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Changes in atmospheric circulation over Europe detected by objective and subjective methods

J. Kyselý and **R. Huth**

With 12 Figures

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Summary

Changes in atmospheric circulation over Europe since 1958 were examined using both objective (modes of low-frequency variability and objective classification of circulation types) and subjective (Hess-Brezowsky classification of weather types) methods. The analysis was performed with an emphasis on the differences between the winter (DJF) and summer (JJA) seasons, and between objectively and subjectively based results. Majority of the most important changes in atmospheric circulation are same or similar for the objective and subjective methods: they include the strengthening of the zonal flow in winter since the 1960s to the early 1990s; the increase (decrease) in frequency of anticyclonic (cyclonic) types in winter from the late 1960s to the early 1990s, with a subsequent decline (rise); and the sharp increase in the persistence (measured by the mean residence time) of all groups of circulation types in winter around 1990 and of anticyclonic types in summer during the 1990s. Differences between the findings obtained using the objective and subjective methods may result from the intrinsically different approach to the classification (e.g. the Hess-Brezowsky weather types have a typical duration of at least 3 days while objective types typically last 1–3 days). Generally, changes in atmospheric circulation which have taken place since the 1960s were more pronounced in winter than in summer. The most conspicuous change seems to be the considerable increase in the persistence of circulation types during the 1990s, which may be also reflected in the increase in the occurrence of climatic extremes observed in Europe during recent years.

1. Introduction

Changes in atmospheric circulation over the North Atlantic and Europe have been studied recently by several groups of authors employing various methods and time periods. These studies mainly focused on objectively determined characteristics of circulation patterns (modes of variability and circulation types/weather regimes; e.g. Slonosky et al., 2000; Plaut and Simonnet, 2001), atmospheric centres of action and indices of atmospheric flow (mostly zonal) (Mächel et al., 1998; Fu et al., 1999; Slonosky et al., 2000; Jacobeit et al., 2001), subjective circulation classifications (Bárdossy and Caspary, 1990; Stefanicki et al., 1998; Werner et al., 2000) or some combination of the objective and subjective approach (Maheras et al., 2000). Only occasionally have objective and subjective classifications been employed as complementary methods (Buishand and Brandsma, 1997).

Most studies dealing with changes in atmospheric circulation have been confined to analyzing changes in the frequency of circulation types and groups of circulation types. However, a few recent studies, examining the Hess-Brezowsky classification of Grosswetterlagen, have indicated that considerable changes in the persistence (measured by the mean residence time of circulation types) of atmospheric circulation types over Europe occurred during the 1980s and 1990s. The increase in the mean residence time of the Hess-Brezowsky types was reported by Werner et al. (2000) for zonal circulation in winter and Kyselý (2000, 2002) for all groups of circulation types in summer. This might promote changes in the occurrence of temperature (and perhaps other climatic) extremes, as demonstrated in Kyselý (2002) who looked at heat wave frequency and intensity in Prague, and Domonkos et al. (2003) who examined the frequency of extreme warm events in Central and Southeastern Europe.

The aim of this paper is to compare changes in atmospheric circulation over Europe as detected by objective and subjective methods. The period analysed covers 1958–1998 for the objective methods and 1958–2000 for the subjective Hess-Brezowsky classification. The winter (DJF) and summer (JJA) seasons are examined separately. The paper is organized as follows: Changes in the atmospheric circulation during the past 40 years are examined in Sections 2 and 3 for the objective and subjective methods, respectively, along with a description of the methods. In Section 4, a discussion focusing on a comparison of objectively and subjectively-based results and on the enhanced persistence of circulation types in the 1990s follows. Conclusions are drawn in Section 5.

2. Changes in atmospheric circulation detected by objective methods

Two complementary objective methods were employed to examine changes in atmospheric circulation over Europe during the period 1958–1998; these are modes of low-frequency variability (part 2.1) and the objective classification of circulation patterns (part 2.2). NCEP-NCAR reanalysis as a 2.5° × 2.5° grid were used as the source of the 500 hPa geopotential height fields at 12 UTC (Kalnay et al., 1996). Modes of low-frequency variability were studied using monthly data while circulation types were based on daily data; see description below.

2.1 Modes of low-frequency variability

2.1.1 Method

Modes of low-frequency variability were analysed over the region bounded by the 45° W and 45° E meridians, and the 35° N and 70° N parallels. Monthly anomalies (departures of monthly values at each grid point from long-term monthly means) were taken as input data. The modes were obtained by principal component analysis (PCA) in the S-mode, i.e. the columns of the data matrix correspond to gridpoints, while rows correspond to time realizations (months). The correlation matrix was used as a similarity matrix and the principal components were obliquely rotated (using the 'Direct Oblimin' method; see e.g. Richman, 1986) so that maximum regionalization would be achieved. A spatial structure of the modes is provided by the principal component (PC) loadings and their temporal behaviour by PC scores. The value of each mode in an individual season was computed as an average of the three monthly values. Two characteristics describing temporal variability were studied to assess long-term changes: the intensity (amplitude) of the modes and their interannual variability.

2.1.2 Description of modes

The number of modes (i.e. the number of retained PCs that are rotated) was determined from an eigenvalue vs. PC number diagram,

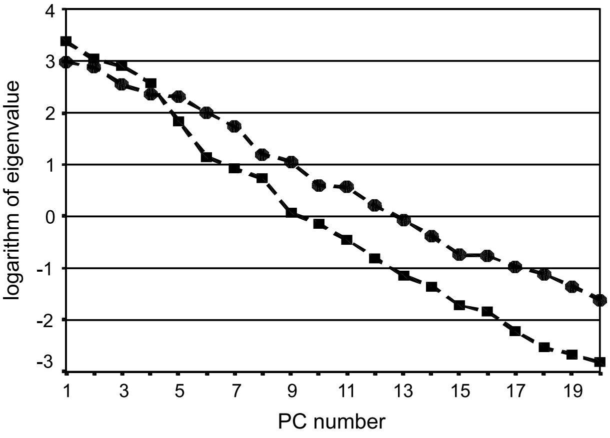

Fig. 1. Logarithm of eigenvalue vs. PC number plot; winter (summer) is denoted by squares (circles). The drop after the 4th (5th) PC in winter (summer) can be clearly seen

using the criterion of O'Lenic and Livezey (1988), which suggests to cut the number of PCs just after the flat section (shelf) in the diagram followed by a drop. These diagrams (Fig. 1) identified four modes in winter and five in summer. The cumulative variance explained by

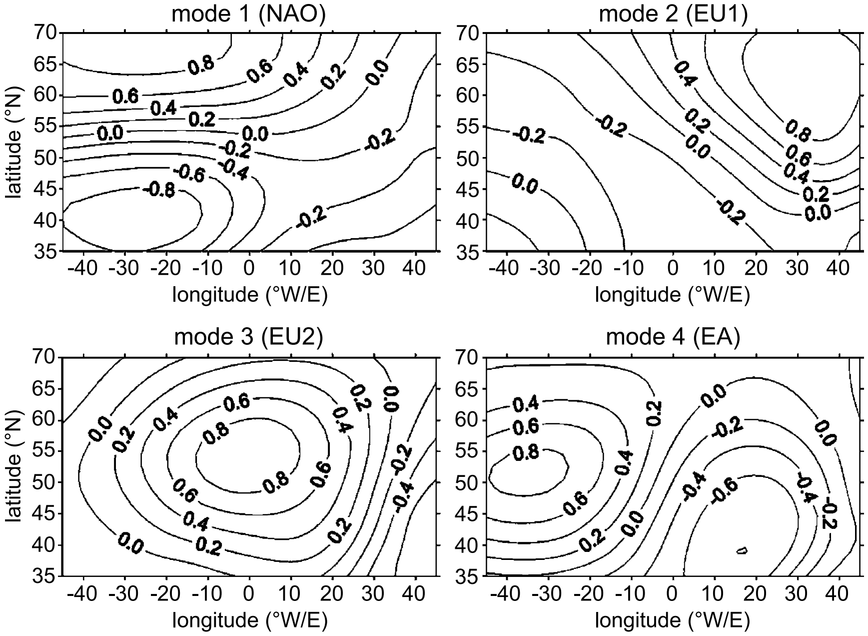
mode 1 (NAO)
mode 2 (EU1)
mode 3 (EU2)
mode 4 (EA)

