changing wind direction	1.7	4.3	3.9	2.2	3.0	8.4

[a] See last row in Table 6

Table 3 Trends of the cyclonic and anticyclonic types for the two classifications for 1958–2010

Period	Automated (Maheras) classification		Subjective (Péczely) types	
	Anticyclone	Cyclone	Anticyclone	Cyclone
Winter	+	–	–	+
Spring	+	–	+	–
Summer	+	–	+	–
Autumn	+	–	–	+
Year	+	–	–	+

The shaded symbols indicate statistically significant trends at the 5% probability level

decreasing (increasing) trends; however, they are not significant. Among the seasons, statistically significant trends occur only in the autumn: anticyclonic types show decreasing trends, while the cyclonic types have an increasing frequency. In the winter, negligible trends occur and this is the case for the spring as well. In the summer the occurrence of the anticyclonic types displays positive trends, while the cyclonic types display negative trends; however, both are not significant (Table 3).

Based on the two classification systems, correlation coefficients of the annual and seasonal occurrence of the circulation types were calculated partly for the cumulated cyclonic/anticyclonic types and partly for the individual types. Table 4 shows only those pairwise circulation types compared for the two classifications for all four seasons, for which the correlation coefficients are statistically significant at the 5% probability level. A positive correlation coefficient between the anticyclonic or cyclonic types of the two classification schemes may be interpreted as the linear correlation of the frequency time-series of the two schemes. This means that an increase in the frequency of the anticyclonic types of the one scheme is associated with a relative increase in the frequency of the anticyclonic types of the second scheme. The opposite case occurs when the correlation coefficients are negative, namely when the increase in the frequency of the anticyclonic types of the one scheme is associated with a decrease in the cyclonic types of the other scheme. Two rather complicated examples of correlation coefficients are presented below. To interpret the positive correlation coefficient between the cyclonic type C_{SE} and the empirical An for the winter season, we computed the mean composite map for the days where the two types appear simultaneously. It was found that An (the anticyclonic type of the

Table 4 Statistically significant correlations (|r| > 0.40, at the 5% probability level) between the objective and the empirical classifications

