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Trends in frequency and persistence of atmospheric circulation types over Europe derived from a multitude of classifications

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ABSTRACT: The aim of this study is to quantify changes of atmospheric circulation over Europe using a large number of classifications of circulation types that were collected and developed within the COST733 Action 'Harmonisation and Applications of Weather Types Classifications for European Regions'. Circulation changes over Europe are studied in terms of changing seasonal frequency and persistence of daily circulation types in the period September 1957–August 2002. The extensive collection of both subjective and objective (computer-assisted) catalogues of circulation types in 12 European domains serves as a platform for comparison of different classification methods, varying numbers of circulation types, sequencing of input sea-level pressure data, and spatial scale of circulation processes. The overall picture of frequency and persistence trends is consistent with two large-scale tendencies: strengthening and eastward shift of the North Atlantic Oscillation, and a northwestward shift of storm tracks. There is, however, a limited consistency in the trends between individual classifications. This inconsistency leads us to the recommendation that results of climatological analyses based on a single classification should not be generalized and overinterpreted; it is highly advisable to simultaneously use multiple, and as many as possible, classifications in climatological studies.

KEY WORDS atmospheric circulation; classification; circulation type; trend; persistence; Europe; COST733cat

1. Introduction

Atmospheric circulation is one of the key factors influencing local weather and climate. Circulation changes are a crucial part of the ever-changing climate system, as they both reflect and affect local climatic trends. One of the ways to study atmospheric circulation over a given area is through classification of fields of variables defining atmospheric circulation [e.g. sea-level pressure (SLP) or geopotential heights] into distinct patterns – circulation types (CTs).

Europe has a long tradition of classifying atmospheric circulation for various purposes. Both subjective and objective circulation classification schemes have been developed in different European regions – e.g. Hess and Brezowsky (1952), Péczely (1957), Lund (1963), Jenkinson and Collison (1977), Huth (1996), Esteban *et al.* (2005), Beck *et al.* (2007), and Philipp *et al.* (2007). An extensive review of existing CT classifications and their applications was provided by Huth *et al.* (2008).

The catalogues of daily CTs have served, among others, as a tool to study regional long-term changes of atmospheric circulation. Stefanicki *et al.* (1998) studied trends in the seasonal frequency and persistence of CTs in the Swiss subjective catalogue of Schüepp (1979) in the period 1945–1994. They note an increasing frequency of the high-pressure type and a decreasing frequency of the northerly type in winter. These trends were caused by changing duration of the respective synoptic situations (i.e. increasing and decreasing persistence, respectively), while their total number per season remained unchanged.

The German subjective Hess-Brezowsky catalogue (Hess and Brezowsky, 1952; Werner and Gerstengarbe, 2010), available from 1881, has been used many times to study circulation and climatic changes in Europe, e.g. by Bárdossy and Caspary (1990), Werner *et al.* (2000), Kyselý and Domonkos (2006), and Kyselý and Huth (2006). All these studies note a growing occurrence of the westerly CTs in winter from the 1960s to the early 1990s, with a concomitant decrease of occurrence of the cold meridional types. These trends were also found in an objective circulation classification and an analysis of modes of variability in Kyselý and Huth (2006). Werner *et al.* (2000) detected an increase in the persistence of the group of westerly CTs in the Hess-Brezowsky classification in winter in the decade 1981–1990, which was also confirmed by a similar trend in one objective classification. Kyselý and Domonkos (2006) found

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increasing persistence of most groups of CTs in most seasons since the 1970s with a major change point in the mid-1980s. None of these studies considered a possible inhomogeneity in the Hess-Brezowsky subjective catalogue as a cause of the trends because it had been claimed homogeneous by Gerstengarbe *et al.* (1999). First doubts about the homogeneity of subjective classifications were raised by Stehlík and Bárdossy (2003). Later on, Kyselý and Huth (2006) ascribed the observed discrepancy between an objective classification and the Hess-Brezowsky catalogue – unrealistically high trends of persistence in the latter – to a different methodology used in the Hess-Brezowsky catalogue where all synoptic situations are set to be at least 3 days long. Cahynová and Huth (2009) uncovered that a sudden increase in persistence occurred in the Hess-Brezowsky classification between 1985 and 1986, that the reason for the increase is that 3-day long situations almost disappeared after 1985, and that such a shift was not present in a handful of objective classifications computed over Europe and four selected European regions. These facts led Cahynová and Huth (2009) to conclude that the increase in persistence in the Hess-Brezowsky classification was likely artificial.

The analysis of the objective classification, using the SANDRA (Simulated ANnealing and Diversified RAndomization clustering) algorithm, of daily reconstructed SLP patterns in the period 1850–2003 by Philipp *et al.* (2007) indicates a pronounced decadal to multi-decadal variability and several long-term trends in the seasonal frequency of individual CTs. In winter, a type resembling the positive phase of the North Atlantic Oscillation (NAO) was abundant between 1850 and 1870 and again since 1985, but no overall trend was detected. Another westerly type connected with a cyclonic activity north of the British Isles shows a significant increase in winter frequency. In spring, there is an increase of blocking highs over Europe and a decrease of types with cyclones in eastern Scandinavia. In summer, the warm type with an anticyclone centred over Europe underwent major long-term fluctuations, with maxima until 1875, during the 1930s, and since about 1980. Autumn shows the least pronounced interdecadal variability, but there are some long-term trends: a decline of strengthened and/or westward extended Russian high, and an increase of southerly shifted Russian highs.

In this study, we present a thorough analysis of long-term changes in atmospheric circulation, namely in the frequency and persistence of CTs, over Europe in the second half of the 20th century, using a data set of CT classifications ‘COST733cat’, version 2.0 (Philipp *et al.*, 2010, 2016). By using this wide collection of classifications, we are able to answer whether the frequency and persistence of CTs has changed over Europe and for which types, without being biased by properties of a single (or a few of) method(s). Since Beck and Philipp (2010) showed that even minor variations in the classification procedure might have a great effect on the properties of the resulting classifications, we also explore how different parameters of the classification methods affect the trends.

This article is organized as follows: In Section 2, classifications of CTs and methods used to study them are described. Details on the nomenclature of CTs are presented in the Appendix. Section 3 contains results of the analysis of the frequency of CTs, while results for the persistence of CTs are described in Section 4. Section 5 discusses our results with one another, as well as with previously published works, draws main conclusions, and puts forward recommendations for potential users of CT classifications.

2. Data and methods

In this study, we analyse circulation classifications selected from the ‘COST733cat’ data set, version 2.0 (Philipp *et al.*, 2016). Seventy-eight objective classifications are analysed in each of 12 domains. One domain (D00) is large and covers most of the Euro-Atlantic region, while 11 regional domains (D01–D11) are located over specific European regions, in total covering the whole of Europe (Figure 1). The objective classifications were produced by 15 different classification methods (Table 1) with SLP as a classified variable, which was taken from the ERA-40 reanalysis (Uppala *et al.*, 2005). Each objective method produces classifications with three different numbers of types, which are equal or close to 9, 18, and 27.

Four objective methods (GWT, JCT, LIT, and KIR; the abbreviations of methods are explained in Table 1) classify only instantaneous daily SLP patterns, while the remaining 11 methods (KRZ, PXE, PCT, PTT, LND, ERP, CKM, CAP, PXK, SAN, and RAC) were applied both to instantaneous daily patterns and to 4-day sequences of daily SLP patterns consisting of the given day and 3 preceding days. These variants are denoted S01 and S04, respectively. All the classification procedures were performed on data from the whole year. For more details on the classification methods, see Philipp *et al.* (2010, 2016).

In addition to the objective classifications, six subjective (manual) classifications, each focusing on a part of central Europe (GWL with ten types, GWL with 29 types, PEC, PER, SUE, and ZMG), and one computer-assisted classification with subjectively pre-defined types (OGW), designed for broader central Europe, are included in our analysis. All days are classified with one of the CTs in all classifications except for the subjective Hess-Brezowsky (GWL) classification, which contains a minor proportion of unclassified days (1.1% in the study period).

The analysis is conducted for the period for which the ERA-40 reanalysis is available, that is, from September 1957 to August 2002. Individual seasons [spring – MAM (March, April, and May), summer – JJA (June, July, and August), autumn – SON (September, October, and November), and winter – DJF (December, January, and February)] are analysed separately; some results are presented for a year-round analysis as well wherever such an analysis provides an additional insight. The nomenclature of CTs is described in the Appendix.

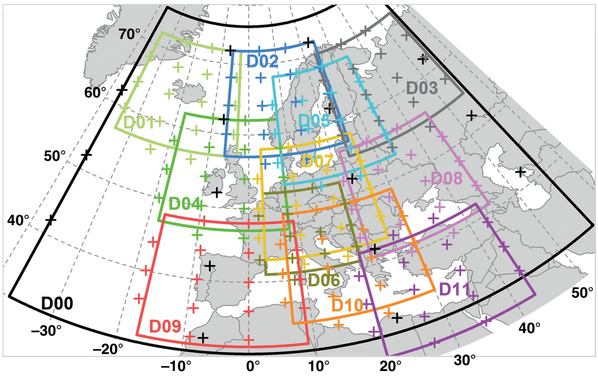

Figure 1. Map of spatial domains used in the COST733 Action for the classification of CTs. Sixteen grid points used to calculate STR, DIR, and VORT indices are also shown for each domain.

Persistence is defined as the length of an uninterrupted sequence of days classified with the same CT (such a sequence is also referred to as 'synoptic situation'). The persistence is studied for all CTs combined, as well as for individual CTs. At the edges of seasons, the synoptic situations are divided into two parts, one belonging to the first season, the other to the second season.

Trends of seasonal averages of CT frequency and persistence are estimated by linear regression using the least-squares method. We use the longest available time series to calculate seasonal trends, i.e. 1957–2001 for SON, 1957/1958–2001/2002 for DJF, and 1958–2002 for MAM and JJA. Trends are only estimated for CTs that occurred in 4 and more years; less frequent CTs are excluded from the analysis. The slope of regression line is multiplied by ten to obtain trend magnitude per decade. Statistical significance of trends is tested by nonparametric Mann–Kendall trend test; trends significantly different from zero at the 5% significance level are further studied. The time series of persistence were tested for sudden shifts using Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986) in the AnClim software (Štěpánek, 2008; Štěpánek *et al.*, 2013).

One of the ways to compare individual classifications is to calculate the correlation of time series of a certain index for all possible pairs of classifications. Here, we calculate Pearson correlation of mean seasonal persistence. The idea is that interannual variation in persistence is a natural feature of atmospheric circulation, and thus should be reflected in every classification method. Anomalously low correlations point to classifications that may not describe the interannual variation of persistence properly.