Fig. 2. Maps of PC loadings for modes of low-frequency variability in winter (DJF)

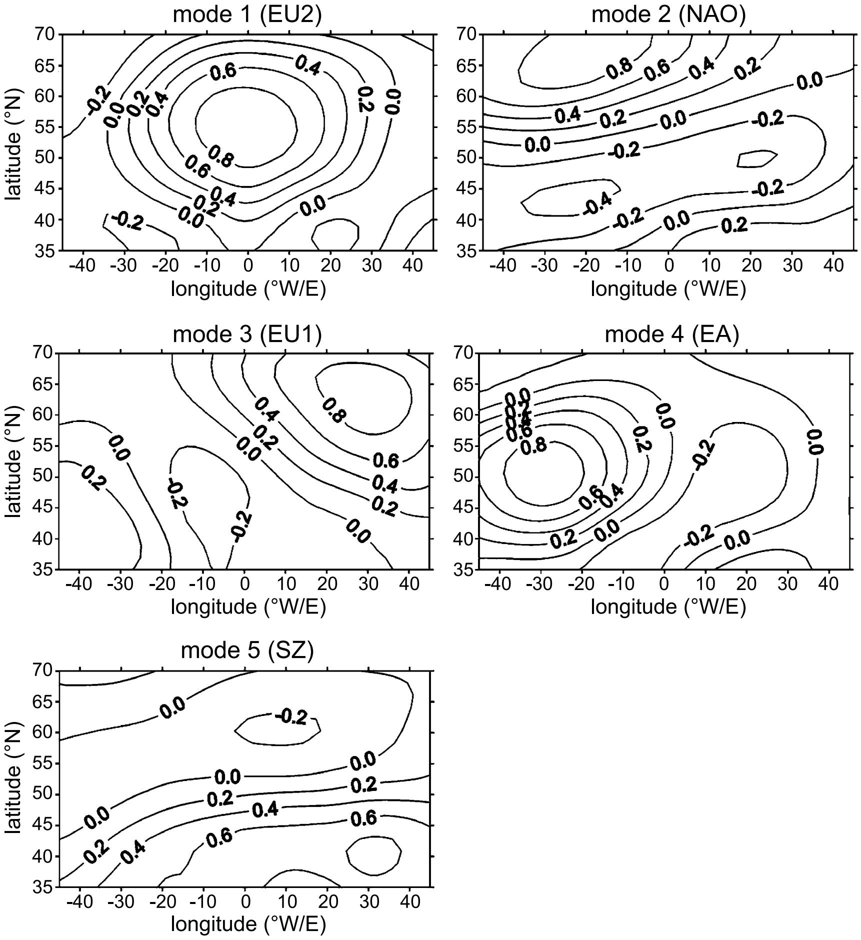
mode 1 (EU2)
mode 2 (NAO)
mode 3 (EU1)
mode 4 (EA)
mode 5 (SZ)

Fig. 3. Same as in Fig. 2 except for summer (JJA)

the leading 4 (5) modes in winter (summer) is 81.3% (70.7%).

The spatial structure of the modes of variability for winter and summer are shown in Figs. 2 and 3, respectively. The most important winter mode (i.e. the mode explaining the largest fraction of the total variation in data) is the North Atlantic Oscillation (NAO) (cf. Barnston and Livezey, 1987; Clinet and Martin, 1992; Ambaum et al., 2001). (Note that its phases are reversed here against the common definition of the NAO: In its positive phase, positive anomalies of geopotential heights occur around the Icelandic Low centre while negative anomalies are found around the Azores High, which leads to a weaker zonal flow over the North Atlantic, and vice versa.) Other modes of variability can be identified with the first and second Eurasian modes (EU1 and EU2) and the East Atlantic mode (EA), according to the nomenclature introduced by Barnston and Livezey (1987). The modes closely resemble the results of other studies (e.g. Barnston and Livezey, 1987; Clinet and Martin, 1992) despite differences in methods and data used. Four of the summer modes can be identified with the winter modes, although locations and intensities of their action centres differ. NAO appears as the second mode in summer. Summer modes 2 (NAO) and 5 (Subtropic Zonal, SZ) correspond to the results of Barnston and Livezey (1987); Clinet and Martin (1992) described the first four modes identified here but with different names.

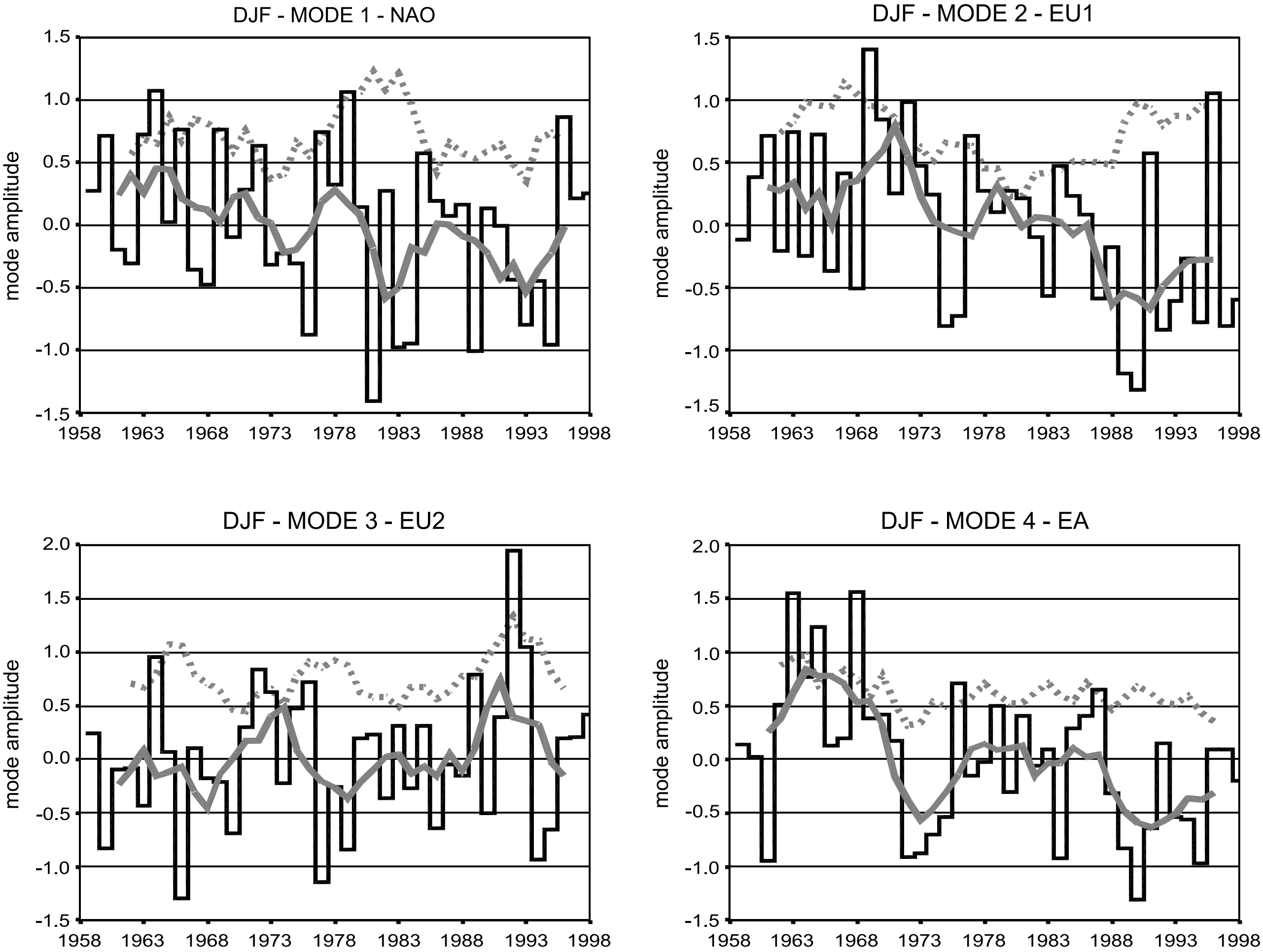

Fig. 4. Temporal variations in the amplitude of low-frequency variability modes in winter: mean seasonal values (columns) and 5-yr running means (bold grey curve). 5-yr running means of absolute values of the year-to-year changes are depicted by a dotted grey line

