INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 461–483 (2006)
Published online 24 November 2005 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.1265

RECENT INCREASE IN PERSISTENCE OF ATMOSPHERIC CIRCULATION OVER EUROPE: COMPARISON WITH LONG-TERM VARIATIONS SINCE 1881

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Received 19 January 2005
Revised 6 August 2005
Accepted 6 August 2005

ABSTRACT

Long-term changes in the persistence of atmospheric circulation (measured by the mean residence time of circulation types) over Europe since 1881 are studied using the Hess–Brezowsky classification of Grosswetterlagen. A comprehensive statistical analysis is performed utilizing tests for change points, trends and outliers. The most remarkable feature of the long-term variations in the persistence of circulation patterns is a general sharp increase from the 1970s to the late 1980s. The shift towards higher persistence is statistically significant in most groups of the types and most seasons and is confirmed by all the statistical tools. The 1986–2000 period is an outlier, and the most pronounced change point in the time series appears in the mid-1980s. The observed increase in the mean lifetime of the circulation types over European mid-latitudes seems to be consistent with the idea of global warming, which is likely to shift the areas with the highest baroclinic activity (storm tracks) northwards. The enhanced persistence of the atmospheric circulation may have also supported the more frequent occurrence of temperature and other climatic extremes in Europe recently. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: atmospheric circulation; Europe; Hess–Brezowsky Grosswetterlagen; persistence; change point detection; climate variability

1. INTRODUCTION

A large majority of studies dealing with variations in the atmospheric circulation over the North Atlantic and Europe have focused on changes in modes of variability, indices of the atmospheric flow and frequencies of circulation types (CT)/weather regimes (e.g. Mächel *et al*., 1998; Slonosky *et al*., 2000; Jacobeit *et al*., 2001; Plaut and Simonnet, 2001; Jacobeit *et al*., 2003; Yiou and Nogaj, 2004). Only a few studies have analysed the persistence (measured by the mean residence time) of circulation patterns, mostly by examining the long-term Hess–Brezowsky classification of Grosswetterlagen (GWL; Hess and Brezowsky, 1952). While Bárdossy and Caspary (1990) found no change in the mean lifetime of GWL over the period 1881–1989, more recent studies pointed to a considerably enhanced persistence of the atmospheric circulation over Europe in the 1980s and 1990s. Werner *et al*. (2000) and Kyselý (2000, 2002) reported a rise in the residence times of the zonal circulation state in winter during the 1980s and of all groups of GWL in an extended summer season (May to September) in the early 1990s, respectively. Kyselý and Huth (2005) found a simultaneous increase in the mean lifetime of objectively determined CT, too, although not as pronounced as the subjective Hess–Brezowsky ones. No study has compared these recent increases to long-term variations for all groups

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of CT, and their significance has not been evaluated. Previous analyses were incomprehensive also in that they did not examine changes in spring and autumn.

The aims of this paper are to investigate long-term changes in the persistence of the atmospheric CT over Europe in all seasons and to assess the significance of the recent increase. After the description of data and methods in Sections 2 and 3, respectively, the paper is organized as follows: In Section 4, changes in the persistence of the atmospheric circulation during the last 120 years are described. Section 5 deals with results of the tests for change points, trends and outliers (note that throughout the paper testing for outliers refers to 15-year-long periods instead of individual years or events). A discussion focussing on the recent increase in the mean lifetime of the CT is given in Section 6. Conclusions follow in Section 7.

2. DATA

The Hess–Brezowsky catalogue of large-scale circulation patterns (Hess and Brezowsky, 1952; Gerstengarbe *et al*., 1999) is commonly used to describe the atmospheric flow over Europe (e.g. Bárdossy and Caspary, 1990; Werner *et al*., 2000; Sepp and Jaagus, 2002; Pryor and Barthelmie, 2003). Three groups of the circulation (zonal, half-meridional and meridional) are divided into 10 major types (Grosswettertypen (GWT)) and 29 types (GWL). Any GWL persists for at least 3 days. For the description of individual GWL as well as for details on the classification itself see, e.g. Gerstengarbe *et al*. (1999). The catalogue extends back to 1 January, 1881, and is considered to be free of artificial biases and trends, although upper-air synoptic patterns have been taken into account since the 1940s (Bárdossy and Caspary, 1990).