CTs from the objective classifications were further studied using three quantities describing atmospheric circulation, calculated from SLP under geostrophic approximation: flow strength (STR), flow direction (DIR), and vorticity (VORT). The indices are calculated according to the equations detailed in Jenkinson and Collison (1977), later adopted e.g. by Blenkinsop *et al.* (2009) and Plavcová and Kyselý (2011), using SLP from ERA-40 reanalysis at 1200 UTC from 16 grid points representing each spatial domain (Figure 1). As the domains have different sizes, we unified the values of STR and VORT so that each unit of STR represents a gradient of 1 hPa per 10° latitude at the central latitude, and VORT unit is hPa per 10° latitude squared at

Table 1. Methods of CT classification used in this study. In the 'sequencing' column, S01 (S04) indicates that instantaneous daily patterns (4-day sequences of patterns) were classified. The prescribed number of CTs is given in the last column; note that the real number may be smaller because in some domains and seasons, some of the CTs may be empty. For Hess-Brezowsky classifications, '+1' indicates an additional type comprising unclassified days. For a more detailed explanation of classification methods see Philipp *et al.* (2010).

Abbreviation	Description	Sequencing	Reference	# CTs
GWLo09	Hess-Brezowsky Grosswettertypen	S01	Hess and Brezowsky (1952)	10 + 1
GWLo27	Hess-Brezowsky Grosswetterlagen	S01	Hess and Brezowsky (1952)	29 + 1
OGWo	Objectivised Hess-Brezowsky Grosswetterlagen	S01	James (2007)	29
PECo	Péczely Carpathian Basin weather types	S01	Péczely (1957)	13
PERo	Perret Alpine weather statistics	S01	Perret (1987)	31
SUEo	Schüepp Alpine weather statistics	S01	Schüepp (1979)	40
ZMGo	ZAMG weather types	S01	Lauscher (1985)	43
GWT	Grosswettertypes (GWT) prototype	S01	Beck *et al.* (2007)	8, 18, 27
JCT	Jenkinson–Collinson Lamb weather types	S01	Jenkinson and Collison (1977)	9, 18, 27
LIT	Lityński advection and CTs	S01	Lityński (1969)	9, 18, 27
KRZ	Kruizinga empirical orthogonal function types	S01, S04	Kruizinga (1979)	9, 18, 27
PXE	Principal component analysis extreme scores	S01, S04	Esteban *et al.* (2005)	10, 18, 26
PCT	Obliquely rotated PCA in T-mode	S01, S04	Huth (1996)	9, 18, 27
PTT	Orthogonally rotated PCA in T-mode	S01, S04	Philipp *et al.* (2016)	9, 18, 27
LND	Lund classical leader algorithm	S01, S04	Lund (1963)	9, 18, 27
KIR	Kirchhofer types	S01	Blair (1998)	9, 18, 27
ERP	Erpicum and Fettweis similarity index	S01, S04	Erpicum *et al.* (2008)	9, 18, 27
CKM	K-means cluster analysis by dissimilar seeds	S01, S04	Enke and Spekat (1997)	9, 18, 27
CAP	Cluster analysis of principal components	S01, S04	Yarnal (1993)	9, 18, 27
PXK	PCA-eXtreme scores reassigned by K-means	S01, S04	Esteban *et al.* (2006)	10, 18, 26
SAN	Simulated ANnealing clustering	S01, S04	Philipp *et al.* (2007)	9, 18, 27
RAC	Clustering with random selection of centroids	S01, S04	Philipp *et al.* (2016)	9, 18, 27

the central latitude. Both STR and VORT are calculated from their two horizontal (westerly and southerly) components. The mean values of the indices are calculated for each CT (the mean value of DIR is calculated using the 'CircStats' package in statistical software 'R', http://cran.r-project.org/web/packages/CircStats/index.html). In this way, we obtain detailed quantitative information about main circulation characteristics of each CT, which is more tractable than having to look at a huge number of composite SLP maps of individual CTs.

3. Long-term trends in the frequency of CTs

3.1. Overall evaluation

First, we present the percentage of CTs with significant trends for all domains and all seasons (Figure 2). This measure is, however, not sufficiently representative as some types are relatively abundant, while others occupy a few days only. To account for unequal sizes of CTs, Figure 2 also displays the percentage of days occupied by CTs with significant trends in frequency. In spring, summer, and autumn in most of the spatial domains, very few CTs bear significant trends in frequency. These CTs usually occupy <20% of days in spring and autumn, and in many domains even <10% in summer. The only exception in summer is the eastern Mediterranean (D11) where significant trends of frequency (both positive and negative) often occur in the most prevalent CT, which occupies a majority of summer days.

In winter, many more CTs bear significant trends in frequency compared to other seasons, except for three northern domains (D01–D03) where the number is low all year round. The proportion of days contained in the CTs with significant trends is highest in D08 (eastern Europe) and D11 (eastern Mediterranean) with values usually exceeding 35%, although results from different classifications differ to a large extent.

The subjective classifications contain more CTs with significant trend in frequency than the objective classifications in domains D06 and D07 (for various parts of which the subjective classifications were developed) in spring, summer, and autumn (Figure 2). Results of the subjective classifications conform to the objective ones only in winter. However, the magnitudes of trends in the frequency of CTs in the subjective classifications do not differ from the objective ones in any season (not shown).

The trend-to-noise ratio (trend magnitude for the whole period divided by standard deviation of annual frequencies) is comparable between all seasons and domains, and even between the subjective and objective classifications (not shown). This means that extreme slopes (whether positive or negative) of linear trends in the subjective classifications are usually connected with high interannual variability of frequency of CTs. Also some unusually high trends in the objective classifications in winter occur in the CTs whose frequency varies highly from year to year.

3.2. Seasonal trends

A more detailed look at the trends in frequencies of CTs and their relation to their circulation characteristics (mean flow strength, direction, and vorticity) is provided in Figures 3–6 for individual seasons from winter to autumn. These figures display four essential properties of CTs together, namely, (1) the significance and sign (in the case of significance) of a trend in their frequency (symbol), (2) their flow strength (*y*-axis), (3) their flow direction (*x*-axis), and (4) their vorticity [that is, (anti)cyclonicity of flow] for the CTs with significant trends (colour of the vertical line: bluish for cyclonic; yellowish and reddish for anticyclonic CTs). These properties are displayed for all the 12 domains (individual panels) and for all seasons (individual figures). Note that each panel carries information on these properties for all CTs from 78 classifications, which amounts to over 1000 types. This kind of display, which may be a bit difficult to comprehend at first sight, allows one to identify properties common or characteristic for CTs with significant trends and also compare properties between CTs with different flow directions, between CTs with different flow strengths, between domains, as well as between seasons.

First of all, we note that the graphs in Figures 3–6 reflect several well-known features, such as a stronger flow in more northerly domains, stronger flow in winter than in summer, a prevalence of anticyclonic flow in the Mediterranean domains especially in summer, and a preference for a stronger flow under specific flow directions in several domains (typically under SW to NW flow in northeastern, central, and western Europe).

However, we concentrate on the CTs with significantly changing frequencies, which are highlighted by triangles (decreasing frequency) or circles (increasing frequency) and colour bars (denoting the cyclonicity of the CT, quantified by the index of vorticity). It is notable that the majority of CTs with significant trends are cyclonic in D01 (Iceland) and anticyclonic in D09 (Iberian Peninsula); this is a natural consequence of a generally cyclonic or anticyclonic circulation conditions in the vicinity of the Icelandic low and Azores high, respectively: the majority of CTs are cyclonic/anticyclonic there, so cyclonic/anticyclonic are those CTs with significant trends in frequency as well.

The largest number of CTs with significant trends in frequency occurs in winter (Figure 3). There are two general features common to the majority of domains [except for D01 (Iceland) and D09–D11 (Mediterranean)]: the CTs with a SW to W (approximately zonal) flow direction become more frequent, while CTs with a N to E to S (meridional) flow direction become less frequent. The increasing frequencies (circles) are observed mainly for CTs with cyclonic flow (positive vorticity, bluish colours of vertical bars) in more northerly domains (in particular D02, D03, and D05), whereas for CTs with anticyclonic flow (warm colours of vertical bars) in more southerly domains (D06, D07, and D08). The approximate opposite holds for the CTs with decreasing frequencies (downward triangles): they tend to be anticyclonic in D03 (northeastern Europe) and D05 (Baltic Sea), whereas cyclonic in D04 (British Isles) and D08 (eastern Europe). In domains D10