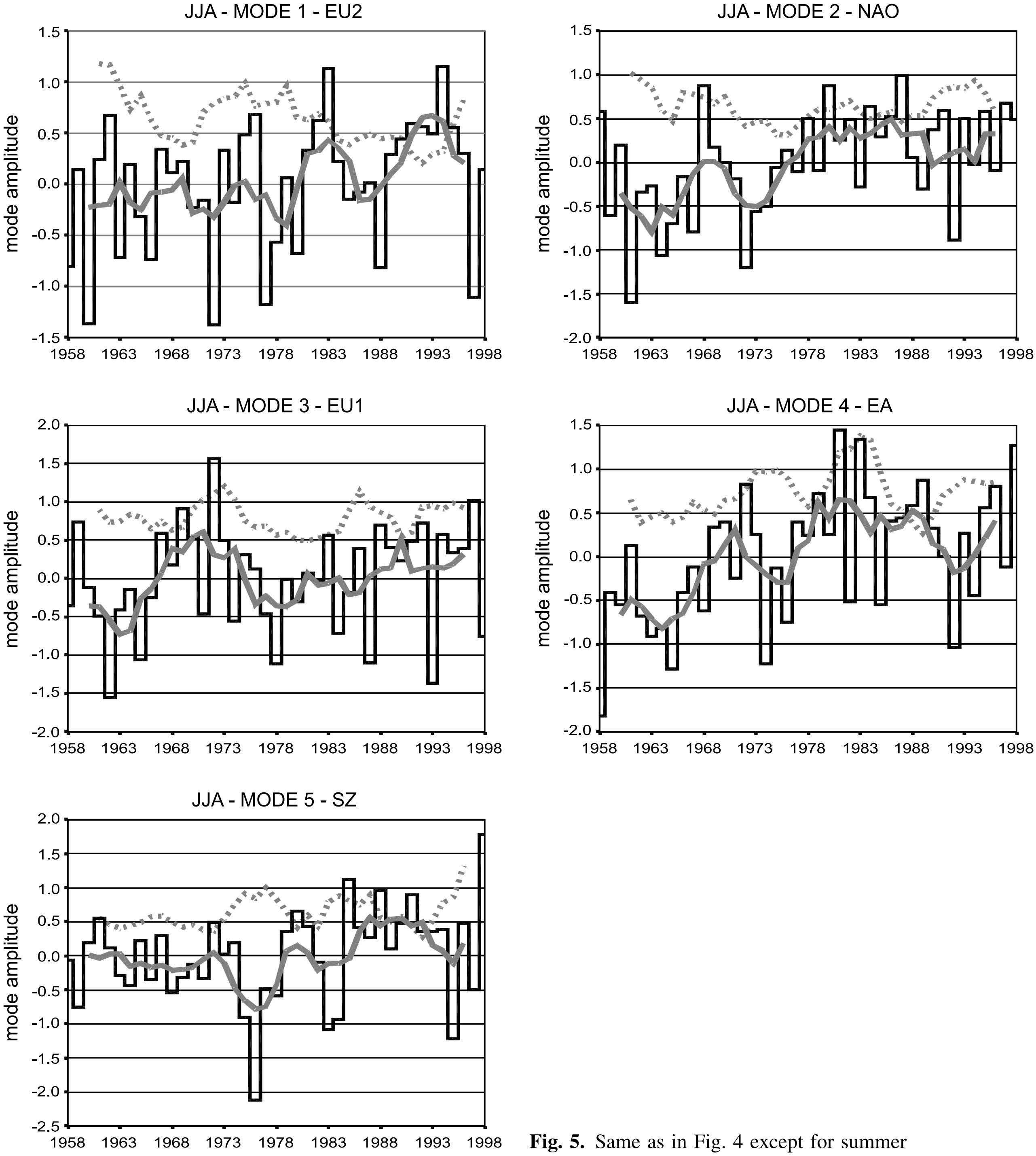

Fig. 5. Same as in Fig. 4 except for summer

2.1.3 Results

The temporal variability of the amplitude of the low-frequency modes over the North Atlantic and Europe is shown in Figs. 4 (winter) and 5 (summer). Five-year running means are shown in addition to annual values since they better express long-term changes; 5-yr running means of absolute values of the year-to-year changes in the mode intensity are shown as a measure of the interannual variability. The main findings are as follow:

Winter:

1. The amplitude of the NAO mode decreased throughout the period examined, i.e. the zonal

Table 1. Significance of trends in the amplitude of low-frequency circulation modes over the period since 1958. ++ (−−) stands for positive (negative) trend significant at the 0.05 level, + (−) for positive (negative) trend insignificant at the 0.05 level but significant at the 0.30 level; no symbol is shown for trends insignificant at the 0.30 level. n.a. denotes 'not analysed'

	NAO	EU1	EU2	EA	SZ
DJF	−	−−	+	−−	n.a.
JJA	++		+	++	+

NAO = North Atlantic Oscillation, EU1 (EU2) = first (second) Eurasian mode, EA = East Atlantic mode, SZ = Subtropical Zonal mode

circulation intensified. The NAO variability was considerably higher during the 1970s and 1980s than any other period.

2. The EU1 mode shows a decrease (i.e. a tendency toward intensified cyclonic activity over Fennoscandia) during the 1970s and 1980s. The interannual variability of EU1 was relatively low during the time of the decline in amplitude, and considerably higher during the 1960s and 1990s. The negative trend over 1958–1998 is significant at the 0.05 level (Table 1).
3. The EU2 mode shows a slight overall increase in the amplitude, corresponding to an increase in blocking patterns over the British Isles, with a maximum in the early 1990s.
4. The EA mode was in the positive phase in the 1960s (which was also the period of its larger interannual variability), and the negative phase dominated during the 1970s and 1990s. The latter can be explained by suppressed cyclonic activity over the Mediterranean; the overall negative trend is significant at the 0.05 level.

Summer:

1. The amplitude of the EU2 mode has increased since the late 1970s (which corresponds to enhanced blockings over the British Isles), this increase being accompanied by lower interannual variability.
2. The amplitude of the NAO mode increased (i.e. the zonal flow became weaker) during the 1960s and 1970s; positive values prevailed from the early 1980s, and the trend is significant at the 0.05 level.
3. A slight increase was observed in the amplitude of the EU1 mode, i.e. a tendency toward intensified anticyclonic activity over Fennoscandia (opposite to winter).
4. The EA mode manifests very similar changes to the NAO (increased North Atlantic blocking since the late 1970s, the overall positive trend is significant at the 0.05 level); it suggests that variability on a decadal scale may be governed by a common dynamical forcing.

At least in a part of the period examined and in both seasons, some modes show quasi-periodic variability of their amplitude or their interannual variability with a period of about 10 years.

2.2 Circulation types

2.2.1 Method

Circulation types were analysed in the 500 hPa geopotential height field over a window covering the central part of Europe (40–60° N, 10° W–25° E). The classification method is that used by Huth (2001) where it is described in a sufficient detail and relevant references are provided. This method employs a two-stage classification procedure connecting PCA in a T-mode with the k-means method of non-hierarchical cluster analysis in order to relieve the respective drawbacks of the individual methods: the inability of T-mode PCA to cope with huge datasets and the sensitivity of the k-means technique to the selection of initial seed points (Huth, 1996). The dataset was first divided into 15 subsets, each comprising every 15th day (i.e. subset 1 contains days 1, 16, 31, 46, etc., subset 2 contains days 2, 17, 32, etc.). Each subset was separately subjected to oblique rotation ('Direct Oblimin' method) in a PCA in the T-mode (time realizations (daily patterns) are arranged in the columns of a data matrix and gridpoint values form rows); cf. Richman (1986) and Huth (1996). In all subsets, both in winter and summer, six principal components (PCs) were retained and rotated, and were subsequently projected onto the full dataset (details e.g. in Huth, 2000). This results in 15 different classifications of all daily patterns, each consisting of 6 types. In the next step, the centroids of the types were determined in the space defined by a few leading PCs (5 [6] in winter [summer], explaining together more than 93% of the cumulative variance) identified from an unrotated PCA in the S-mode. The centroids enter the k-means clustering method (Gong and Richman, 1995). The resulting 15 classifications, each still consisting of 6 types, were then merged together. The final types were defined as those groups of days that belong to a single type in each of the 15 classifications. For example, the days classified with type 1 in all classifications form final type 1, the days classified with type 1 in classifications 1 to 14 and with type 2 in classification 15 form final type 2, etc. In practice, only a small number of combinations of types occur, and only a few types are occupied by a relatively large number of daily patterns. The groups with a small sample size cannot be considered 'typical' and their statistical analysis would not therefore be sensible; for this reason, only sufficiently large groups are retained for further analysis. The threshold for considering the group 'large enough' was set, somewhat arbitrarily, to 50. The days classified by groups with fewer than 50 members were excluded from further consideration.