The present analysis is carried out for eight groups of CT, roughly corresponding to the major types of the Hess–Brezowsky classification. The reason for a slight modification in the aggregation of CT into groups was the fact that long-term frequencies of some major types are too low in all or some seasons to examine changes in their persistence; this is the case, namely, for the southeast (SE) and southwest (SW) major types (Gerstengarbe *et al*., 1999). Thus, the major types S, SW and SE were merged together into one new group, denoted S hereafter.

After the above-mentioned modification against Gerstengarbe *et al*. (1999), the analysed groups of CT are west (W), north (N), central European high (HM), south (S), east (E), northwest (NW), northeast (NE) and central European low (TM). The list of the groups of CT together with their relative frequencies is given in Table I. We decided to examine only groups of CT with higher than 5% long-term relative frequency in a given season; that is why the northeast type (NE) is not analysed in autumn (relative frequency 2.4%) and winter (2.5%), and the central European low (TM) is omitted in all individual seasons (relative frequencies 1.9–3.7%) and is considered only in the analysis of annual data.

For any group of CT and any year or a period of years, the persistence is defined as the mean lifetime (mean residence time) over all occurrences of individual CT that form the group. In Section 4.3, the definition is modified in that the persistence is considered to be the mean lifetime over occurrences *of the group of CT* (i.e. not of individual CT in the group; within-group transitions between CT are not taken into account in this definition), and differences between the two approaches are shown.

Seasons are defined in a standard way as DJF, MAM, JJA and SON and the term 'annual' is used for investigations without seasonal distinction. The analysis covers the period 1881–2000; in winter, only whole seasons are considered, which implies that January and February 1881 as well as December 2000 were omitted.

3. METHODS

To evaluate the statistical significance of the recent transition towards the enhanced persistence of CT, three kinds of tests are performed: tests for the presence of change points, trends and outliers. Each event (a sequence of days classified with the same CT) is taken into account one by one instead of examining the series of the mean annual or seasonal values. (The series of annual and seasonal values is employed only

Table I. Examined groups of the Hess–Brezowsky circulation types (CT) and their relative seasonal frequencies in 1881–2000

Group of CT	Abbreviation	Consists of CT	Relative frequency (%)			
			DJF	MAM	JJA	SON
West	W	West cyclonic (WZ), West anticyclonic (WA), West angular (WW), Southern West (WS)	30.45	20.74	29.83	28.18
Central European high	HM	Central European high (HM), Central European ridge (BM)	17.80	13.06	16.01	18.81
South	S	Southwest anticyclonic (SWA), Southwest cyclonic (SWZ), South anticyclonic (SA), South cyclonic (SZ), British Isles low (TB), Western Europe trough (TRW), Southeast anticyclonic (SEA), Southeast cyclonic (SEZ)	18.02	17.53	10.56	19.94
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)	12.07	19.71	16.98	14.32
East	E	Fennoscandian high anticyclonic (HFA), Norwegian Sea/Fennoscandian high anticyclonic (HNFA), Fennoscandian high cyclonic (HFZ), Norwegian Sea/Fennoscandian high cyclonic (HNFZ)	8.25	10.95	5.63	6.30
Northwest	NW	Northwest anticyclonic (NWA), Northwest cyclonic (NWZ)	8.12	7.31	11.47	6.65
Northeast	NE	Northeast anticyclonic (NEA), Northeast cyclonic (NEZ)	2.48	5.77	6.60	2.44
Central European low	TM	Central European low (TM)	2.32	3.73	1.86	2.35

in the analysis of the persistence of all groups of CT taken together.) The reason is that the frequency of independent events might be too low to make reliable estimates of means in individual seasons, and that the number of events may considerably differ from year to year.

The time of occurrence of each event i is set according to

$$t_i = YR_i - 1881 + \frac{DAY_{i1} + DAY_{i2}}{2L_Y}$$

where YR_i denotes the year, L_Y is the length of the year (365 or 366 days), and DAY_{i1} and DAY_{i2} are the serial numbers of the first and last days of event i within the year. (Events stretching from one year to another need a special treatment, but the same approach is kept.) As a result of this transformation, all t_i values lie within the range (0, 120). The lifetime of event i is denoted d_i hereafter. If the number of events over 1881–2000 was higher than 800, the size of the sample was reduced below 800 through averaging neighbouring events (and the corresponding d and t values). This adjustment was made for computational reasons and had no effect on results of the tests.

3.1. Tests for detection of change points

Several methods are applied to detect change points in climatological time series. We employed (1) the Pettitt test (Pettitt, 1979; Bárdossy and Caspary, 1990; Fraedrich *et al.*, 2001), (2) the standard normal homogeneity test (SNHT) (Alexandersson and Moberg, 1997; Moberg and Alexandersson, 1997; Ducré-Robitaille *et al.*, 2003) and (3) the modified sequential t-test for differences between neighbouring decades (described below).