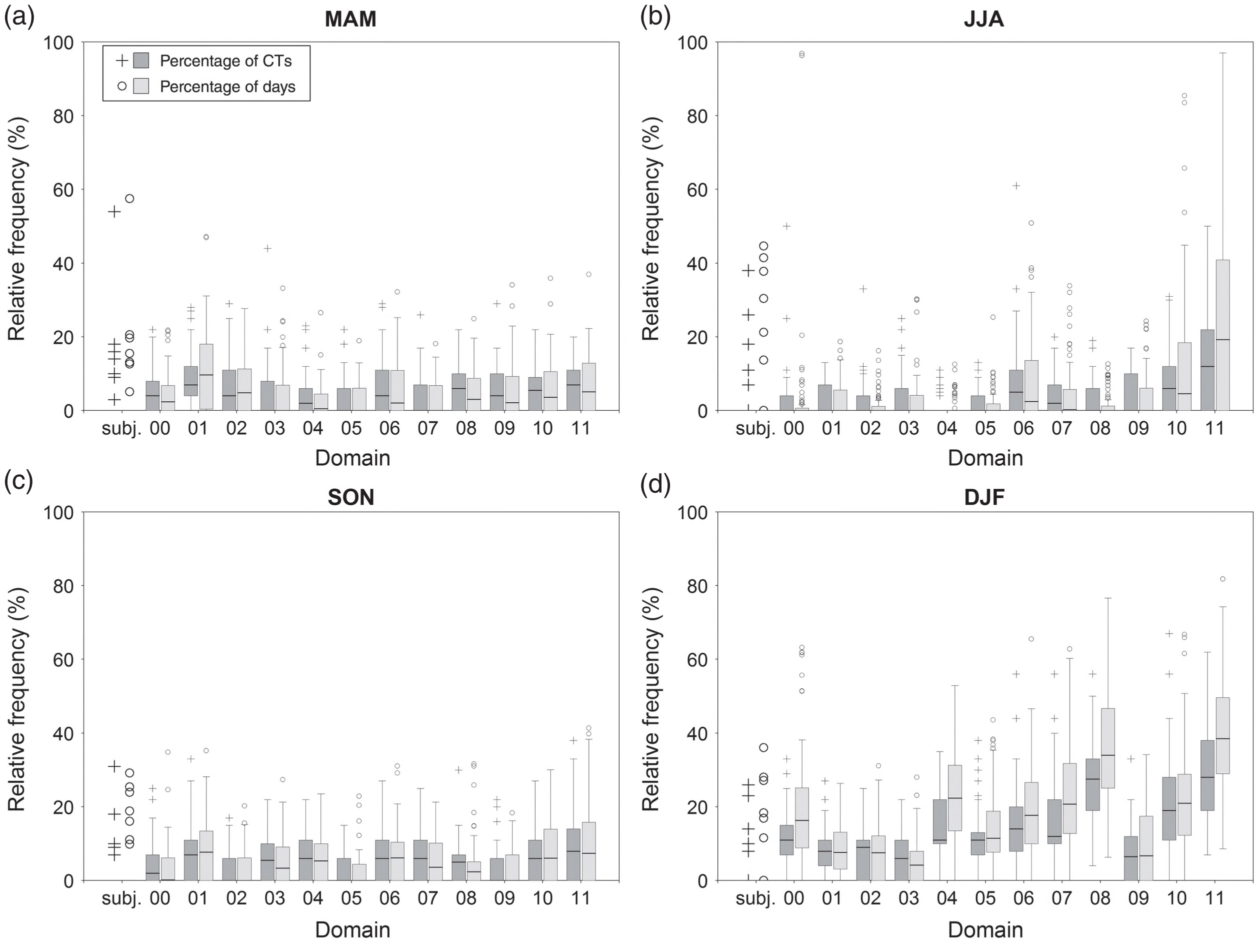

Figure 2. Percentage of CTs with trends in seasonal frequency significant at the 5% level (left, dark grey), and percentage of days contained in these CTs (right, light grey), in individual domains (D00–D11). Box plots show median, upper, and lower quartile of the 78 objective classifications. Symbols on the left (marked 'subj.') show results for the seven non-scalable (subjective and objectivized subjective) classifications.

and D11 (central and eastern Mediterranean), decreasing frequencies pertain to CTs with SE to W flow, while increasing frequencies occur for CTs with N to SE flow. There is no clear directional preference for CTs with significant trends in frequency in domains D01 (Iceland) and D09 (Iberian Peninsula). An interesting feature appears for the continental-scale flow patterns in D00: the significant trends in frequency occur almost exclusively for the westerly CTs (which itself is a manifestation of a tendency for a large-scale background flow to be zonal), but those with a strong flow become more frequent, while those with a weaker flow become less frequent.

All these trend features are consistent with a strengthening of the NAO and its shift towards its positive phase in the 1990s, reported in many previous studies (e.g. Ostermeier and Wallace, 2003): the large-scale zonal flow becomes stronger, there is little change in the domains under or in the vicinity of the NAO's action centres (D01 and D09), and zonal (meridional) flow becomes more (less) frequent over the majority of northern and central Europe. The strengthening of the NAO was accompanied by a shift of its action centres eastward to northeastward (Jung *et al*., 2003; Beranová and Huth, 2007, 2008). The eastward extension of the Azores high results in more frequent northerly flow in the central and eastern Mediterranean, which found itself at or close to the eastern flank of the Azores high.

In other seasons, significant changes in frequency occur for considerably fewer CTs than in winter. In spring (Figure 4), we notice a general tendency towards a more zonal flow in northern and central Europe (domains D01–D08), manifesting in increasing frequencies of SW to NW CTs and decreasing frequencies of N to E to S CTs. The changes are not systematic with respect to the flow direction in the Mediterranean (D09–D11). This again may point to a springtime intensification of the NAO, reported by Malberg and Bökens (1997), particularly in conjunction with the fact that its action centres travel northward from winter to summer (e.g. Folland *et al*., 2009; Pokorná and Huth, 2015).

In summer (Figure 5), significant trends in frequency are quite sparse in most domains and do not exhibit any clear relationship with the flow characteristics. In the Mediterranean (D09–D11), the significant trends concentrate in the NW to E directions, which is probably a reflection of a general prevalence of flow from these directions in summertime.

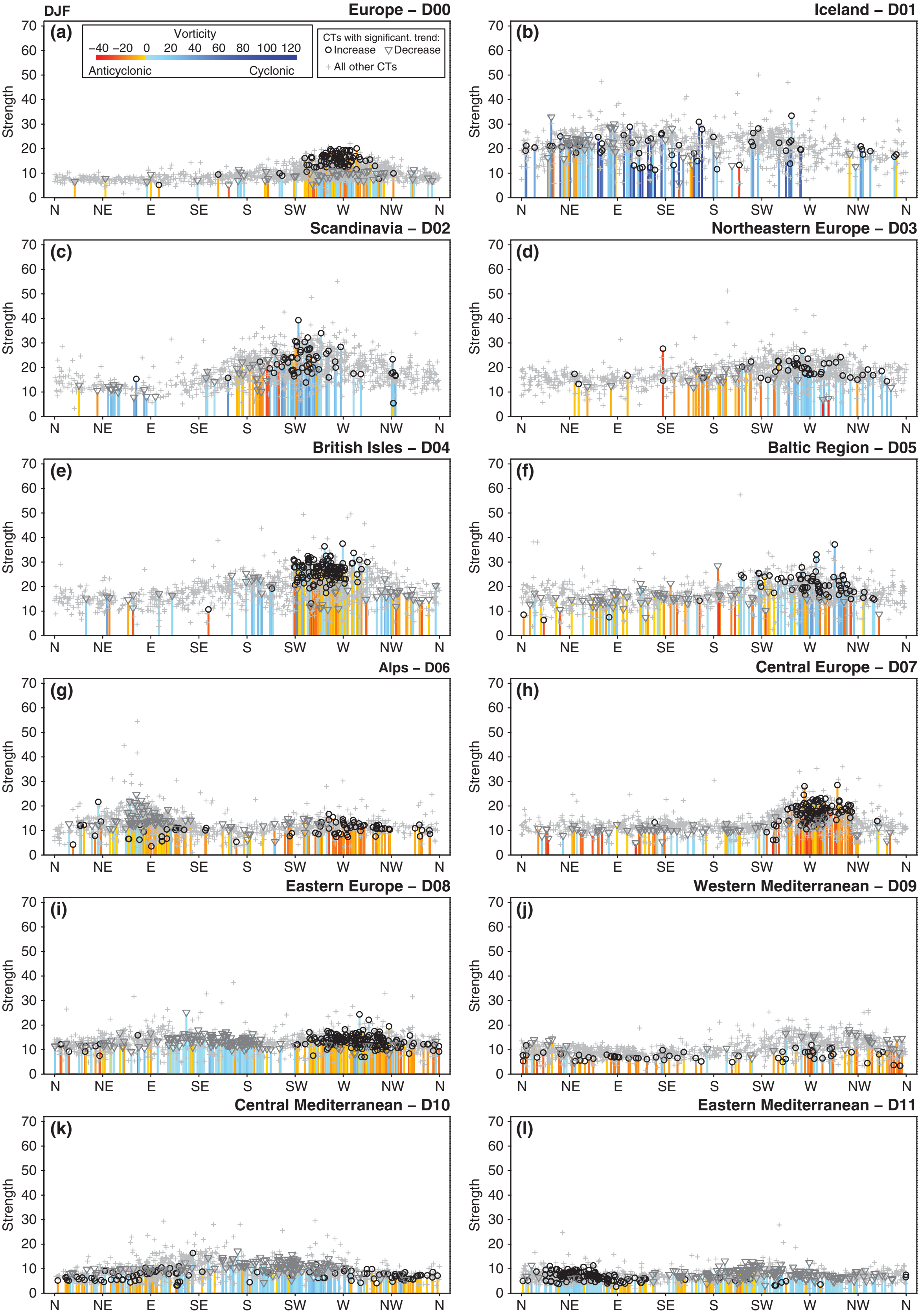

Figure 3. Mean flow strength (on vertical axis) and direction (on horizontal axis) for all CTs from 78 objective classifications, separately for individual domains, in winter. Triangles (circles) indicate CTs with a negative (positive) trend in frequency significant at the 5% level. CTs with an insignificant trend in frequency are shown as light grey crosses. Mean vorticity is shown as colour bars (bluish for cyclonic and reddish for anticyclonic) for the CTs with significant trends. The key for the symbols is inset in the panel for domain D00.

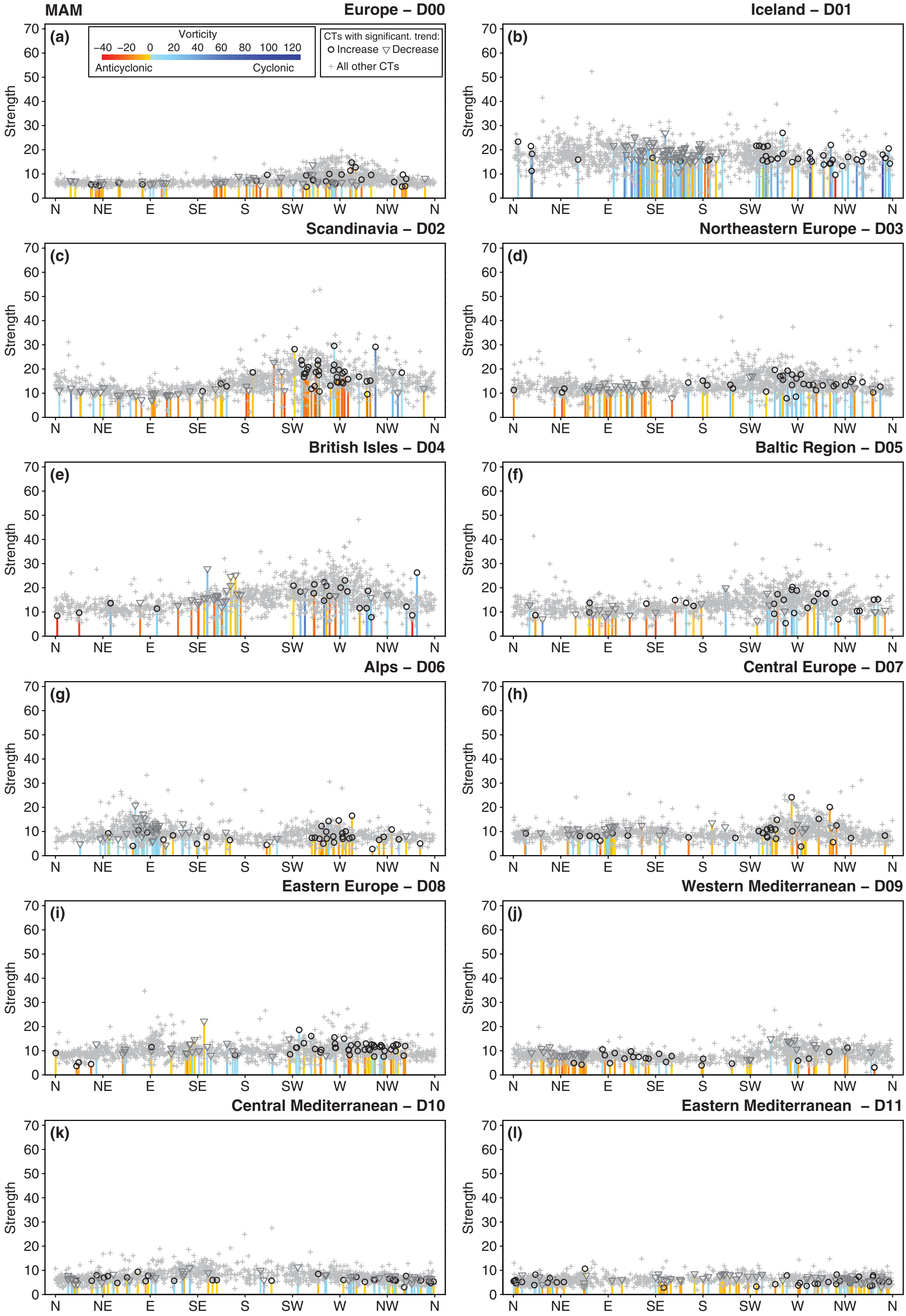

Figure 4. As in Figure 3 except for spring.