This classification system resulted in the identification of 17 types in winter and 14 types in summer. The percentage of classified days is 80.3% in winter and 65.5% in summer. The fact that not all patterns were classified may be considered beneficial as the patterns difficult to classify (e.g. outliers) were excluded from the analysis.

2.2.2 Results

Since the interpretation of trends in the frequency and persistence (the mean lifetime) of individual types is rather difficult, the types were grouped into several (not necessarily disjointed) 'supertypes' with common features, with an emphasis on the nature of the flow over Central Europe. The grouping was based on the mean 500 hPa height patterns of the types (not shown here), with emphasis on the circulation characteristics (cyclonicity/anticyclonicity) and prevalent flow direction over Central Europe. In winter, 5 'supertypes' were created: zonal (consisting of 5 types/ 686 days), cyclonic (5 types/990 days), anticyclonic (7 types/1506 days), with a blocking anticyclone (4 types/700 days), and northerly (with northwest to northeast flow; 6 types/921 days). In summer, 5 'supertypes' were constructed as well: zonal (7 types/995 days), cyclonic (7 types/1190 days), anticyclonic (5 types/1093 days), southwest (5 types/707 days) and northwest (4 types/483 days). The 5-yr running means of the frequencies of these groups are shown in Fig. 6.

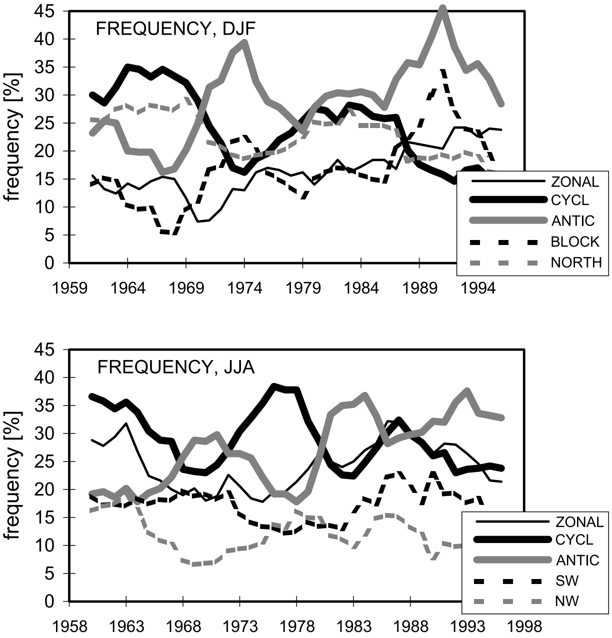

Fig. 6. 5-yr running means of frequencies (in %) of all groups of types ('supertypes') defined in the text, in winter (top) and summer (bottom). ZONAL = zonal types, CYCL = cyclonic, ANTIC = anticyclonic, BLOCK = blocking anticyclone, NORTH = north flow, SW = southwest flow, NW = northwest flow

Considerable interannual and decadal variability was found in the frequency of 'supertypes'; however, some long-term changes were also notable. Both in winter and summer, an increase in the frequency of anticyclonic conditions occurred in the last 40 years, while the frequency of cyclonic types has decreased (Fig. 6). These trends are significant at the 0.05 level in both seasons (Table 2). In winter these trends terminate in the early 1990s from which time a decline in the frequency of anticyclonic conditions dates. This decrease is not compensated for by a corresponding rise in the frequency of the cyclonic types. An increase in the frequency of the anticyclonic types in winter has been caused almost entirely by a rise in the occurrence of blocking anticyclones over Western and Central Europe. In winter, a long-term increase in the frequency of zonal flow has been observed as well as a decrease in the occurrence of the

Table 2. Significance of trends in the frequencies and mean residence times of circulation types over the period since 1958. ++ (−−) stands for positive (negative) trend significant at the 0.05 level, + (−) for positive (negative) trend insignificant at the 0.05 level but significant at the 0.30 level; no symbol is shown for trends insignificant at the 0.30 level. n.a. denotes 'not analysed'

a. objectively defined circulation types

		All types	ZONAL	CYCL	ANTIC	BLOCK	NORTH
DJF	frequency	n.a.	++	−−	++	++	−−
DJF	persistence		+			+	
		All types	ZONAL	CYCL	ANTIC	SW	NW
JJA	frequency	n.a.		−	++		
JJA	persistence	+					

ZONAL = zonal types, CYCL = cyclonic types, ANTIC = anticyclonic types, BLOCK = blocking anticyclone, NORTH = north flow, SW = southwest flow, NW = northwest flow

b. subjective Hess-Brezowsky types

		All types	W	N	HM	S	E	NW	NE	CYCL	ANTIC
DJF	frequency	n.a.	++	−−				++	n.a.		++
DJF	persistence	++	++		+		++	+	n.a.	++	++
JJA	frequency	n.a.		++	+		−	−−	−		
JJA	persistence	++	+	++	++	++	++		+	++	++

W = west types, N = north types, HM = central European high, S = south types, E = east types, NW = northwest types, NE = northeast types, ANTIC = anticyclonic types, CYCL = cyclonic types

north 'supertype' (both significant at the 0.05 level), although the latter oscillates with an approximately 20-yr periodicity; the north flow was more (less) frequent in the 1960s and 1980s (1970s and 1990s). Such quasi-oscillatory behaviour dominates over long-term trends in the frequency of 'supertypes' in summer.

Five-year running means of the persistence of the 'supertypes' (defined as the mean lifetime of the individual types) are shown in Fig. 7. Most notable is the fact that the mean lifetime does not depend on the occurrence frequency (i.e. if a type is more frequent in a given period, it does not necessarily persist longer); the only exception to this rule is that higher frequencies of anticyclonic types and blockings in the early 1990s in winter were associated with considerably increased persistence. The persistence of all 'supertypes' increased in the late 1980s and/or early 1990s in winter but has decreased since then. In summer, an increased persistence of cyclonic and anticyclonic types was found in the late 1960s and early 1970s while the late 1980s were a period of high (low) persistence of cyclonic (anticyclonic) types. During the 1990s, the persistence of the anticyclonic types in summer rose while the persistence of the cyclonic types declined. The persistence of zonal flow was found to decrease from the late 1980s.

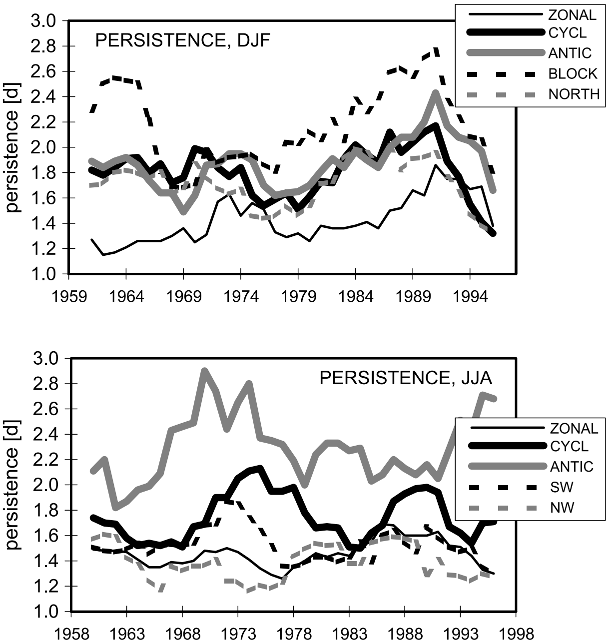

Fig. 7. 5-yr running means of the mean lifetime (persistence; in days) for groups of types ('supertypes'). For the description see Fig. 6