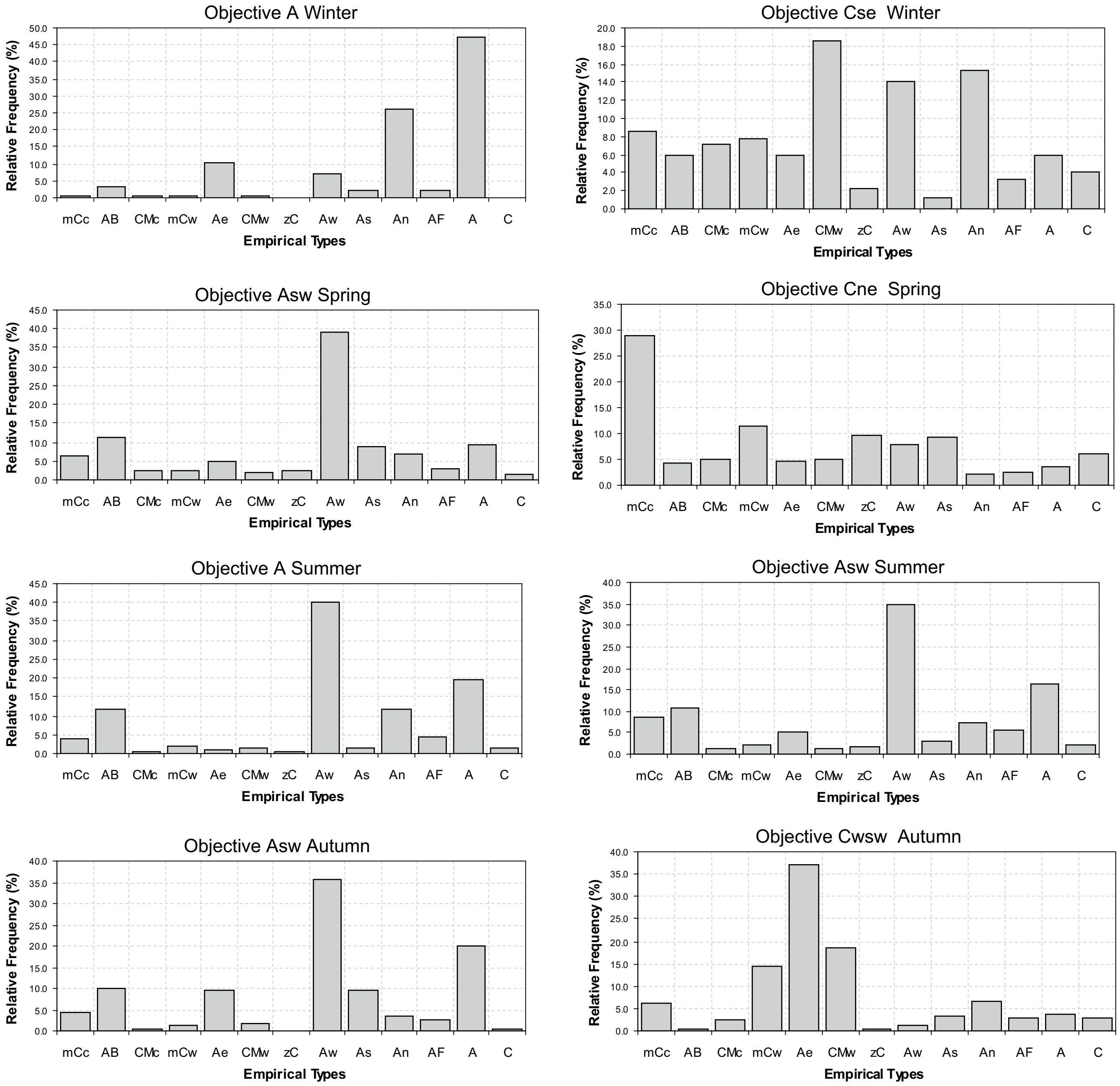
Year/season	Maheras	Péczely	Correlation coefficients
Year	Anticyclonic	Anticyclonic	0.49
	Cyclonic	Cyclonic	0.49
Winter	Anticyclonic	Anticyclonic	0.74
	Cyclonic	Cyclonic	0.74
	A_{NW}	AB	0.53
	A_{NE}	Ae	0.63
	A	A	0.69
	A_{SW}	Aw	0.54
	A_{SE}	A	0.55
	C	CMw	0.55
	C_{WNW}	mCw	0.62
	C_{WSW}	CMw	0.54
	C_{SE}	An	0.56
Spring	Anticyclonic	Anticyclonic	0.62
	Cyclonic	Cyclonic	0.62
	A_{NE}	Ae	0.46
	A	A	0.42
	A_{SW}	An	−0.58
	C_{WNW}	mCw	0.48
	V_{WSW}	CMw	0.53
	C_{SSW}	CMw	0.48
	C_{SE}	CMw	0.43
Summer	Anticyclonic	Anticyclonic	0.46
	Cyclonic	Cyclonic	0.46
	A_{NW}	AB	0.44
	C	mCw	0.44
	C_{WNW}	mCw	0.44
	C_{NE}	zC	0.64
Autumn	Anticyclonic	Anticyclonic	0.69
	Cyclonic	Cyclonic	0.69
	A	A	0.41
	A_{SE}	mCw	−0.47
	C	mCw	0.42
	C_{WNW}	mCw	0.41
	C_{WSW}	mCw	0.41
	C_{SE}	mCw	0.53