The Pettitt test and the SNHT define test statistics at each point of a time series. Values of these statistics tend to be highest at points that divide the series into two parts with most pronounced differences between their statistical characteristics. If the maximum of the test statistics exceeds a given threshold, a change point is detected. Each of the two parts of the time series is examined separately for further change points in the same way, as long as it contains more points than a fixed threshold (set to 20 here).

The Pettitt test examines sums of same-sign differences between pairs of sample elements chosen from different parts of a series. The test statistic is

$$K = \max_{10 \leq i \leq n-10} \left| \sum_{i=1}^{k} \sum_{j=k+1}^{n} \operatorname{sgn}(d_i - d_j) \right|$$

where n is the number of events. The probability p^* of a change is given by the formula

$$p^* = 1 - \exp\left(\frac{-6K^2}{n^3 + n^2}\right)$$

and the significance threshold value ($K_{\mathrm{th},n}$; evaluated at $p = 0.05$) is

$$K_{\mathrm{th},n} = \sqrt{\frac{-\ln p(n^3 + n^2)}{6}}$$

Two versions of the SNHT exist; the test for shifts without trend is applied here. To take into account the possibility of more than one shift in the same series, a two-phase detection of discontinuities is utilized. The core of this procedure is that points of potential breaks are flagged only first, and then the series is examined again in windows containing exactly one potential change point.

The first step of the SNHT is a standardization of the variable under study (D)

$$Z = \frac{D - \overline{d}}{s_d}$$

where $Z = [z_1, z_2, \ldots z_n]$, $D = [d_1, d_2, \ldots d_n]$, and $\overline{d}$ and s_d are the average and the standard deviation of D, respectively. Afterwards, the mean values of Z over two parts of the time series (denoted $y_{i,j}$ where the indices show the first $[i]$ and last $[j]$ elements of the subseries) are examined utilizing the test statistic

$$S = \max_{10 \leq i \leq n-10} \{i \cdot y_{1,i}^2 + (n - i) \cdot y_{n-i+1,n}^2\}$$

The significance threshold of $S(S_{\mathrm{th},n};\ p = 0.05)$ depends on n. Key threshold values (for $n = 20, 30, 40, \ldots$ 100, 150 and 250) were taken from Alexandersson and Moberg (1997), and an interpolation was performed for n between 20 (which is the minimum number of events required) and 250. For this purpose, a monotonously increasing continuous function was introduced which fits on the key values with lower than 1% error at each point. Finally, an extrapolation was carried out up to $n = 800$ (the maximum number of events allowed) using a formula that keeps the shape of the curve above the uppermost key value,

$$S_{\mathrm{th},n} = S_{\mathrm{th},250} + \sqrt{\frac{n}{250}} - 1 \quad (250 < n < 800)$$

Table II. Significance threshold values ($S_{\text{th},n}$; $p = 0.05$) for the Standard Normal Homogeneity Test. n stands for sample size of the series

n	20	40	60	80	100	150	250	400	600	800
$S_{\text{th},n}$	7.00	8.10	8.62	8.93	9.13	9.41	9.65	9.92	10.20	10.44

The significance threshold values for the SNHT test statistic are given in Table II.

The modified sequential t-test utilized here (termed simply t-test hereafter) is based on a sequential t-test applied in Gullett *et al.* (1990) and Ducré-Robitaille *et al.* (2003). The approach to the change point detection is different from the above-described methods; the test uses fixed-width windows that have a time dimension. Results of the evaluation of the performance of the sequential t-test on artificial series of 100 values by Ducré-Robitaille *et al.* (2003) indicate that the window should be larger than 10 years; 20-year windows are applied here.

Using this method, values of the examined variable in neighbouring decades $(t_i - 10, t_i)$ and $(t_i, t_i + 10)$ are compared for each $t_i \in (10, 110)$. A difference from the method introduced by Gullett *et al.* (1990) is that before the procedure, D is transformed to a standard normal distribution keeping the rank order of the elements (r_i) unchanged. The vector of the transformed lifetimes $D^* = [d_1^*, d_2^*, \ldots d_n^*])$ is obtained using the formula

$$d_i^* = f(r_i) = N\left(p^* = \frac{r_i}{n+1}\right)$$

where N denotes the standard normal distribution N (0,1) and p^* stands for the probability.