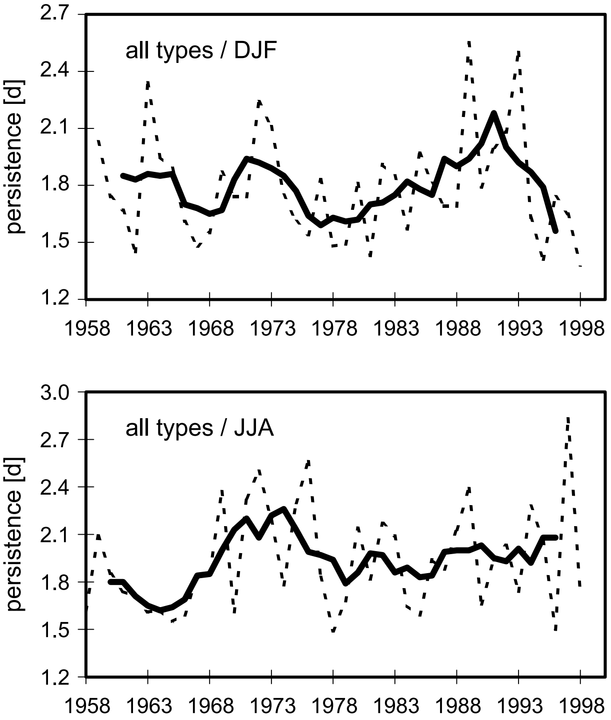

Fig. 8. Temporal changes in the mean lifetime averaged over all circulation types in winter (top) and summer (bottom) for objectively defined types. Solid curves show 5-yr running means

Due to the quasi-oscillatory behaviour, the long-term trends are mostly insignificant (Table 2).

If all the objectively-defined circulation types are considered together, their persistence was enhanced on average around 1990 in winter (the rise in the mean residence times in 1985–1994 compared to the previous decades is statistically significant at the 0.05 level according to the t-test) but have been decreasing relatively sharply thereafter (Fig. 8). In summer, no clear trend was identified for the period examined. Note that averaging is performed over individual types in each 'supertype' again; averaging over the 'supertypes' is impracticable because they are not mutually exclusive.

3. Changes in atmospheric circulation detected by the subjective classification

3.1 Hess-Brezowsky classification of circulation patterns

The Hess-Brezowsky catalogue of large-scale circulation patterns (Hess and Brezowsky, 1952; Gerstengarbe and Werner, 1993; Gerstengarbe et al., 1999) is frequently used to characterize atmospheric flow over the eastern North Atlantic and Europe (Klaus and Stein, 1978; Bárdossy and Caspary, 1990; Keevallik et al., 1999; Werner et al., 2000; Pryor and Barthelmie, 2003). The classification recognizes three groups of circulations types (zonal, half-meridional and meridional) which are divided into 10 major types (Grosswettertypen, GWT) and 29 subtypes (Grosswetterlagen, GWL; see Table 3). Any circulation type (GWL) persists for several days (normally at least three days), which is different from objective circulation types, as well as from the Lamb classification of weather types used for the British Isles (Lamb, 1972). For the description of individual GWL see e.g. Gerstengarbe et al. (1999). A list of the types and major types is given in Table 3.

Analyses were conducted for individual types (GWL) and the groups corresponding approximately to the major types (GWT) given in Table 3. The only difference is that the major types S, SW and SE were grouped together into one new major type (denoted by S hereafter) in both seasons. The reason for this adjustment is the relatively low frequency of the major types SW and SE. Following this aggregation, the frequencies of the S (south) and N (north) major types are comparable in their long-term means, which facilitates their direct comparison. We decided to examine only major types with higher than 5% long-term relative frequency in a given season. This is why the northeast type (NE) is not analysed in winter (relative frequency 2.5%) and the Central European low (TM) is omitted in both seasons. The long-term mean annual relative frequencies of the analysed groups of GWL are as follows (Gerstengarbe et al., 1999): west (W) 27.2%, central European high (HM) 16.4%, south (S) 16.3%, north (N) 15.9%, northwest (NW) 8.4%, east (E) 7.8%, northeast (NE) 4.4%. In total these comprise 96.4% of all days. The period examined was 1958–2000.

Furthermore, 12 (13) GWL which prefer an anticyclonic (cyclonic) circulation over Central Europe (Gerstengarbe et al., 1999) were selected, and the same analysis, as described above, was carried out for the anticyclonic (A) and cyclonic (C) groups of GWL.

Table 3. List of Hess-Brezowsky major types (GWT) and types (GWL) (Bárdossy and Caspary, 1990; Gerstengarbe et al., 1999)

Major type (GWT)	Abbrev.	Type (GWL)	Abbrev.
A. zonal circulation			
West	W	West cyclonic	WZ
		West anticyclonic	WA
		West angular	WW
		Southern West	WS
B. mixed circulation			
Central European high	HM	Central European high	HM
		Central European ridge	BM
Central European low	TM	Central European low	TM
Southwest	SW	Southwest anticyclonic	SWA
		Southwest cyclonic	SWZ
Northwest	NW	Northwest anticyclonic	NWA
		Northwest cyclonic	NWZ
C. meridional circulation			
East	E	Fennoscandian high anticyclonic	HFA
		Norwegian Sea/Fennoscandian high anticyclonic	HNFA
		Fennoscandian high cyclonic	HFZ
		Norwegian Sea/Fennoscandian high cyclonic	HNFZ
South	S	South anticyclonic	SA
		South cyclonic	SZ
		British Isles low	TB
		Western Europe trough	TRW
Southeast	SE	Southeast anticyclonic	SEA
		Southeast cyclonic	SEZ
North	N	North anticyclonic	NA
		North cyclonic	NZ
		North, Iceland high, anticyclonic	HNA
		North, Iceland high, cyclonic	HNZ
		British Isles high	HB
		Central European trough	TRM
Northeast	NE	Northeast anticyclonic	NEA
		Northeast cyclonic	NEZ

3.2 Changes in frequency and persistence of groups of GWL in 1958–2000

3.2.1 Winter

Several conspicuous and statistically significant changes in the frequency and persistence of the major types occurred during winter over the period 1958–2000 (Figs. 9, 11):

1. A gradual increase in the frequency of the zonal type (W) up to around 1990, followed by a slight decrease. This increase was not due to the enhanced number of onsets (which reveals no trend over the period examined), but due to the increased mean residence time. The positive trend over 1958–2000 is significant at the 0.05 level (Table 2).
2. A considerable decline in the frequency of the north type (N) until the mid-1970s (from values as high as above 25% down to 10%); a very slight increase appeared in the 1990s. The decreasing trend over 1958–2000 is significant at the 0.05 level.
3. A minimum frequency of the Central European high (HM) in the late 1960s and a pronounced maximum around 1990, due to the increased mean residence time; the number of onsets was lower in the 1990s than 1970s and 1980s.
4. An upward trend in the frequency of the south type (S) until a maximum in the 1970s, followed by a decrease until 1990 and a slight increase during the 1990s.
5. A pronounced increase in the persistence of all major types (with the exception of the east