empirical classification) has a centre over the east and it is expanding to the west, while over its southern part it creates cyclogenesis with a centre over the Balkans that covers the Mediterranean region and Hungary. In the empirical classification this circulation is anticyclonic An, while for the automatic classification it is C_{SE}. The geopotential anomalies over Hungary are negative; hence change in the frequency of An results in the change of C_{SE}. For an interpretation ($r = -0.58$) between the A_{SW} (objective) and the An (empirical) in the spring season, we computed the equivalent mean composite maps. It was found that this time, the anticyclone has its centre at the NW of Hungary, between the British Isles and Scandinavia, and it extends to the south, creating a secondary anticyclonic centre at the southwestern part of Hungary. In the objective classification this is the centre identified by the software package, since it is much closer to the region of investigation. The negative correlation is explained by the fact that the increase in the A_{SW} results in a decrease in An, and vice versa. The highest correlations occur in the winter season, when—compared to the remaining seasons—the weather-influencing effect of the atmospheric circulation is the most prevalent. The highest correlation coefficient between the cyclonic and anticyclonic types of the two classifications also occurs in the winter season ($r = 0.74$). It is followed by the winter correlations between the A types ($r_{max} = 0.69$). Only these A types result in high correlations in the remaining seasons (spring: $r = 0.42$, autumn: $r = 0.41$), except for the summer. High correlations occurred between A_{NE} and Ae ($r = 0.63$), as well as between C_{WNW} and mCw ($r = 0.62$) in the winter and between C_{NE} and zC ($r = 0.64$) in the summer.

To better understand the association between the two classification systems, the seasonal occurrence of every circulation type was calculated for both classifications. In other words, we calculated how many given empirical types occur during the existence of an objective type. The results are presented in seasonal diagrams (Fig. 4). It was found that we could match a rarely or frequently occurring anticyclonic or cyclonic empirical type with each automated type. Since the analysis of the pairwise matching of the seasonal occurrence of the circulation types resulted in lots of diagrams, only those with the highest occurrence of a given empirical type during the existence of an automated type are presented here. In the winter, the anticyclonic type A (Table 1) of the objective classification displays the closest relationship with the empirical types. During the existence of the objective type A, the empirical type A occurs most frequently (45%), while the empirical type An (25%) is the second most frequent. For the same season, during the existence of the objective types (C_{SE}) a wide spectrum of the empirical types with relatively high occurrence can be observed.

In the spring, the highest concentration of the empirical types occurs during the existence of the objective type A_{SW}, when the predominance of the empirical type Aw has a frequency of 41%. Furthermore, the second highest concentration of the empirical types occurs when, during the existence of the objective type C_{NE}, an extreme high frequency of the empirical type mCc (29%) occurs (Fig. 4).

In the summer, two examples are presented for the highest concentrations of the empirical types during the occurrence of a given objective type. During the existence of the objective types A and Asw the frequency distribution of



Objective A Winter

Objective Cse Winter

Objective Asw Spring

Objective Cne Spring

Objective A Summer

Objective Asw Summer

Objective Asw Autumn

Objective Cwsw Autumn

Fig. 4 Comparison of the frequency occurrences of the objective (Maheras) classification (see Table 1) with those of the empirical (Péczely) types (see Table 2) for all four seasons

the empirical types is almost the same. For both cases the occurrence of the empirical type Aw is the most frequent, reaching 40 and 35% during the existence of the objective types A and A_{SW}, respectively (Fig. 4).

In the autumn, the highest concentrations of the empirical types occur during the existence of the objective type A_{SW}. At the same time, the objective type C_{WSW} is closely associated with the empirical type Ae (37%) (Fig. 4).

Intercomparison of the Maheras objective types (Maheras et al. 2000a, b), the Péczely empirical types (Péczely 1957b, 1961, 1983) and the Makra objective types (Makra 2006; Makra et al. 2009) was performed concerning the frequency (in percentage) of the anticyclonic and cyclonic situations for every season. Altogether pairwise comparisons occurred regarding the three different classification types. The χ^2 test homogeneity analysis showed no significant difference between the pairwise comparisons, which means that each of the three classifications behaves in the same way when classifying the seasonal occurrences of these extreme air pressure formations (anticyclonic and cyclonic weather situations). However, we should note that the analysis concerning the Makra objective types (1) restricted only to the extreme seasons (winter and summer), (2) covered just a 5-year period 1997–2001, without a joint study period of the analysis of the current paper; and (3) neglected an analysis of precipitation (Makra 2006; Makra et al. 2009).