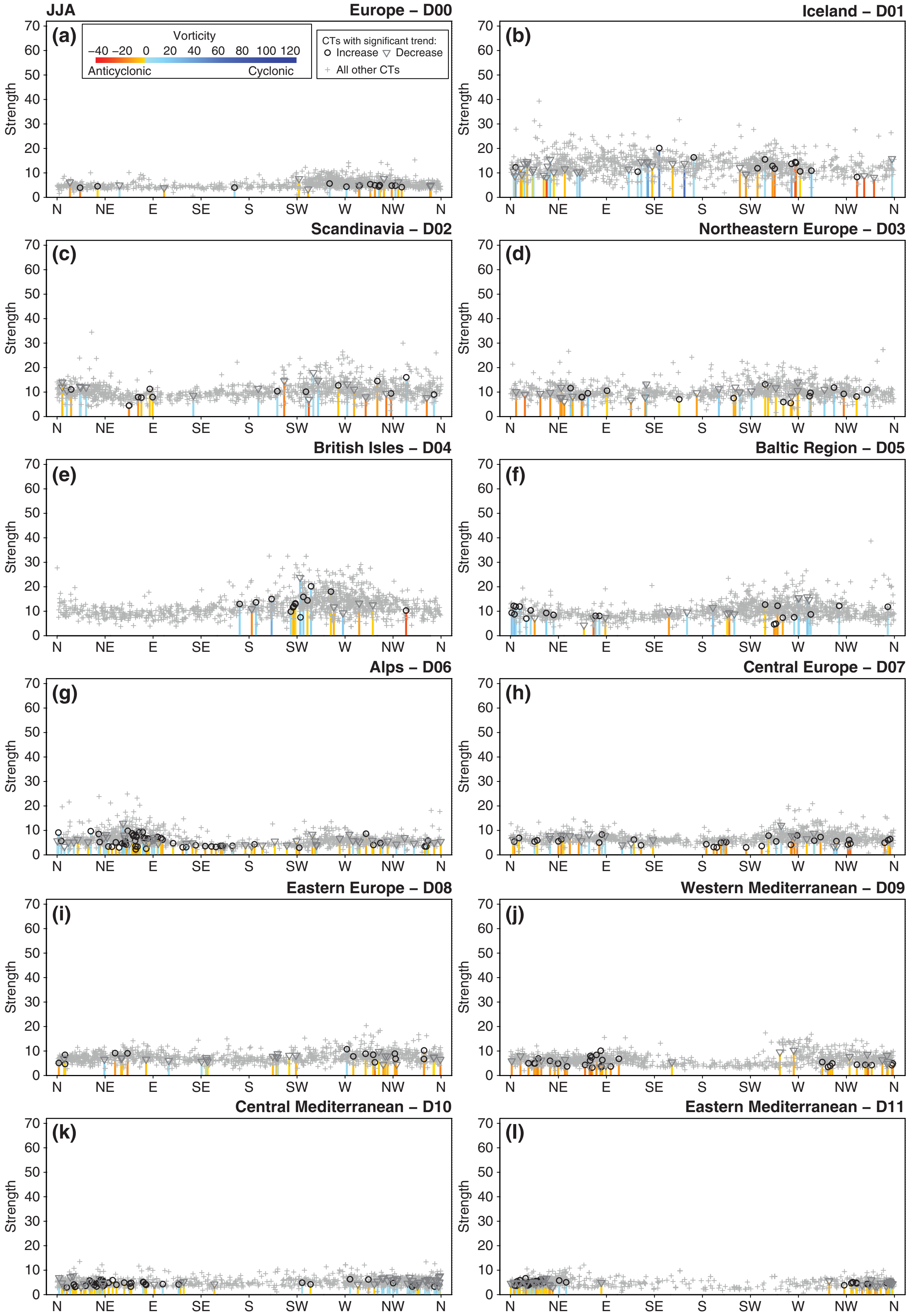

Figure 5. As in Figure 3 except for summer.

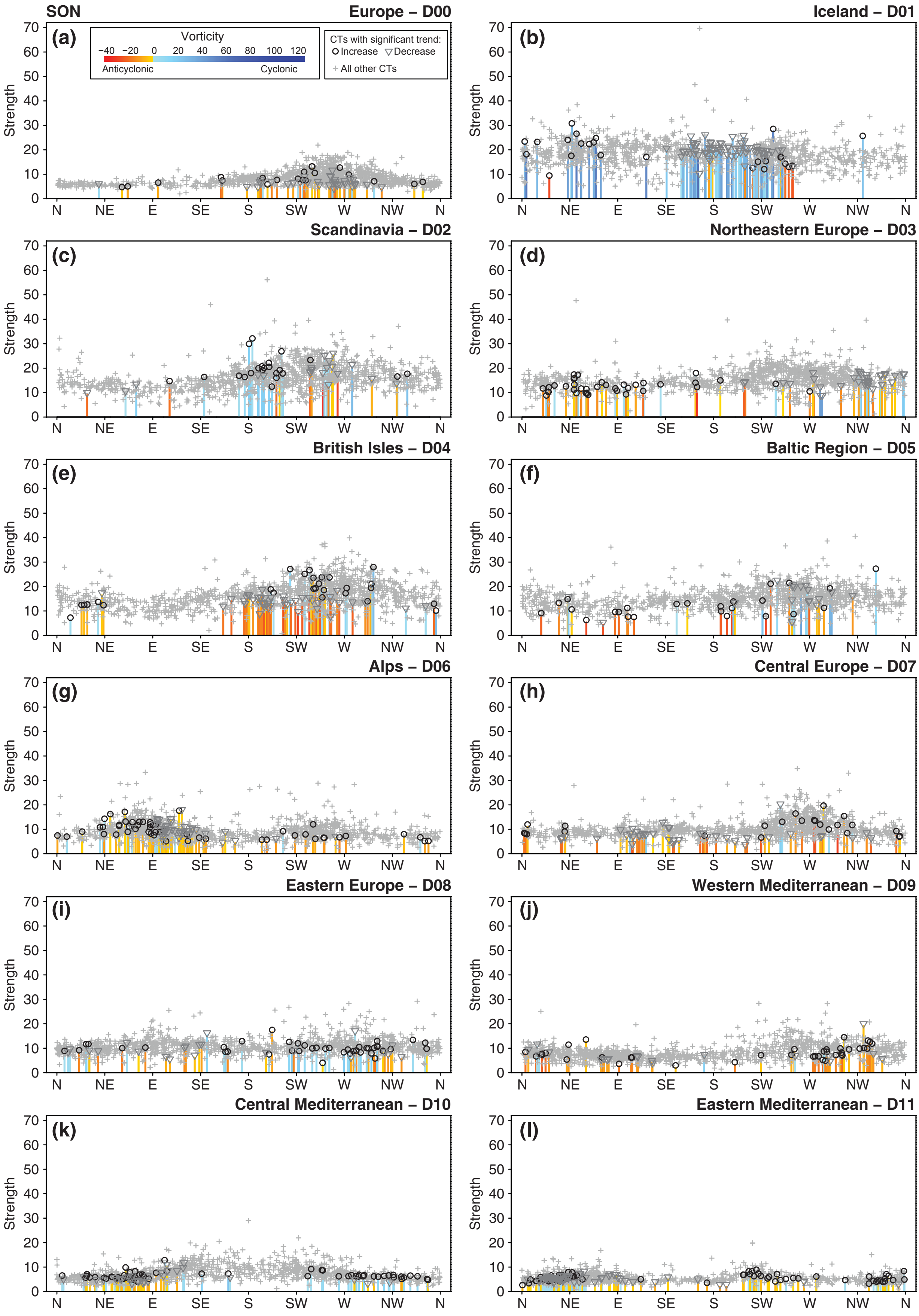

Figure 6. As in Figure 3 except for autumn.

In autumn (Figure 6), directional preference of significant trends can be observed in several domains (most notably in D01 to D04, D06, and D07); these trend patterns do not seem, however, to be consistent among domains. An exception is central European domains D06 and D07, which overlap to a considerable extent: increasing frequencies occur for CTs with SW to W flow there, while decreasing frequencies are observed for CTs with E to S flow; however, there are notable differences in the trend patterns between D06 and D07. This, together with the lack of coherence between other domains, mentioned before, points to the fact that smaller-scale mechanisms are likely to act behind the frequency trends in autumn and that in autumn, unlike in winter and spring, changes in continental-scale circulation features (such as the NAO) are not the cause of the observed trends in CT frequencies. An interesting feature can be seen in D04 (British Isles): a decreasing frequency of CTs with a weak anticyclonic flow (downward triangles appear together with warm colours) in a S to W direction, accompanied with increasing frequencies of CTs with a strong cyclonic flow (circles appear together with bluish colours) from the same sector.

There are large differences in the trend behaviour between the 78 objective classifications: in any domain and any season, there are several classifications with no significant trend in frequency of any CT. An example is provided in Figure 7, showing magnitudes of significant trends for central Europe (D07) in winter: considerable differences among classifications can be seen in the number of CTs with a significant trend. For example, two classifications (GWLo09_S01 and KIR27_S01) have no CT with a significant trend, while for one classification (CAP09_S01), more than a half of CTs have a significant trend. Similar observations can be made for other seasons and other domains. The trend magnitudes are usually higher (in absolute values) in winter than in the other seasons, the extreme trend values being -4.4 days decade^{-1} (in D08) and $+6.0$ days decade^{-1} (in D00).