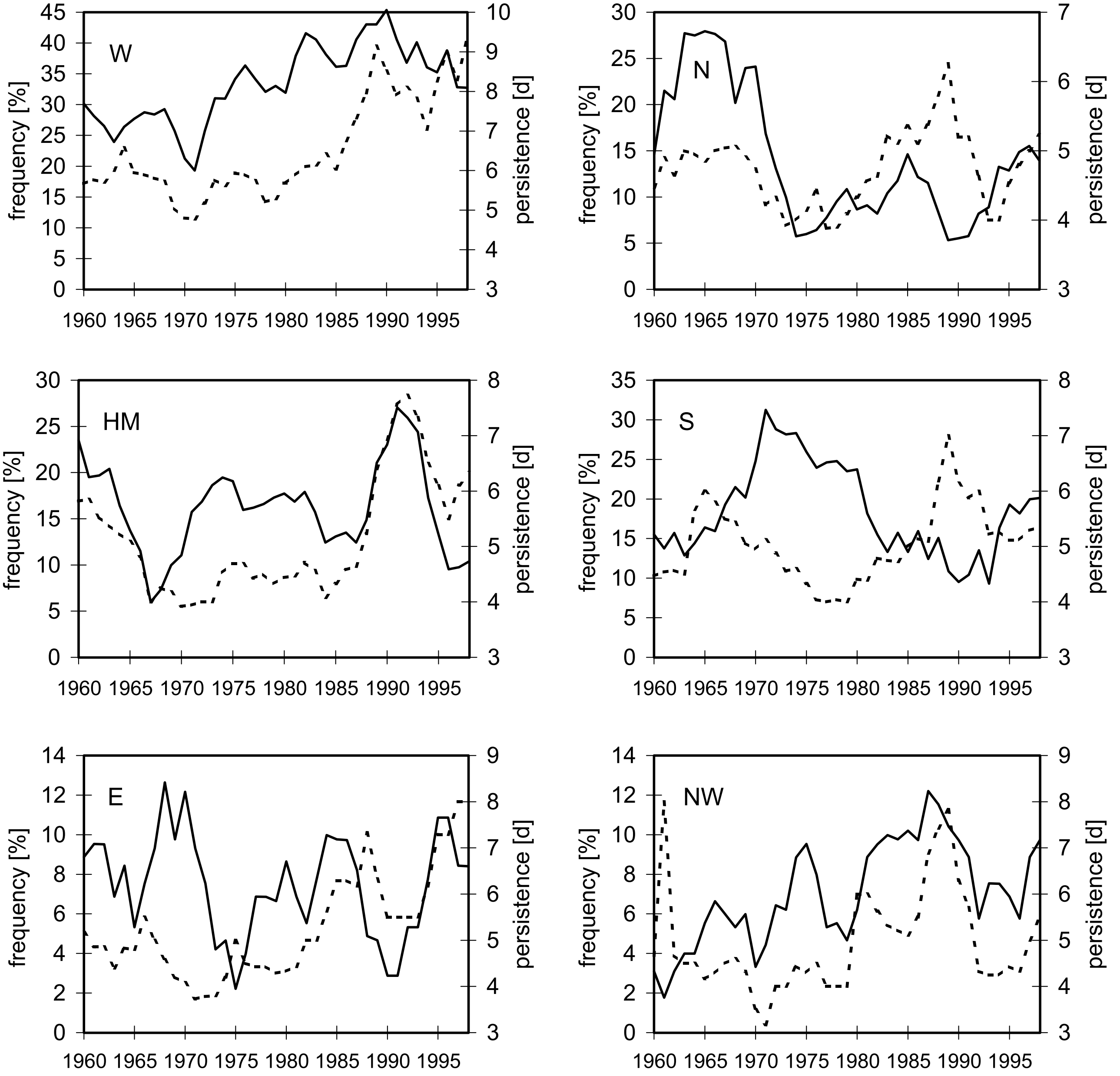

Fig. 9. Temporal changes in the relative frequencies of occurrence (in %; solid curve) and mean lifetime (in days; dashed curve) of groups of GWL in winter in the period 1958–2000. 5-yr running means are shown

type (E) with a later maximum at the end of the 1990s) around 1990, followed by a decrease until the mid-1990s and a rise at the end of the 1990s again. The trends in the mean residence times are significant at the 0.05 level for the W and E types as well as for the anticyclonic and cyclonic types and all types considered together.

6. A minimum frequency of the anticyclonic types during the late 1960s and a maximum around 1990; opposite changes for the cyclonic types. The long-term positive trend in the occurrence of the anticyclonic types is significant at the 0.05 level.

The significance of the long-term trends is summarized in Table 2; very similar results are obtained when non-parametric correlations are calculated (not shown).

3.2.2 Summer

The main features of the temporal changes in the characteristics of the major types in summer are as follows (Figs. 10, 11):

1. Small changes in the frequency of the zonal type (W), which is in contrast to winter, but a conspicuous increase in the persistence in the 1990s.

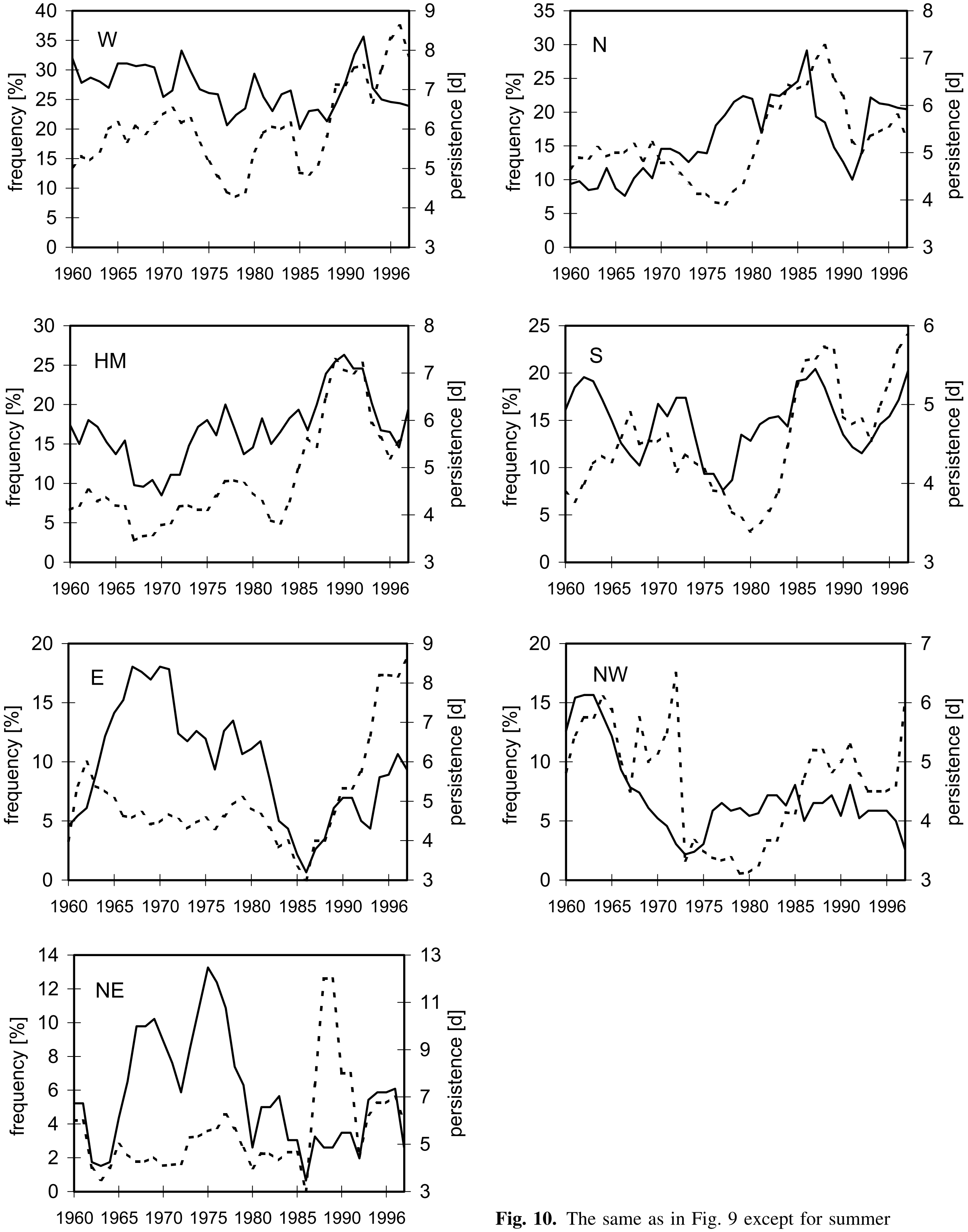

Fig. 10. The same as in Fig. 9 except for summer

2. A gradual increase in the frequency of the north type (N) until the mid-1980s, followed by a decrease; the rise was associated with a pronounced increase in persistence, and both the trends are significant at the 0.05 level.