3.2 Circulation types and precipitation in Budapest

To further evaluate the circulation types ratios, precipitation amounts measured in Budapest were calculated for both classification systems and all circulation types, on an annual and seasonal basis (Tables 5, 6). As regard the objective classification, cyclonic types are responsible for 77.4% of the annual precipitation, while anticyclonic types account for 22.6%. The wettest of all cyclonic types are C_{WSW} (16.7%) and C (16.5%). Furthermore, substantial amount of the measured precipitation amounts may be associated with the C_{SE} type (11.4%), while the types responsible for the south winds occur more rarely and also cause significant amounts of rainfall (C_{WNW} 9.9% and C_{SSW} 8.7%).

In the winter, the heaviest rainfalls take place during the occurrence of cyclonic types (94.2%), while anticyclonic types have the smallest precipitation (5.8%). Among cyclonic types, C_{WSW} (23.4%) and C_{WNW} (18.2%) are the most rainfall sensitive, followed by C (15.7%), C_{NE} (13.4%), C_{SE} (9.6%) and C_{NNW} (8.2%), respectively (Table 5). The share of the spring rainfall due to cyclonic types is ranked third in decreasing order (82.2%). As a result, the second smallest ratio can be observed for the anticyclonic types (17.8%). The wettest cyclonic type in the spring is C (22.0%) followed by C_{WSW} (14.8%), C_{SE} (13.6%) and C_{NE} (13.2%), in decreasing order. Cyclonic types are characterised by the smallest rainfall during the summer season (57.3%), while it is the highest for the anticyclonic types (42.7%). The wettest cyclonic types in the summer are C_{WSW} (13.7%), C (12.4%), C_{SE} (8.9%) and C_{NE} (8.1%), respectively. However, the wettest anticyclonic type is A_{NE} (15.6%) (Table 5). In autumn, the ratio of occurrence of the cyclonic and anticyclonic types is 83.7 and 16.3%, respectively. The rainiest type in the autumn is C (17.2%), followed by C_{WSW} (16.6%), C_{SSW} (14.3%) and C_{SE} (14.1%), in decreasing order.

Interestingly, on an annual basis substantially smaller precipitation is characteristic for the cyclonic types (64.5%) in the case of the empirical classification (Table 6) compared to that for the objective classification (77.4%) (Table 5). It is clear that the anticyclonic origin precipitation is much higher for the empirical types (35.4%). The wettest cyclonic types in decreasing order are CMw (19.9%), mCw (16.4%), mCc (12.5%) and C (8.4%), respectively (Table 6). In the winter, 67.0% of the total precipitation is associated with the cyclonic circulation types, while the remaining 33.0% is associated with the anticyclonic types. These percentages differ substantially from those of the objective classification (Tables 5, 6). Most of the precipitation is associated with the cyclonic types mCw (25.1%) and CMw (21.6%), while the wettest anticyclonic type is Ae (12.9%) (Table 6).

Table 5 Precipitation amount on a seasonal and annual basis in the individual circulation types and their anticyclonic and cyclonic groups, objective (Maheras) classification, %, 1958–2010

Maheras	A_{NW}	A_{NE}	A	A_{SW}	A_{SE}	C	C_{NNW}	C_{WNW}	C_{WSW}	C_{SSW}	C_{SE}	C_{NE}	Anticyclonic	Cyclonic
Winter	1.4	1.6	0.4	1.4	1.0	15.7	8.2	18.2	23.4	5.7	9.6	13.4	5.8	94.2
Spring	5.0	4.2	1.5	3.5	3.6	22.0	2.5	7.8	14.8	8.3	13.6	13.2	17.8	82.2
Summer	5.5	15.6	2.8	7.6	11.1	12.4	1.6	6.1	13.7	6.6	8.9	8.1	42.7	57.3
Autumn	3.9	3.5	1.9	2.4	4.6	17.2	3.0	9.6	16.6	14.3	14.1	8.9	16.3	83.7
Year[a]	4.1	7.0	1.8	4.1	5.6	16.5	3.6	9.9	16.7	8.7	11.4	10.6	22.6	77.4

[a] See last column in Table 1

Table 6 Precipitation amount on a seasonal and annual basis in the individual circulation types and their anticyclonic and cyclonic groups, empirical (Péczely) classification, %, 1958–2010