3.3. Example of two classifications

An example of trends in frequency of CTs is shown in Figure 8 for the GWT classification with eight types and the JCT classification with nine types in all domains. Both classifications have eight CTs determined by the prevalent flow direction (westerly, northwesterly, etc.); the JCT classification has an additional type containing patterns with an indeterminate flow direction. Therefore, although the two classification methods are different, they produce sets of CTs, which are mutually comparable and easy to interpret. Figure 8 shows that for many combinations of domain, season, and CT, the trends are consistent between the two classifications, i.e. either there is no significant trend in both classifications or frequencies of both types increase or decrease. However, there are other numerous cases for which the trend is highly significant in one classification while insignificant in the other (e.g. NW type in spring in D01, NE type in autumn in D03, E type in autumn in D06 and D07, etc.), or even significant trends of opposite sign occur (e.g. S type in spring in D00, SW type in spring in D06, NE type in summer in D10, etc.). The fact that CTs with similar flow patterns may undergo different or even opposite temporal changes in their frequencies gives us a warning that to rely on a single classification when describing temporal changes in atmospheric circulation may not be appropriate and may lead to confusing interpretations. For example, a generalization of the result for the NE type in the GWT classification in D10 in summer by claiming that the frequency of situations with a northeasterly flow has increased would at least be dubious because the counterpart CT in the JCT classification indicates the opposite (The explanation of the discrepancy between the two classifications in this particular case consists in the fact that most of the daily patterns classified as northeasterly in the GWT classification have very low horizontal SLP gradients, i.e. weak flow, and thus are classified as a type with ‘indeterminate flow’ in the JCT classification.). A similar picture of differing trends in frequency of comparable CTs appears also if other classifications are compared. An analysis of a larger number of classifications whenever one wishes to make firm statements on long-term changes in atmospheric circulation is, therefore, highly advisable.

4. Persistence of CTs

4.1. Mean persistence of CTs

Persistence of CTs varies between domains as well as between classifications. The mean persistence of all CTs in the 78 objective classifications is highest in whole Europe (D00) and in the eastern Mediterranean (D11) in summer. The extremely high mean persistence of >20 days, which is reached by several classifications in D11 in summer (52 days for PTT_S04, 38 days for PCT09_S04, 22 days for PTT_S01) is indicative of an unrealistic temporal behaviour of these classifications.

A comparison of mean persistence between domains and seasons is provided in Figure 9. In D00 in summer, the median of mean persistence of 78 classifications is 3 days. In the other domains in summer, the mean persistence is usually between 1.3 and 2.2 days with little differences between domains [higher values in eastern Europe (D08) and in the Mediterranean (D09–D11), and lower values over the smallest Alpine domain (D06)]. In spring, autumn, and winter, the mean persistence is always highest in D00 with a median of 2.3 days in all the three seasons. D11 has slightly higher mean persistence in autumn (compared to the other small domains), but in spring and winter all the small domains exhibit almost the same mean persistence of around 1.6 days. Except for summer, the mean persistence seems to be independent of the geographical position of the domains.

Mean persistence decreases with an increasing number of CTs in most classifications (not shown). The reason is straightforward: the CTs in classifications with a higher number of types are typically formed by splitting the CTs in classifications with a lower number of types.

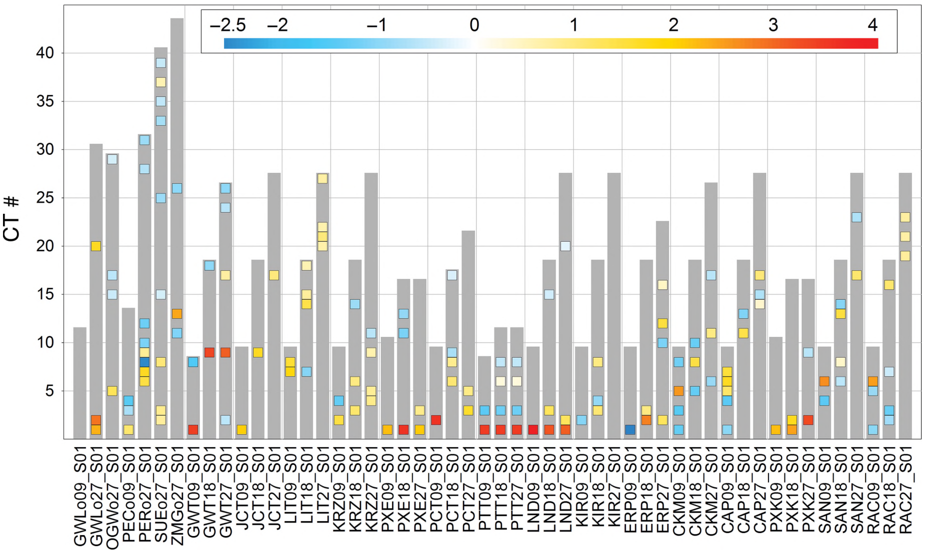

Figure 7. Magnitude of linear trends in the frequency of CTs (in days per decade in 1958–2001) for central Europe (D07) in winter. Seven non-scalable (subjective and objectivized subjective) classifications are also included (in the leftmost part of the graph) as they were developed for various parts of central Europe. Only CTs with trend in frequency significant at the 5% level are shown by a coloured square, the colour indicating the magnitude of trend (blue for negative, yellow and red for positive). Grey bars indicate the total number of CTs in each classification. Note however that some CTs are empty, so that the total number of really occurring CTs may be lower than that indicated by the grey bar.

Mean persistence of CTs in classifications based on 4-day sequences (S04) of daily input data is usually higher than persistence in those based on daily data (S01) (not shown). This difference is largest in D00 with the mean persistence longer by about 0.8 days for S04 compared to S01 in spring, autumn, and winter, and by about 1.5 days in summer. In the small domains, the differences in the mean persistence are usually around 0.3 days; larger differences are observed only in D11 in summer. On the other hand, the differences between S04 and S01 are smallest in the smallest domain, the Alps (D06). The proportion of short situations (lasting up to 3 days) is usually a bit lower in S04 classifications in all the domains.

Most of the non-scalable (subjective) classifications (OGW, PEC, PER, SUE, and ZMG) share a mean persistence of around 1.6 days in all seasons. The Hess-Brezowsky classification (GWLo09 and GWLo27) is methodologically constrained to a minimum 3-day persistence of all CTs except for the unclassified days, so its mean persistence is notably higher: around 5 days in all seasons except winter when it is as high as 5.8 days for GWLo09.

The relative frequency of days in situations of the length of 1, 2, 3, … days is displayed in Figure 10 by means of box plots summarizing all the 78 objective classifications for each spatial domain. There is a notable difference between D00 and the small domains: the CTs in the large domain (D00) tend to last longer than CTs in small domains, which manifests itself by a majority of days occurring in 2-day situations in D00, whereas the 1-day situations are most frequent in the small domains. The proportion of days contained in 1-day situations ranges from 16% (median in D00) through around 33% (median in D09 and D11) up to around 40% in the other domains. The share of situations shorter than 4 days is 53% in D00, while between 70 and 82% in all the small domains.

Large differences exist also between individual classifications. Figure 11 shows the proportion of days occupied by situations of the length of 1, 2, 3, … 10 days and longer than 10 days (11+ in Figure 11) in central Europe (D07) during the whole year for classifications based on daily input data (S01) as an example. The share of short situations is clearly higher for classifications with a higher number of types in almost all classification methods. A very low number of 1- and 2-day situations in the Hess-Brezowsky classification (GWL) is due to the methodological constraint of minimum 3-day persistence, mentioned before already. A relatively low proportion of short situations is present in all variants of PTT in all domains. It is worth noting that in the eastern Mediterranean (D11), extremely long situations occur occasionally in PCT and PTT classifications: in an extreme case, 173 days in a row are classified with one CT. This suggests that temporal structure of classifications based on the PCT and PTT methods may be unrealistic because classification algorithms are not able to distinguish circulation patterns that differ only slightly from each other. On the other hand, such behaviour may at least partly be attributed to the fact that atmospheric circulation is relatively stable in the eastern Mediterranean in summer, with a high-pressure ridge extending northeastwards from the Azores high towards the European mainland, bringing northerly 'Etesian' winds (e.g. Tyrlis and Lelieveld, 2013).

4.2. Trends in the mean persistence of all CTs combined

Trends of seasonal mean persistence were estimated for all types combined, as well as for each type separately. The magnitudes of trends are presented in days per decade.

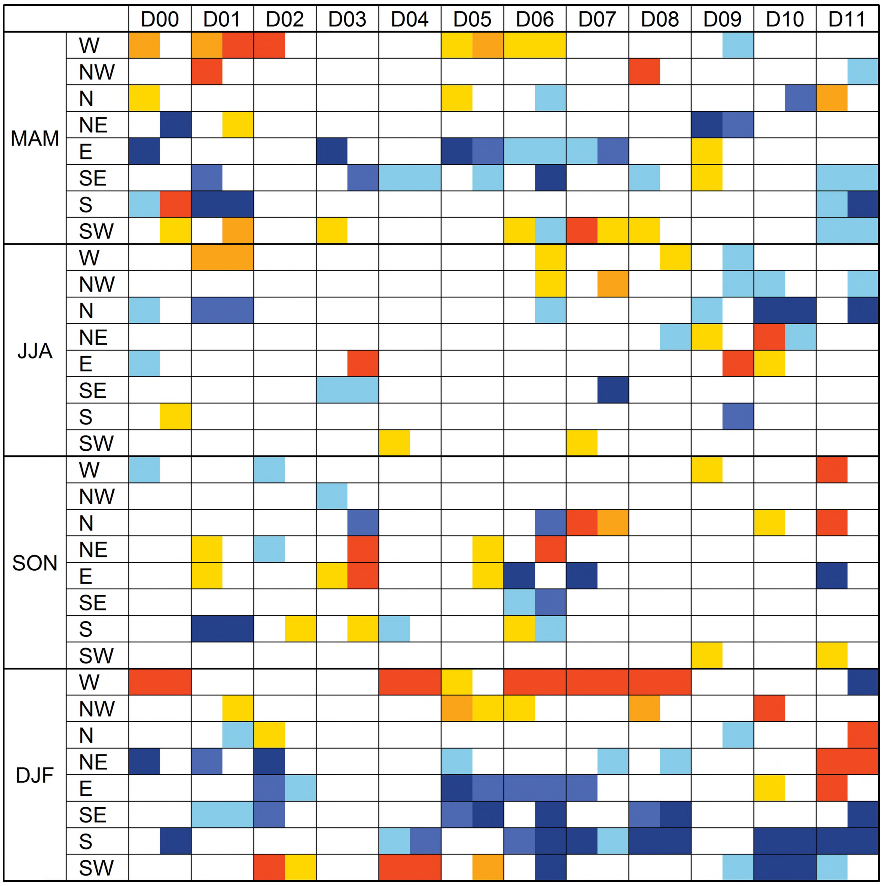

Figure 8. Linear trends in seasonal frequency of CTs from classifications GWT09_S01 (left square in each pane) and JCT09_S01 (right square). The CTs are denoted by the prevalent flow direction. Positive trends significant at the 20, 10, and 5% level according to Mann–Kendall trend test are in yellow, orange, and red, respectively. Negative trends significant at the 20, 10, and 5% level are in light, medium, and dark blue, respectively.