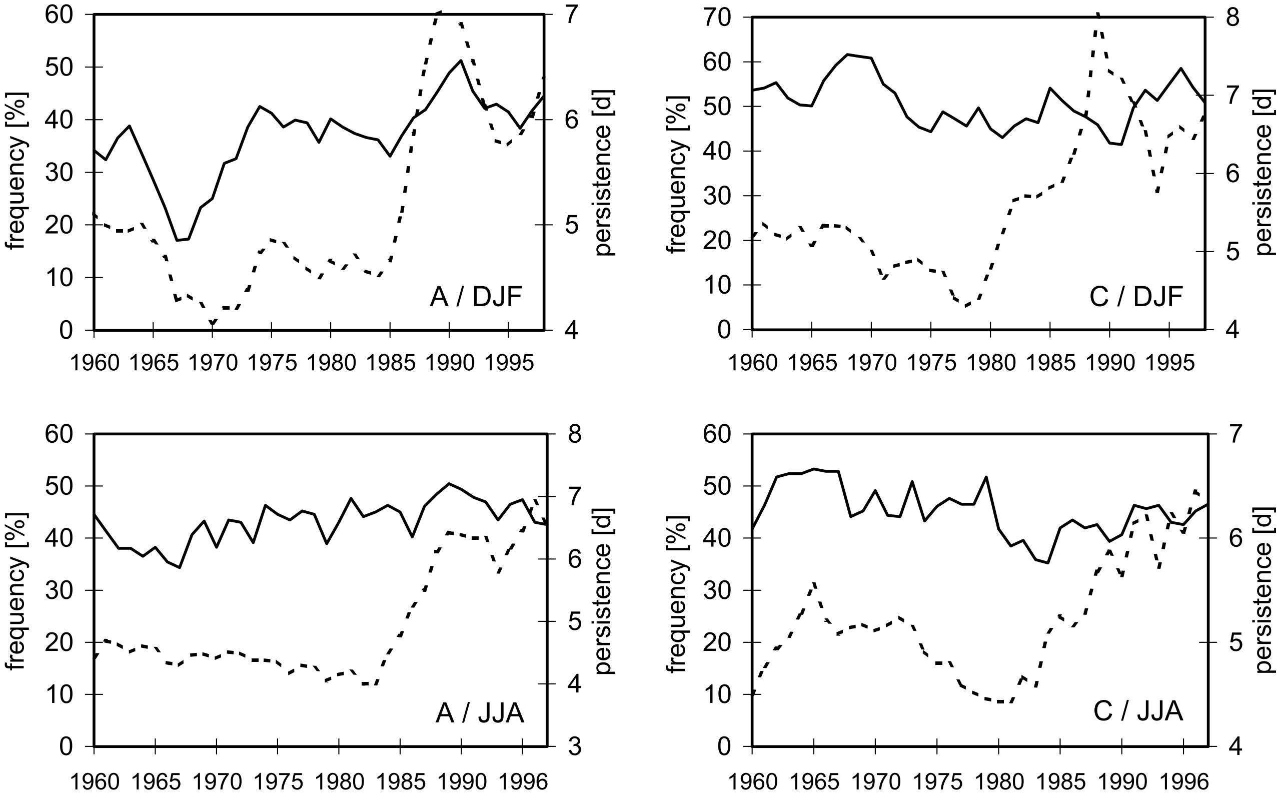

Fig. 11. Temporal changes in the relative frequency of occurrence (in %; solid curve) and the mean lifetime (in days; dashed curve) of GWL predominantly anticyclonic (left) and cyclonic (right) over central Europe in winter (top) and summer (bottom) in the period 1958–2000. 5-yr running means are shown

3. An upward trend in the frequency of the Central European high (HM) until around 1990, followed by a decrease; the increase was again due to the enhanced persistence while the frequency of onsets remained unchanged.
4. A negative link between the frequency of the Central European high (HM) and the east type with high over Fennoscandia (E); a maximum of E occurred in the late 1960s while a minimum in the mid-1980s, and opposite changes are typical of HM. The correlation between annual frequencies of HM and E types is significant at the 0.10 level.
5. A sharp fall in the frequency of the northwest type (NW) until the early 1970s, followed by generally consistent values; the negative trend over 1958-2000 is significant at the 0.05 level.
6. A considerable increase in the persistence of all major types in the late 1990s (types W, S, E, NW) and/or around 1990 (types N, HM, S, NE). The long-term trends in the mean residence times are positive and significant at the 0.05 level for the N, HM, S and E types, for the anticyclonic and cyclonic types, and for all types taken together (Table 2).

3.2.3 Changes in the persistence of circulation types

The increased persistence of the Hess-Brezowsky circulation types observed in both seasons in the 1990s is typical of multi-year periods and does not stem from the occurrence of individual years with extremely enhanced values (Fig. 12). The course of the variations is similar during the whole period of 1958–2000 in winter and summer. The most conspicuous difference is that while in summer the peaks around 1990 and in the late 1990s are of the same magnitude, higher values were attained around 1990 in winter. However, the increase at the end of the 1990s is clearly apparent in winter as well. The mean residence times of GWL are 1.5 days longer in the 1990s than in the previous decades both in winter and summer (a 30% relative increase), and

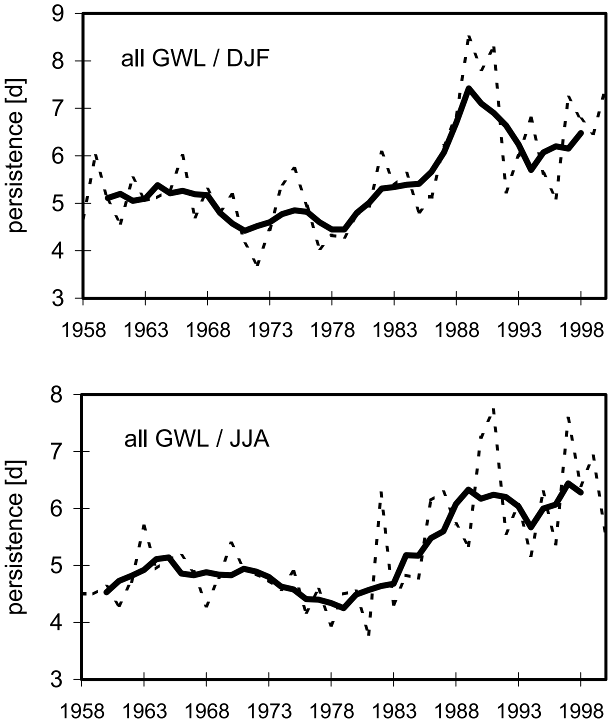

Fig. 12. Temporal changes in the mean lifetime averaged over all circulation types in winter (top) and summer (bottom) for subjective GWL. Solid curves show 5-yr running means

the difference is statistically significant at the 0.05 level according to the t-test in both seasons.

4. Discussion

4.1 Differences between results obtained by objective and subjective methods

The main differences in the detected changes of the atmospheric circulation between the objective and subjective methods are:

1. The subjective Hess-Brezowsky classification yields a double maximum in the persistence of most groups of circulation types around 1990 and in the late 1990s both in winter and summer. The objective classification, however, captures a single maximum for all groups of types around 1990 in winter, and a rise during the 1990s only for the anticyclonic types in summer. The objectively-defined anticyclonic types manifest a decreased persistence in summer around 1990 which is not reproduced by the subjective classification.
2. The long-term changes in the frequency of anticyclonic and cyclonic types are more pronounced using the objective than subjective classification.
3. The increased frequency of the north types in winter in the 1980s compared to the 1990s is observed only when the objective classification is employed.
4. The statistically significant long-term increase in the amplitude of the NAO in summer (corresponding to a weaker zonal flow) is not manifested in a decreased frequency of the zonal circulation types over Europe.

Since the Hess-Brezowsky catalogue is considered to be homogeneous (Gerstengarbe et al., 1999), the differences between the objective and subjective methods result from the intrinsically different approaches to the classification. First, the objective classification does not deal with a typical duration of circulation types that is characteristic of the Hess-Brezowsky catalogue; the subjective circulation types normally persist for at least three days and their duration is typically much longer than the duration of the objectively-defined types. Second, the percentage of unclassified days is much larger in the objective than subjective classification, which means that days with little pronounced or transition circulation patterns tend to be classified in the Hess-Brezowsky catalogue but remain unclassified by the objective algorithm. In addition to the methodological differences, the objective types are based on fields of the 500 hPa heights only while the Hess-Brezowsky classification takes both the surface pressure and the 500 hPa geopotential height fields into account. The different areas upon which the classifications are performed (for the objective types) or focus (for the subjective types), as well as the slightly different time period covered (the analysis based on the objectively-defined types ends in 1998) may also support the disagreement between the methods.

4.2 Enhanced persistence of atmospheric circulation in the 1990s

The enhanced persistence around 1990 and during the late 1990s is likely to be the most remarkable recent change in atmospheric circulation over Europe. Using long-term subjective catalogues of circulation types, changes in the mean residence times of weather states have been studied recently. While Bárdossy and Caspary

(1990) found no significant change in the duration of periods with the same GWL over 1881–1989, Werner et al. (2000) and Kyselý (2000, 2002) reported recent increases in the mean lifetime of zonal circulation in winter and of all main groups of circulation types in an extended summer season (May–September), respectively. These studies employed the Hess-Brezowsky catalogue of the weather types only, and no corresponding analysis has been carried out on objectively-based classifications.