Péczely	mCc	AB	CMc	mCw	Ae	CMw	zC	Aw	As	An	AF	A	C	Anticyclonic	Cyclonic
Winter	7.4	1.8	2.9	25.1	12.9	21.6	6.2	6.1	4.1	5.5	0.8	1.8	3.8	33.0	67.0
Spring	14.7	4.8	4.3	14.6	4.5	23.9	2.8	4.7	2.1	7.9	3.7	1.8	10.2	29.5	70.5
Summer	15.5	7.0	2.7	11.2	6.7	9.1	3.4	11.1	1.3	10.6	4.1	5.3	12.0	46.1	53.9
Autumn	11.3	2.4	3.2	17.5	9.3	28.5	3.9	4.5	2.8	5.9	2.3	2.2	6.2	29.3	70.7
Year[a]	12.5	4.3	3.3	16.4	8.2	19.9	4.0	6.9	2.4	7.7	2.9	3.0	8.4	35.4	64.5

[a] See last column in Table 2

In the spring, 70.5% of the total precipitation falls during the cyclonic circulation types and 29.5% during the anticyclonic types. These values, similarly to the winter data, substantially differ from those of the objective classification. The cyclonic types with the highest precipitation amounts in decreasing order are CMw (23.9%), mCc (14.7%), mCw (14.6%) and C (10.2%), respectively. At the same time, the anticyclonic type is An with the highest precipitation (7.9%) (Table 6; Fig. 3).

In the summer, for the cyclonic types, similar to the objective classification, precipitation is the smallest of all four seasons (53.9%). More precisely, the highest rainfall amounts in decreasing order are associated with the types mCc (15.5%), C (12.0%), mCw (11.2%) and CMw (9.1%), respectively. However, the amount of rainfall is the highest of all four seasons during anticyclonic types (46.1%). The most sensitive anticyclonic types to precipitation are Aw (11.1%) and An (10.6%) (Table 6).

In the autumn, cyclonic types are the rainiest (70.7%), while anticyclonic types are the driest (29.3%). These values again substantially differ from those associated with the objective classification. Among the cyclonic types the wettest one is CMw (28.5%) and this ratio is the highest of all types, during all four seasons and for both classifications. In addition, other wet types are mCw (17.5%) and mCc (11.3%). As for the anticyclonic types, Ae (9.3%) is the wettest one (Table 6).

4 Discussion and conclusions

When comparing the quite different automated (objective) and empirical (subjective) classification methods (the latter dates back to the end of the 19th century) of circulation types for the Pannonian basin, it was found that the frequency of the empirical anticyclonic (cyclonic) types both on an annual and seasonal basis is much higher (lower) than that for the objective anticyclonic (cyclonic) types. This can be partially attributed to the fact that different methods were employed for the two classification schemes.

Taking into account the fact that the daily anomaly values are computed for each month separately using the mean monthly geopotential heights at the 1000 hPa level for the period 1971–2000, it becomes apparent that if the monthly average of the geopotential values of 9 grid points, used in the classification scheme, is high (for example, during winter), then the classification scheme probably will include more cyclonic types than in the case where the monthly average of the anomalies of the 9 grid points was low (e.g., during the summer). As regard the manual methods, the type depends upon the subjective judgement of the classifier. For this reason, they can become subjectively excessive. For example, different researchers will not necessarily agree on the classification of a given day. Another possibility is the high likelihood for artefacts caused by changing classifiers, which at least is the case for the empirical typing applied here (Péczely 1961, 1983; Károssy 2016). In addition, the empirical classification is not the best way of separating different situations from each other, since there is frequently a smooth gradual transition from one situation to another (Philipp et al. 2010), especially for the slack pressure fields over Hungary with a frontal passage. The highest geopotential values at a height corresponding to an air pressure of 1000 hPa occur in winter, when the differences in these values are the highest between the anticyclonic and the cyclonic types for both classifications (Table 7). Bartholy et al. (2009) mentioned in their study the differences in the behaviour of the frequencies of the anticyclonic and the cyclonic types between winter and summer. Moreover, according to their results during the negative NAO phase, the cyclonic types are more frequent, while during the positive phase of the index the anticyclonic types present a higher frequency of occurrence.