Both the percentage of CTs and the percentage of days in CTs with significant trends in persistence were calculated, analogously to the trends in frequency.

The objective classifications show an inconclusive long-term behaviour of overall persistence (Table 2): both positive and negative significant trends are present in all domains except D01 (Iceland) where all significant trends are negative in all seasons. In the Mediterranean, the overall persistence was increasing in summer in some objective classifications, while in autumn it was decreasing (mostly in classifications other than those with positive trends in summer). The decreasing persistence of synoptic situations over Iceland may be associated with a northward shift of storm tracks and increasing cyclonic activity in the North Atlantic related to global climate change (as modelled by Knippertz *et al*., 2000 and Geng and Sugi, 2003, and discussed by Kyselý and Huth, 2006). However, a uniform decrease of persistence was only found for all synoptic situations combined (irrespective of the CT). The individual CTs underwent both increases and decreases of persistence over Iceland.

Relatively few objective classifications have a significant trend of persistence (Table 2). The numbers of significant trends in persistence for most combinations of domains and seasons are so low that they cannot be distinguished from a random effect. The numbers of CTs with significant persistence trends are collectively significant at 16 (out of 48) entries in Table 2. The significant numbers of non-zero persistence trends concentrate in the northwest (domains D01 and D02) and south (domains D09, D10, and D11) of Europe and appear also in D06 (Alps) and for the large continental domain (D00).

Concerning the effect of sequencing on trends in persistence, there is no preference for classifications of either individual daily patterns (S01) or 4-day sequences (S04) to have more significant trends (not shown). The differences between the two variants of sequencing vary from season to season and from domain to domain.

Time series of the mean annual persistence in subjective (non-scalable) classifications are displayed in Figure 12. Trends of overall persistence in the subjective Hess-Brezowsky classifications (GWLo09 and GWLo27) are positive and significant at the 5% level for all seasons and in the whole year, and are usually larger than the absolute values of significant trends in the other classifications by an order of magnitude. Also the trend-to-noise ratio is about twice as high as in the objective classifications. In GWLo09 and GWLo27 (red and orange line in Figure 12, respectively), trends of about +0.5 days decade^{-1} occur in all seasons, while such dramatic increases of overall persistence are only present in four objective classifications in D11 in summer and in one objective classification in D00

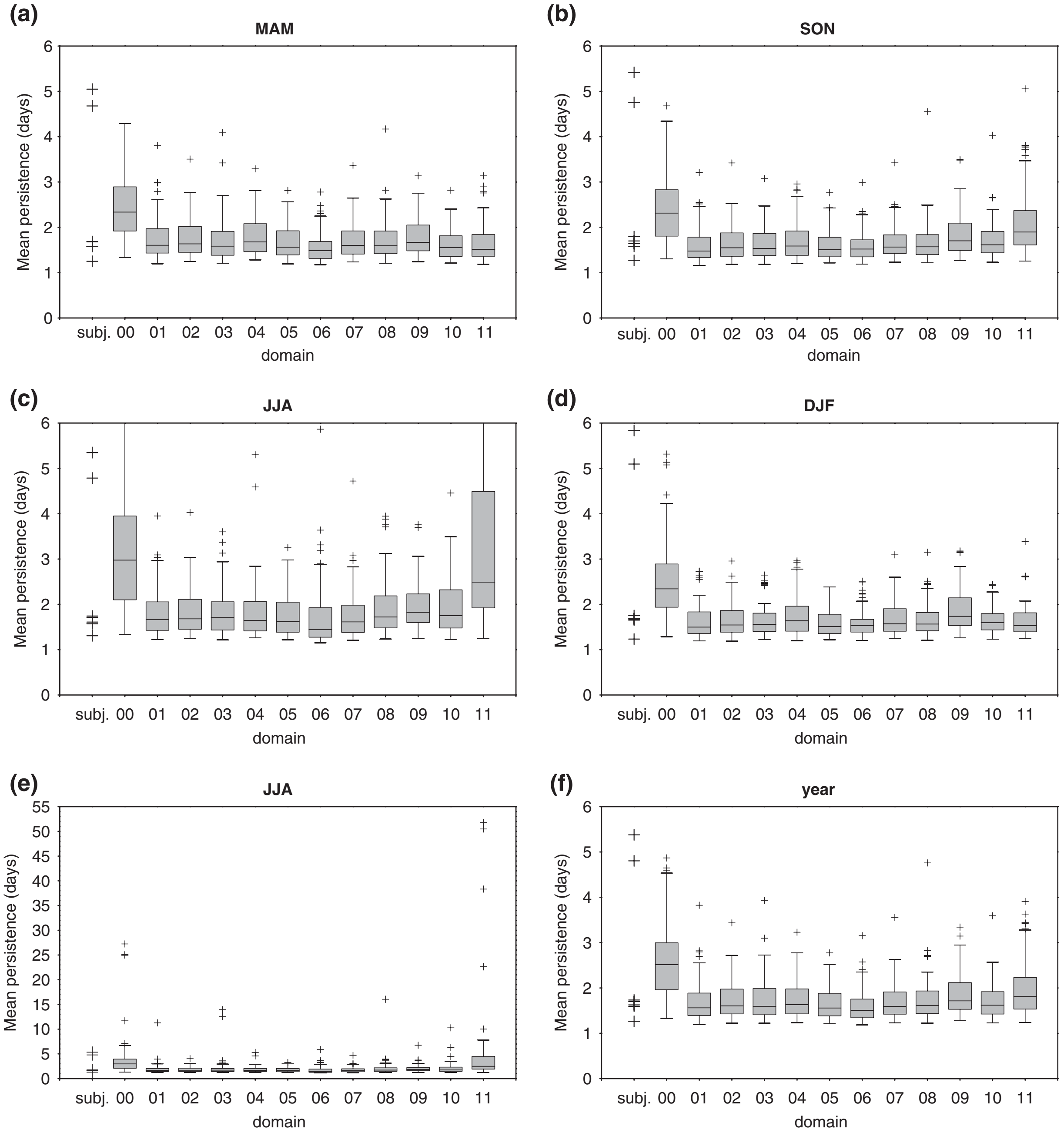

Figure 9. Mean persistence of all synoptic situations, irrespective of the CT, for all seasons and year round. Two panels are shown for JJA with a different vertical scale in order to capture the outlying cases with very high persistence. Box plots show median, upper, and lower quartile of the 78 objective classifications; symbols in the leftmost column (marked 'subj.') show results for the seven non-scalable (subjective and objectivized subjective) classifications.

in winter. The automated (objectivized) Hess-Brezowsky classification (OGWo27; green line in Figure 12) does not bear any significant trend in persistence. In the Hungarian catalogue (PEC), significant negative trends of overall persistence occur in all seasons, while in the PER and ZMG classifications, smaller but still significant negative trends take place in autumn.

We have applied homogeneity tests (several variants of SNHT: single shift of mean, double shift of mean, single shift of mean and standard deviation, trend in mean, and cumulative deviations) to the time series of overall annual persistence to see if there are any sudden changes that may underlie outstanding values of the linear trend. In the objective classifications, such shifts are rarely significant at the 5% level. The situation is, however, very different for subjective classifications. First, a major shift to a higher persistence is detected in both Hess-Brezowsky classifications between 1985 and 1986. A massive increase in persistence of 1.5 days (difference between 1958–1985 and 1986–2001) is unprecedented and unrivalled, and most probably stems from a change in the methodology of the manual classification of synoptic types [despite the fact that Gerstengarbe *et al.* (1999) claim the catalogue to be homogeneous]. This is further substantiated by the fact

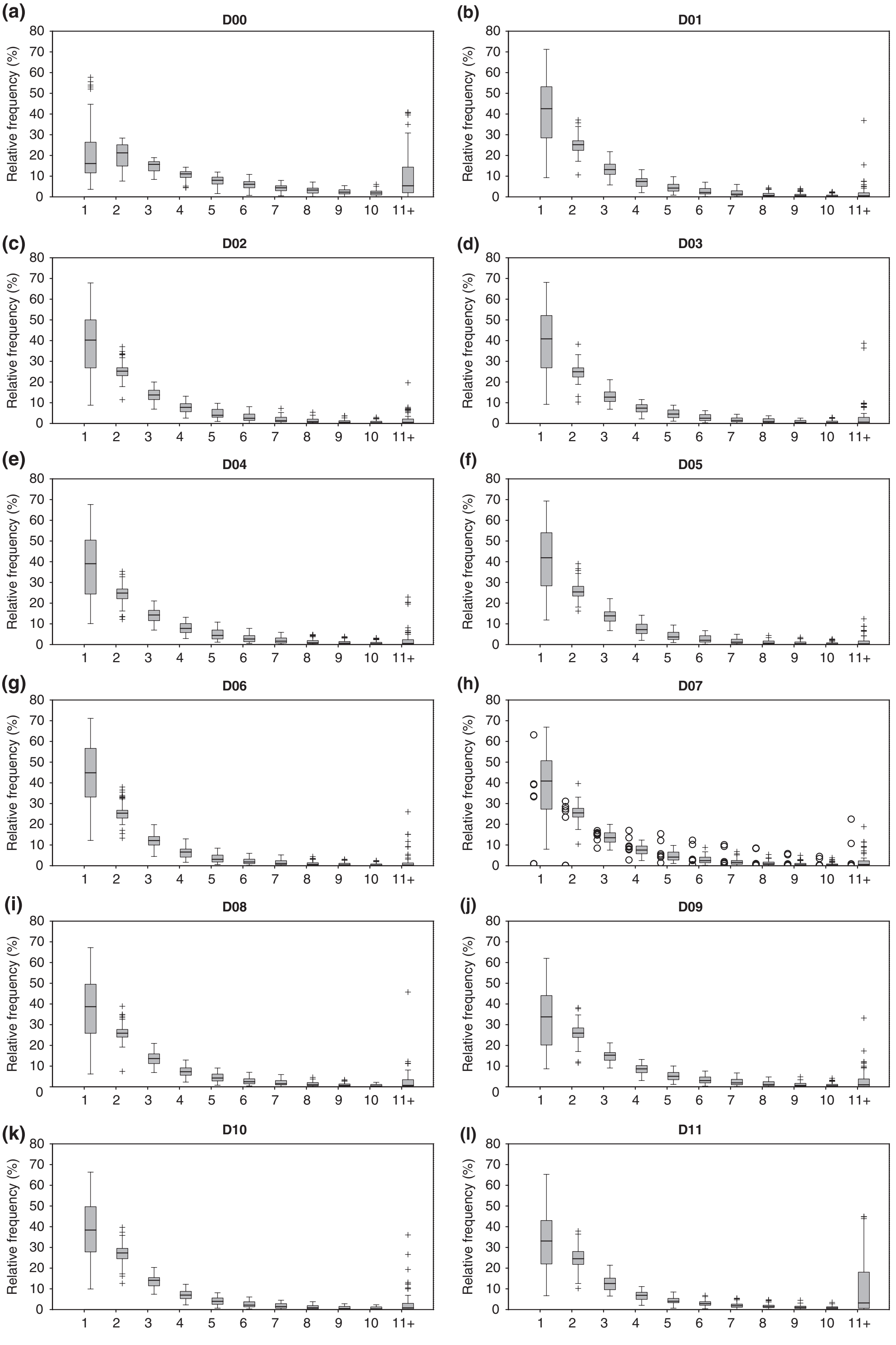

Figure 10. Percentage of days contained in synoptic situations of the given length (horizontal axis), irrespective of the CT, for the whole year. Box plots show median, upper, and lower quartile of the 78 objective classifications. Circles in the graph for D07 denote the seven non-scalable (subjective and objectivized subjective) classifications.