Let the number of events within range $(t_i - 10, t_i)$ and $(t_i, t_i + 10)$ be n_1 and n_2, respectively. Then, the mean decadal difference around event i (h_i) is given by

$$h_i = \frac{1}{n_1}\sum_{k=1}^{n_1} d_k^* - \frac{1}{n_2}\sum_{k=1}^{n_2} d_k^*$$

The test statistic

$$T = \frac{h_i}{\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}}$$

is similar to the one published by Gullett *et al.* (1990) and Ducré-Robitaille *et al.* (2003), with a difference that, owing to the transformation, the standard deviation of T equals 1 and T has the standard normal distribution. If $|T|$ is higher than a critical value (T_{th}), there is a statistically significant shift in the series at point i.

Since there are a large number of tests performed on the same series (note that the number of tests equals the number of events for each 'group of CT–season' pair in 100 years, and that the 5% minimum frequency of the group of CT, 90 days in a season, and a 5-day mean lifetime lead to the minimum number of events to almost 100, taking into account each event of the series except for the two 10-year-long tails), the detection of 'discontinuities' would be relatively frequent even in a white noise process. Ducré-Robitaille *et al.* (2003) bridged this issue by introducing a strongly enhanced critical value obtained from test experiments. Here, we assume that differences for 11 decade pairs (1881–1890 and 1891–1900, 1891–1900 and 1901–1910, ..., 1981–1990 and 1991–2000) are independent and the threshold for the significance level of $2(1 - 0.975^{1/11})$, $|T_{\text{th}}| = N(p^* = 0.975^{1/11}) = 2.83$ is chosen. An evaluation of the performance of the t-test on artificial white noise series shows that the identification of significant change points using the threshold value of 2.83 is more frequent by the t-test than by the other two methods. However, this is not a disadvantage of the t-test in the current application since it is utilized here mainly for the detection of possible smaller and less significant change points (see Section 5); because of the independence of the examinations between distant parts of the time series, the test is suitable for this purpose.

In this procedure, the event with the highest test statistic is selected first, followed by the others according to the rank order of the test statistics. However, when a change point was detected, the adjoining ±5-year periods were excluded from further consideration so that the possibility of detecting more than one change point caused by the same shift would be eliminated.

3.2. Tests for trend

The common t-tests of the regression model and the Mann–Kendall tests (e.g. Wilks, 1995) were performed to evaluate the statistical significance of trends in the persistence of CT.

3.3. Tests for outliers

Whether the period of the last 15 years (1986–2000) is an outlier from the whole series was tested by two Monte Carlo experiments:

(i) The time series of the residence times of CT was divided into two parts, for each group of CT and each season: (A) events in 1881–1985 and (B) events in 1986–2000. The number of events (n) and the mean lifetime (m) were calculated for period (B). A 'model' mean lifetime (g) was then obtained by a Monte Carlo resampling (averaging n events randomly chosen from period (A)). The simulation procedure was repeated 10 000 times and the relative frequency of $g > m$ (denoted P) was calculated for each 'group of CT–season' pair.
(ii) The time series of the residence times of CT was divided into eight 15-year long subperiods. A simulation similar to (i) was performed, but (B) was always a subperiod under examination, while (A) was the whole series (1881–2000) instead of the rest of the series. The frequencies of $g > m$ were set for each 'group of CT–season' pair and each of the eight subperiods.

Both tests result in P values (relative frequencies of $g > m$); $P < 0.05$ ($P > 0.95$) indicates a significant positive (negative) difference of the mean lifetime in a given subperiod from the rest of the sample (i) or the whole sample (ii).

4. LONG-TERM CHANGES IN THE PERSISTENCE OF CIRCULATION TYPES

4.1. Seasonal changes in the persistence of CT for groups of CT over 1881–2000

4.1.1. Winter (DJF). In winter, a clear tendency towards an increased persistence of CT appears at the end of the twentieth century, mainly for the west (W) and south (S) types for which the highest ever observed values of the mean lifetime were reached in the 1980s and 1990s (Figure 1). The enhanced persistence in the last two decades is found for most other groups of CT as well, although the values are not exceptional in the long-term context. The 1910s and 1920s were a period of a higher persistence of central European and Fennoscandian highs (HM and E), while in the 1960s and 1970s, the mean residence times were below the long-term averages for all groups of CT.

If all CT are aggregated, the most pronounced positive (negative) anomalies appear in the 1980s and 1990s (the 1970s) (Figure 5(a)).