Analysing daily precipitation amounts of Budapest on an annual and seasonal basis, the highest amounts—regardless of the classification used—are associated with the prevalence of certain circulation types: for the objective classification these are the C, C_{WSW}, C_{SE} and C_{NE} types, while for the empirical classification they are the CMw, mCw, mCc and C types. This result is consistent with the analysis of Mika (2014), which shows that for the Péczely classification the highest average precipitation totals are accompanied with the cyclonic types CMw, mCw and C. Overall, for the objective classification, cyclonic (anticyclonic) types are responsible for 77.4% (22.6%) of the total annual precipitation. In contrast, for the empirical classification, these ratios are 64.5 and 35.5% for the cyclonic and anticyclonic types, respectively. The possible reason for the observed difference in the total precipitation between the two classifications on an annual and seasonal basis is that the cyclonic types are much

Table 7 Monthly mean values of the 1000 hPa absolute topography (objective classification) and the sea-level air pressure (empirical classification), ($\varphi = 47.5°$N, $\lambda = 20.0°$E)

Pressure surfaces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1000 hPa (m)	165.8	150.9	135.8	112.2	121.5	122.9	126.5	130.2	147.9	159.3	149.8	154.6
SLP (mb)	1019.8	1018.0	1016.2	1013.2	1014.2	1014.0	1014.2	1014.7	1017.0	1018.8	1017.7	1018.4

more frequent for the objective classification compared to the empirical one.

After having calculated the correlation coefficients between the occurrences of the circulation types of the two classifications, it was found that the highest and statistically significant correlations between the cumulated seasonal anticyclonic and cyclonic types occur in the winter for both classifications. Though significant correlation coefficients also occur in the remaining seasons, they do not attain the high values calculated for the winter. Possible reasons for this are: (1) differences in the classification methods as analysed above, (2) different measurement levels (geopotential values a height corresponding to an air pressure of 1000 hPa) and the surface level, and (3) possible errors in the classification methods resulting from their deficiencies. Finally, after having compared the occurrences of all circulation types of the objective and empirical classifications, we established that there occur types in a given classification that are usually accompanied by high ratios of certain types in the other classification.

Overall, the authors believe that both classification schemes not only have some significant advantages, but also some drawbacks. One of the key advantages of the empirical classification scheme is that it consists of a rather small number of circulation types (13) and so it is relatively easy to comprehend and interpret the results. Moreover, due to the fact that the calendar of this classification scheme was developed for a very large time period (1883–the present), it may be a beneficial tool for the study of the atmospheric circulation over the Pannonian basin over many years. Another important aspect is that these 13 types were placed into five main groups according to the flow direction of air masses into the Pannonian basin. The drawbacks of this approach are mostly associated to the fact that even though the frequencies of the cyclonic types display a positive trend, the precipitation amounts display a negative trend. Furthermore, although the anticyclonic types on the whole display a negative trend, the trend of the SLP level values is positive. Despite the empirical shortcomings, both classifications provide a remarkably good reproduction of the current climate statistics for monthly and regional scale climatic features.

Regarding the objective classification scheme, its advantages can be summarised as follows:

1. It can reproduce the wind fluxes at both different heights and at the surface, as well as the expected weather conditions over the domain of interest.
2. The trends of the anticyclonic and cyclonic types are in accordance with the precipitation trends in Budapest, as well as with the trends of SLP and geopotential values at a height corresponding to a pressure of 1000 hPa. These findings are in agreement with the results for Europe (Kyselý and Huth 2006) and for Eastern Europe (Bartoszek 2017).

At the same time, the drawbacks of the objective classification are as follows:

1. The classification scheme is applied each time for one geographically limited region and the same classification cannot be applied to a neighbouring region.
2. The scheme is quite susceptible to any changes in the geopotential values due to regional geographical factors.

In a future study, the authors would like examine the mean and extreme precipitation in Hungary to ascertain whether there is any statistical connection with the objective classification of the circulation types.

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