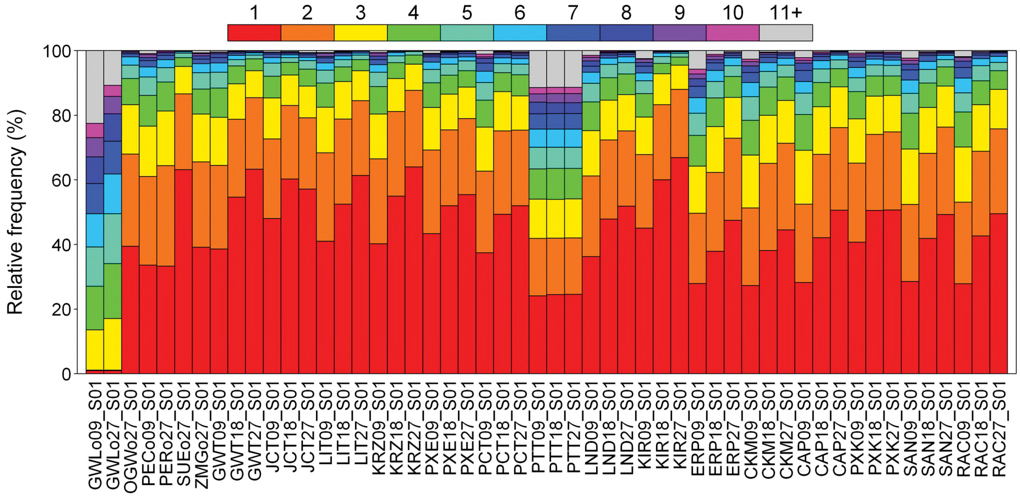

Figure 11. Percentage of days contained in synoptic situations of the given length (indicated by colour), irrespective of the CT, in central Europe (D07) for the whole year, including the non-scalable (subjective and objectivized subjective) classifications (seven leftmost bars).

Table 2. Percentage of classifications with trends in mean persistence significant at the 5% level: total (positive/negative). There are six subjective classifications, one objectivized subjective classification (OGWo27) and 78 objective classifications. For objective classifications, the collective statistical significance of trend tests at the 5% level (that is, the numbers of trends detected as significant at the 5% level that cannot occur randomly at the 5% level) is indicated in bold. Assuming independence of individual trend tests, the probability of the given number of significant trend tests follows binomial distribution (Wilks, 2006), resulting in the critical value of the number of individual trend tests being slightly below seven, that is, 9%.

		MAM	JJA	SON	DJF
Subjective		50 (33/17)	50 (33/17)	83 (33/50)	50 (33/17)
OGWo27		–	–	–	–
Objective classifications	D00	**9** (0/9)	3 (3/0)	3 (1/1)	**12** (12/0)
	D01	**21** (0/21)	**17** (0/17)	4 (0/4)	**12** (0/12)
	D02	**10** (3/8)	1 (1/0)	3 (3/0)	5 (0/5)
	D03	3 (1/1)	0 (0/0)	4 (4/0)	**9** (1/8)
	D04	5 (0/5)	8 (3/5)	**9** (1/8)	4 (1/3)
	D05	4 (1/3)	0 (0/0)	5 (4/1)	1 (0/1)
	D06	1 (0/1)	3 (1/1)	**23** (0/23)	4 (4/0)
	D07	3 (0/3)	3 (1/1)	8 (0/8)	6 (6/0)
	D08	1 (1/0)	**9** (9/0)	0 (0/0)	6 (1/5)
	D09	1 (1/0)	0 (0/0)	4 (1/3)	**14** (9/5)
	D10	3 (3/0)	**9** (9/0)	**17** (0/17)	4 (3/1)
	D11	5 (5/0)	**19** (19/0)	**19** (0/19)	**18** (8/10)

that neither a shift nor a significant trend appears in the objectivized version of GWL (OGWo27). Second, in the Hungarian catalogue (PEC) a smaller but opposite shift to a lower persistence occurs between 1985 and 1986, probably by mere coincidence. A small negative shift also occurs in PER in 1970.

The fact that the previously reported increase of persistence in the Hess-Brezowsky catalogue in the mid-1980s (Werner *et al.*, 2000; Kyselý and Huth, 2006; Cahynová and Huth, 2009) is not reflected in any objective classification, and namely that it does not appear in the objectivized version of the catalogue (James, 2007), clearly indicates that the persistence increase is not real but is an artefact of the particular catalogue. Cautious use of subjective classifications in climate evolution studies was already recommended by Stehlík and Bárdossy (2003), and we only can concur with their warning.

4.3. Trends in the mean persistence of individual CTs

In the objective classifications, the magnitude of significant trends of mean seasonal persistence is much higher (in absolute values) for some individual CTs than for all CTs combined: it ranges from -1.3 to $+1.5$ days decade^{-1} (with one exception of $+3.3$ days decade^{-1} for D00 in winter). Usually very few CTs undergo a significant trend in persistence, and such CTs only occupy a minority of days. However, the picture varies between classifications, domains, and seasons; e.g. in D11, the persistence increases in summer and decreases in autumn in several major CTs, mostly with a northerly and northeasterly flow, in some classifications. A typical example of trends in persistence is provided in Figure 13 for central Europe (D07) in winter for classifications based on daily input data without sequencing (i.e. S01). One can see that strongest trends appear for several CTs in two Hess-Brezowsky classifications (in

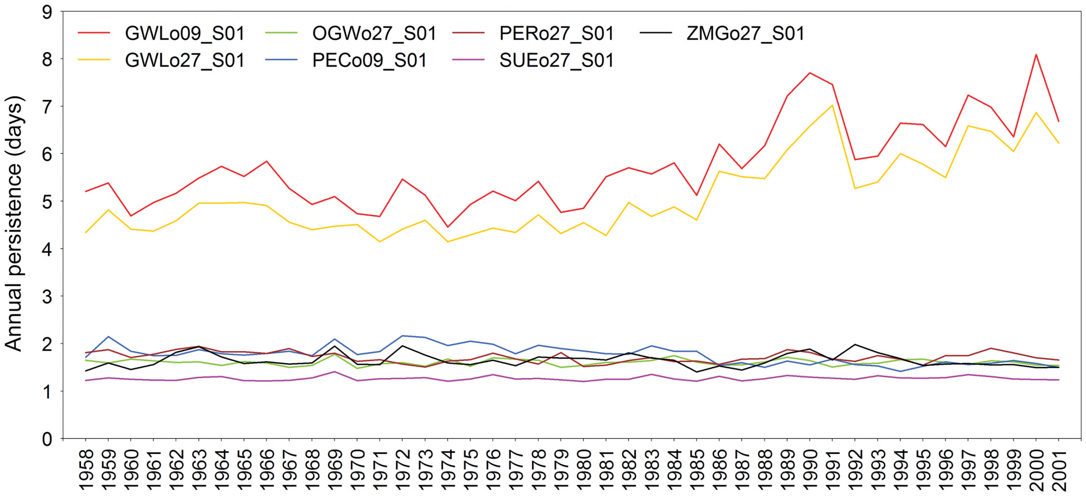

Figure 12. Time series of mean annual persistence of all CTs in the non-scalable (subjective and objectivized subjective) classifications.

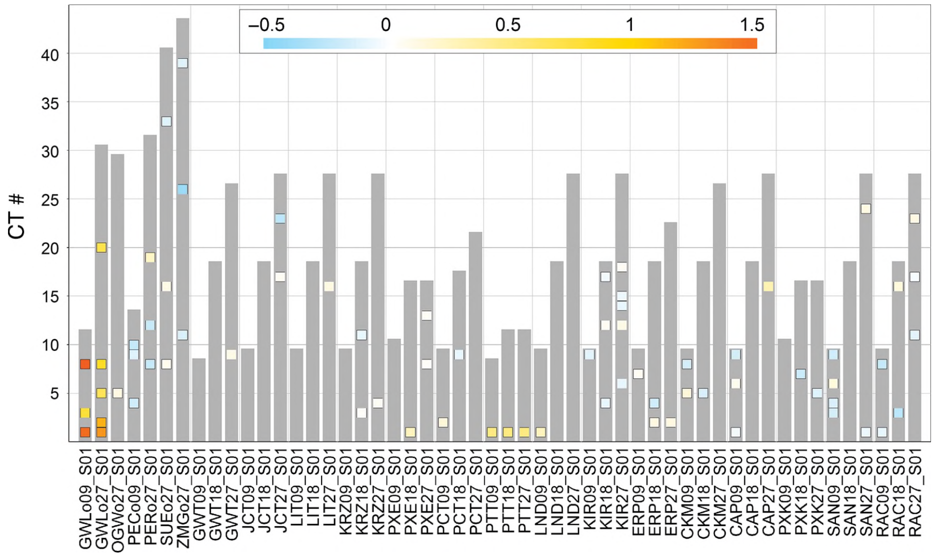

Figure 13. As in Figure 7 except for persistence.

the first two columns), that the trends, even when significant, are generally weak for the objective classifications, and that there are many classifications within which no CT exhibits a significant trend in persistence.

The subjective GWLo09 and GWLo27 classifications contain several CTs with a significant positive trend in persistence of up to +1.6 days decade^{-1} in winter, and these types together occupy up to 87% of all days during the whole year in GWLo09 (values for the seasons and for GWLo27 are much lower, though). PEC contains several CTs with a significant negative trend in persistence, but the trend magnitudes are much smaller compared to GWL. The OGWo27, PER, SUE, and ZMG classifications conform more to the objective ones with only scarce significant trends in persistence, both positive and negative, and almost always close to zero.