4.1.2. Spring (MAM). In spring, the highest values of the persistence of CT are found in the recent decades for the west (W), north (N) and central European high (HM) types (Figure 2). The long-term trend is towards a higher persistence in all groups of CT except for the northeast type (NE); note that the NE type is relatively infrequent, which leads also to the missing values in the 1980s. Other periods with an enhanced mean lifetime

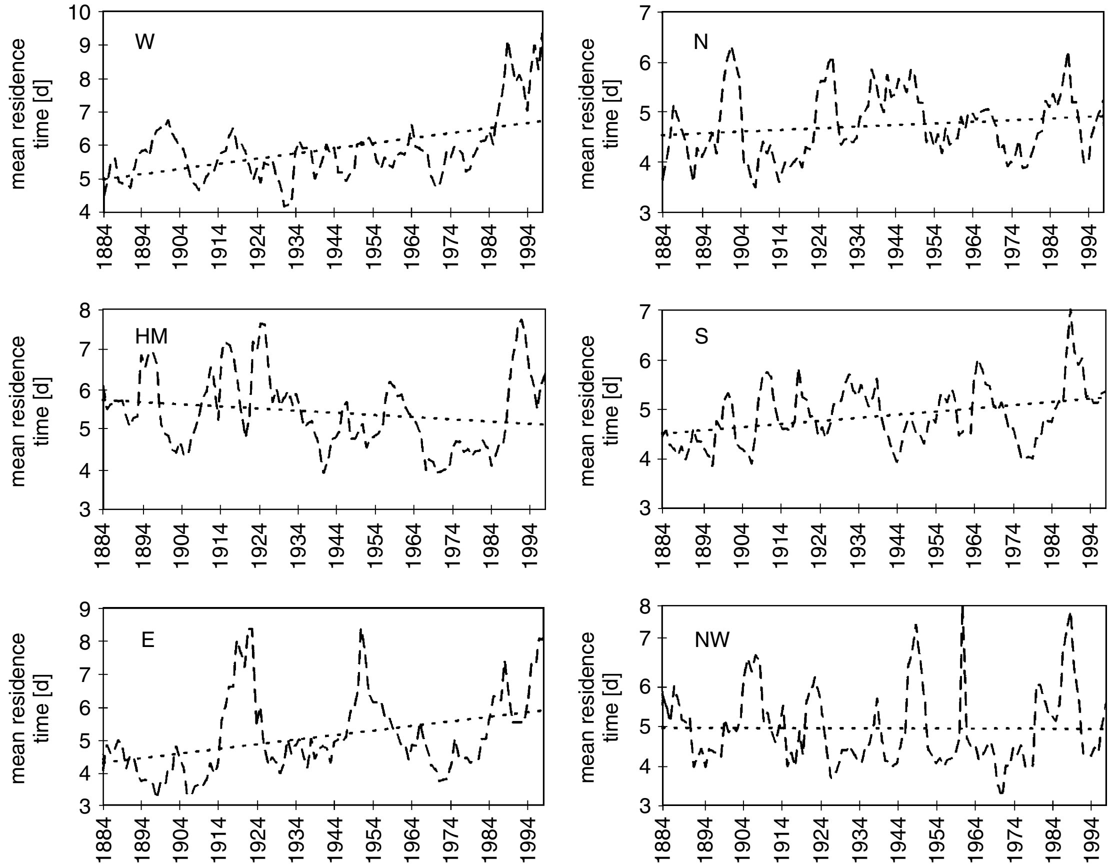


Figure 1. Long-term changes in the mean residence time of CT for groups of CT in winter in 1881–2000. Values are computed as averages over 5-year periods; linear trends of the 5-year running means are depicted by dashed lines

of most groups of CT were the 1910–1920 and the late 1940s. On the other hand, the 1960s and/or 1970s were a period of exceptionally low persistence of the north (N), northwest (NW) and northeast (NE) types.

Treating all CT together, the most pronounced positive (negative) anomalies are observed in the 1980s and 1990s (the 1900s, 1930s and 1970s) (Figure 5(b)). The atmospheric circulation has been more persistent in all years since 1985, compared to the long-term mean.

4.1.3. Summer (JJA). In summer, record-breaking values of the persistence of CT appear in the recent decades for the west (W), north (N), central European high (HM) and northeast (NE) types (Figure 3). The 1960s and 1970s were a period of a relatively low persistence. The long-term trend is towards a higher persistence in most groups of CT. (Note that outlying values for the NE type during the late 1980s are related to a low frequency of occurrence.)