The rise in the persistence of atmospheric circulation in winter around 1990 is also observed for all groups of the objectively-defined circulation types, although this increase is not as pronounced as for the Hess-Brezowsky types, and is followed by a decline during the 1990s. The enhanced mean lifetimes around 1990 are not detected by the objectively-defined circulation types in summer when only the persistence of the cyclonic types increases while that of the anticyclonic types declines. However, the mean residence time of the anticyclonic types in summer has been rising during the 1990s.

The partial discrepancy between the results for the objective and subjective circulation types raises a question regarding the homogeneity of the Hess-Brezowsky catalogue. However, this has been revised recently and has been found to be homogeneous (Bárdossy and Caspary, 1990; Gerstengarbe et al., 1999), which indicates that the statistically significant changes in the mean residence times of the major types should not reflect artificial disturbances in the time series. A substantial part of the difference between the objectively and subjectively-derived findings is likely to originate from the intrinsically different approaches to the classifications, as discussed in Section 4.1. The relatively large percentage of unclassified days in the objective catalogue, mainly in summer (35%), seems to be particularly responsible for the differences between the findings obtained by the two methods.

It is likely that the nature of the atmospheric circulation over Europe has changed towards a higher persistence in the 1990s. Perlwitz and Graf (2001) demonstrated that stratospheric circulation is much more persistent than tropospheric one, and discussed reasons for this variation in behaviour. They include the generation of baroclinic and barotropic instabilities. Hence, a decreased winter frequency of cyclones observed over large parts of Northern Hemisphere midlatitudes (30–60° N; McCabe et al., 2001; Paciorek et al., 2002), which include the area examined in this current study, along with increases in the occurrence of blockings (lifetimes of which are longer than of circulation types) in both seasons seem to be consistent with the observed rise in persistence. If global warming is associated with a northward shift of storm tracks in the Northern Hemisphere, as indicated by several modelling studies (e.g. Knippertz et al., 2000; Geng and Sugi, 2003), the increased persistence of atmospheric circulation over regions with decreased storm activity may be expected.

4.3 Potential links between increased persistence of atmospheric circulation and occurrence of extremes

Since circulation conditions that persist for relatively long periods of time may support anomalies of air temperature in one direction, the enhanced persistence of atmospheric circulation may have been one of the causes of the increased occurrence of climatic (mainly high-temperature) extremes in Central Europe during the 1990s and early 2000s (Heino et al., 1999; Domonkos et al., 2003; Beniston, 2004). Kyselý (2002) showed that increases in the frequency of anticyclonic circulation types at the expense of cyclonic ones contributed to the fact that the higher persistence of the atmospheric circulation in the early 1990s was reflected mainly in the occurrence of positive summer temperature extremes in Central Europe. To demonstrate circulation conditions during severe heat waves, two examples are provided for the longest heat waves since 1775 in Prague (the Czech Republic). These occurred in 1992 (duration 26 days) and 1994 (22 days); during both these hot periods, unusually long sequences of days classified with one GWL appeared (10-day HM followed by 6-day WA in 1992; 8-day BM followed by 7-day SA in 1994). Domonkos et al. (2003) also reported that the mean residence times of the Hess-Brezowsky circulation types (averaged over all types) have a positive correlation with the frequency of extreme warm events in Central and Southeastern Europe in summer, and that the relationship is significant at the 0.05 level for anticyclonic circulation types. The hypothesis of the link between the occurrence of extreme temperature events in summer and the changing persistence of circulation patterns, mainly anticyclonic, deserves further investigation.

The increased persistence of atmospheric circulation is also consistent with the results of Werner et al. (1999) who found a growing tendency of the persistence of temperature characteristics (particularly of sequences of warm and hot days) in Potsdam (Germany) towards the end of the 20th century. They hypothesized that this indicates a more stable atmospheric circulation over Europe.

4.4 Comparison of detected changes in atmospheric circulation with results of other studies

Most other findings compare well with the results of recent studies dealing with changes in the atmospheric circulation over Europe, and extend them in that they employ both the objective and subjective methods.

A strengthening of the zonal circulation in winter since the 1960s, reflected also in the positive trend of the NAO/AO index (Hurrell, 1995; Thompson et al., 2000) as well as the Central European Zonal index (Jacobeit et al., 2001), is likely the best documented change in the atmospheric circulation over the North Atlantic during recent decades (e.g. Bárdossy and Caspary, 1990; Slonosky et al., 2000; Plaut and Simonnet, 2001). The fact that changes in the strength of the zonal flow were much weaker and non-systematic in summer over the same period was also reported by several authors (e.g. Jacobeit et al., 2001).

A decline in the occurrence of the cold meridional circulation (the north and east types) in winter since the early 1970s was found by Bárdossy and Caspary (1990) who analysed data extending to 1989; a slight increase is observed in the 1990s. A rise in the frequency of anticyclonic circulation, consistent also with the decrease in the amplitude of the EA mode, as well as a decrease in the northerly weather type in winter over 1945–1994 was reported in the Alpine region by Stefanicki et al. (1998). They also pointed out that these frequency changes were primarily caused by changes of episode lengths, which is in accord with our findings for the objectively defined anticyclonic 'super-type', and that the circulation changes were most pronounced in winter.

A considerable increase in the frequency of winter blockings centred over southern Scandinavia and extending to Central Europe since the 1960s was documented by Plaut and Simonnet (2001). A decreasing frequency of the north type over Central Europe in the same period is reflected in the decline in the occurrence of the Atlantic Ridge weather regime (Plaut and Simonnet, 2001).

5. Conclusions

In this study, changes in the atmospheric circulation over the Euro-Atlantic domain were examined by objective and subjective methods. For this purpose, we utilize the concepts of modes of low-frequency atmospheric variability and circulation classifications. To our knowledge, this is the first attempt to put these methods into a common framework.

The majority of the most important changes in the characteristics of atmospheric circulation over Europe during the past 40 years detected by the objective (using the modes of low-frequency variability and the objective classification of atmospheric circulation fields) and subjective (examining the Hess-Brezowsky catalogue of circulation patterns) methods are similar. They include

- the strengthening of the zonal flow in winter between the 1960s and early 1990s;
- the rise in the frequency of anticyclonic patterns in winter upto the early 1990s, with a subsequent decline, and opposite change for the cyclonic conditions;
- less pronounced changes in the occurrence of anticyclonic and cyclonic types in summer, but with a long-term increase (decrease) in the frequency of anticyclonic (cyclonic) types throughout the period examined;
- the decrease in frequency of the north types in winter upto the mid-1970s; the increase (decrease) in the frequencies of the north types in summer until (from) the mid-1980s;
- the rise in the frequency of blockings mainly in winter, with a maximum in the early 1990s;

- the sharp increase in the persistence (measured by the mean residence time) of all groups of circulation types in winter around 1990, and of anticyclonic types in summer in the late 1990s; and
- generally more pronounced changes in the frequency of circulation types in winter than in summer.

Some differences between findings obtained using the objective and subjective methods are likely to stem from the fact that the objective methods are based on 500 hPa height fields while the Hess-Brezowsky classification considers both the surface and upper-air fields, from slightly different time-periods and regions covered, and intrinsically from the different approach to the classification (e.g. the Hess-Brezowsky weather types have a typical duration of at least 3 days while the objective types usually last 1–3 days).

The most conspicuous change seems to be the considerable rise in the persistence of the circulation types during the 1990s, which may have been reflected by the enhanced occurrence of climatic extremes recently observed over Europe. The comparison with the previous work of Bárdossy and Caspary (1990), who examined changes in the persistence of the Hess-Brezowsky circulation types in 1881–1989, indicates that such a change is unprecedented during the 20th century.

The increased persistence of atmospheric circulation over European midlatitudes is likely to be related to decreased cyclonic activity and enhanced blocking, and seems to be consistent with the influence of global warming. If global warming is associated with the northward shift of storm tracks in the Northern Hemisphere, the increased persistence of the atmospheric circulation over regions with the reduced cyclonic activity may be expected.

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Authors' address: Jan Kyselý (e-mail: kysely@ufa.cas.cz), Radan Huth, Institute of Atmospheric Physics AS CR, Boční II 1401, 141 31 Prague, Czech Republic.