Unlike CTs with significant trends in frequency, the individual CTs with significant trends in persistence do not tend to share common features in terms of three circulation indices, viz., strength, direction, and vorticity. There are, though, a few exceptions, for which the trends in persistence tend to be accompanied by trends in frequency of the same sign (not shown); most of such cases occur in winter. All seasons and spatial domains being put together, there are 1369 CTs with a significant trend in both frequency and persistence (although this number may look impressive, these CTs make up <2% of all CTs included in the analysis), of which only one CT has a trend in frequency and trend in persistence of opposite sign. All the other 1368 CTs bear the trends in frequency and persistence of the same sign, that is, either both trends are increasing or both are decreasing. However, significant trends in persistence are more commonly not accompanied by significant trends in frequency for the majority of individual CTs. The question on whether increases (decreases) in the frequency of CTs are caused by increases (decreases) in the number of synoptic situations or by increases (decreases) in their duration cannot thus be resolved on the basis of current results.

4.4. Correlation of time series of annual persistence between classifications

Individual classifications are compared with respect to interannual variations of the mean persistence of CTs by calculating Pearson correlation of the time series of the annual persistence of all CTs combined. The correlations were calculated also for detrended time series, the results being very similar.

All domains taken together, correlations for 62% pairs of classifications are significant and positive. The highest similarity occurs between classifications that are based on the same classification method, and only differ in the number of CTs or the sequencing of input data. Several classifications have low or even negative correlations with many other classifications. This indicates that their persistence characteristics strongly differ from the majority of other classifications, thereby casting doubts on the realism of the former. The negative correlations are most pervasive for the PTT classifications, and occur also for the ERP and RAC methods, for which the picture varies from domain to domain.

Given the unparalleled trends in annual persistence of CTs in GWL (Hess-Brezowsky) subjective classifications, it is no surprise that the correlations between GWL and other classifications are also mostly close to zero or even negative in the domains that roughly fit the spatial extent of GWL (D00, D06, and D07). The objectivized Hess-Brezowsky classification (OGWo27) has mostly positive correlations with other classifications in these domains, yet even in central Europe (D07) more than half of the correlations are insignificant.

5. Conclusions

This study provides a comparative analysis of changes in frequency and persistence of daily CTs from the COST733cat database produced within the COST733 Action for the period September 1957–August 2002 (Philipp *et al.*, 2010, 2016). In total, we analyse six subjective and one objectivized classification of CTs from central Europe, and 78 objective (computer-assisted) classifications in 12 spatial domains in Europe and the adjacent North Atlantic region, differing in the classification method, number of CTs, and whether instantaneous patterns or their 4-day sequences are classified. The total number of individual CTs in the database is almost 80 000.

Observed trends in frequencies of CTs are quite varied: the behaviour of trends varies between domains, as well as from one season to another. Nevertheless, a consistent large-scale picture is formed in winter by increasing frequencies of CTs with zonal flow and decreasing frequencies with meridional flow over most of Europe except Iceland and Mediterranean, the increases being stronger for cyclonic types in the north of Europe, while for anticyclonic types in central and eastern Europe. This is accompanied by increases in frequencies with northerly to easterly flow in central and eastern Mediterranean. A qualitatively similar pattern appears in spring. These sets of trends comply with the large-scale circulation change, consisting in a strengthening and eastward shift of the NAO, reported for winter and spring in several studies (Malberg and Bökens, 1997; Jung *et al.*, 2003; Ostermeier and Wallace, 2003; Beranová and Huth, 2007, 2008).

Significant trends in frequency are most numerous in winter except for three northern domains (D01, D02, and D03) where very few trends are significant all year round. However, a relatively small share of days (typically <20%) only occurs in CTs with significant trends; the eastern Mediterranean domain (D11) in summer and winter, and eastern Europe (D08) in winter are exceptional with around 20, 40, and 35%, respectively, of days being included in CTs with significant trends. The presence of CTs with significant trends in frequency varies widely between classifications. There are classifications in which no CT undergoes significant long-term changes in frequency; on the other hand, there are classifications with more than a half CTs having significant trends in some seasons and regions.

The persistence of CTs is sensitive to the size of the domain: the mean persistence is highest for the largest domain (D00, whole Europe), while lowest for the smallest domain (D06, Alps). The persistence clearly depends on the number of CTs in a classification: the more types in the classification, the lower their mean persistence. Also, the sequencing affects the persistence of CTs: classifications of 4-day sequences (S04) tend to have higher persistence than those of single daily patterns (S01). The mean persistence tends to be higher in southeastern Europe (domains D08, D10, and especially D11, i.e. eastern Europe and central and eastern Mediterranean) in summer; in other seasons, it appears to be independent of the geographical position. Some classification methods (PCT and PTT) yield unrealistically long synoptic situations, especially in D11 (eastern Mediterranean), which indicates their limited suitability for classification of CTs.

Significant trends in persistence occur more seldom than significant trends in frequency. The numbers of significant trends in persistence are collectively significant mainly in northwestern and southern Europe. The persistence trends do not form any consistent or systematic pattern; only in D01, we note a prevalence of negative trends, which may be a reflection of a northwestward shift of storm tracks. There is no discernible difference between persistence trends for 4-day sequences and daily patterns.

Our results confirm previous conjectures that highly positive persistence trends detected in the subjective Hess-Brezowsky classification are unrealistic since they are not matched by trends in any of the large number of other classifications. These spurious trends result from an artificial step-like increase of persistence in the Hess-Brezowsky classification to have occurred in the mid-1980s. This gives a warning that subjective classifications are not suitable for assessments of long-term trends because of their inherent subjectivity and potential lack of homogeneity due to changes, whether abrupt or gradual, in the procedures of their production.

It is quite frequent a case that two CTs coming from different classifications that have a very similar flow configuration (e.g. westerly cyclonic flow) disagree in their trends in frequency and/or persistence. This suggests that the use of only a single CT classification or a limited number of CT classifications in synoptic-climatological studies produces results that are impossible to generalize or may even be misleading.

A general advice stemming from our results is, therefore, that the use of multiple classifications in parallel when studying a long-term behaviour of atmospheric circulation is strongly recommended.

Acknowledgements

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Appendix

A1. Nomenclature of circulation types

For a detailed description of the CT classifications used in this study, see Philipp *et al.* (2010, 2016). Here we provide a basic description of CTs for the interested reader.

The subjective GWLo27 (German Hess-Brezowsky classification) contains 29 CTs (Grosswetterlagen), classified according to the main direction of airflow and the position of cyclones and anticyclones. Additionally, a minor proportion of days are unclassified. The CTs from GWLo27 are grouped into eight directional ‘supertypes’, and cyclonic and anticylonic types in GWLo09 (Grosswettertypen). OGWo is a computer-assisted classification of the 29 Hess-Brezowsky types. Both versions of the GWLo contain a constraint of a minimum 3-day persistence of synoptic situations. The Hungarian Péczely classification (PECo) contains 13 types, and the Alpine classifications by Perret (PERo), Schüepp (SUEo), and ZAMG (ZMGo) contain 31, 40, and 43 types, respectively.

In the objective classifications, the number of CTs was unified as much as possible to allow for a direct comparison of the resulting catalogues of daily CTs. For each classification method, three versions with approximately 9, 18, and 27 CTs are available. The idea behind these numbers is that naturally there should be eight types according to the eight basic directions of airflow, plus one non-directional type. Then the nine types split into two and three types, describing circulation in more detail, in classifications with 18 and 27 types, respectively. Also, the number of 27 is close to the number of types in most widely used manual classifications. Some classification methods produce slightly different numbers of CTs than 9, 18, and 27 for technical reasons: e.g. eight or ten instead of nine, and 26 instead of 27 (Table 1).

In many classifications some CTs are not present in some seasons (this further varies among the 12 domains), so the actual number of CTs present in a given season and domain can be lower than the declared number (and even much lower in a few cases). Typically, in summer, not all CTs are present – this can be viewed as a natural interannual variability of circulation patterns; however, some classifications reflect it while others do not.

Most classification methods end up with the most frequent CT being denoted as CT #1, the second most frequent as CT #2, etc. The exceptions to this rule (GWT, JCT, LIT, and KRZ methods) are described further.

The nomenclature of CTs is almost the same in the GWT and JCT methods, which use pre-defined types, as follows: in GWT, CT #1 = W, 2 = SW, 3 = NW, 4 = N, 5 = NE, 6 = E, 7 = SE, and 8 = S. In JCT, CT #1 = W, 2 = NW, 3 = N, 4 = NE, 5 = E, 6 = SE, 7 = S, and 8 = SW. JCT has an additional ninth CT in version ‘09’, which is an Azores high extended over Europe with well-pronounced lows over Iceland and the Middle East. The eight directional CTs split into cyclonic and anticyclonic CTs in versions ‘18’ (numbers 1–8 for C, 9–16 for A). Purely cyclonic CT #17 and anticyclonic CT #18 contain days from all CTs from version ‘09’. The ninth CT in JCT09 is dispersed into all 18 CTs in JCT18. In the ‘27’ version, CTs 1–8 are cyclonic directional, 9–16 anticyclonic directional, 17–24 purely directional, 25 is purely cyclonic, 26 purely anticyclonic, and 27 is a type with unclassifiable circulation. In GWT27, CT #27 contains days from all CTs from version ‘09’, while in JCT27, this type is equal to CT #9 from the ‘09’ version.

In the LIT classification, the eight directional CTs are numbered clockwise from N: CT #1 = N, 2 = NE, 3 = E, 4 = SE 5 = S, 6 = SW, 7 = W, 8 = NW, and 9 = undefined. The nine CTs split evenly into 18 and 27 CTs as in GWT and JCT. Although the LIT method uses pre-defined CTs based on simple circulation indices, it further optimizes the thresholds between CTs so that the long-term frequency of all CTs is equal in every day of the year. The properties of CTs then change from day to day because classification criteria change from one calendar day to another. As a result, even though CT #1 is supposed to be northerly, #2 north-easterly, etc., in reality the CTs are ‘shifted’ in the direction of the most frequent circulation pattern. And because the definition of CTs depends on the actual data entering the classification process, we might obtain different classifications with irreproducible patterns for different time periods or for different geographical domains.

In the KRZ method, which is based on principal component analysis, the CTs are defined as follows: For 27 types, each of the three leading principal components is split into three equiprobable classes according to their scores. For 18 types, the ‘zonal’ and ‘meridional’ principal components are split into three and the ‘cyclonic’ principal component is split into two classes. And for nine types, the ‘zonal’ and ‘meridional’ principal components are each split into three classes, while the ‘cyclonic’ principal component is not considered (not split).

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