Similar to the winter season, the most pronounced positive (negative) anomalies are found in the 1980s and 1990s (the 1970s) (Figure 5(c)) if all CT are considered together. In all years since 1985, above-average mean residence times of CT have been observed.

4.1.4. Autumn (SON). In autumn, the highest persistence of the atmospheric circulation occurs in the 1980–1990 for all groups of CT except for the east type (E); all long-term trends are positive (Figure 4). The 1960s were again a period of a relatively low persistence of most groups of CT.

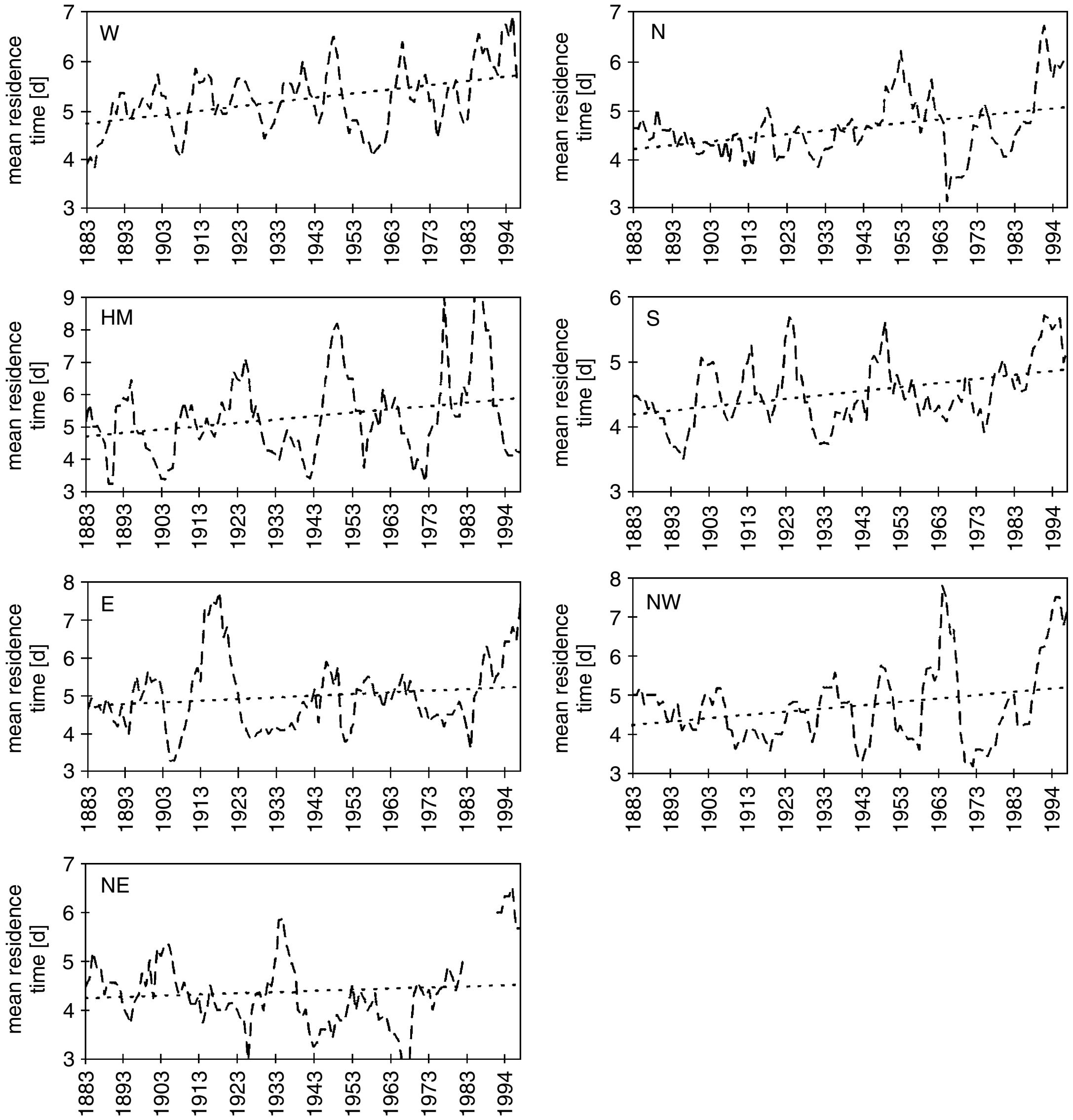


Figure 2. As in Figure 1 except for spring

If all CT are aggregated, the most pronounced positive (negative) anomalies appeared in the 1980s and 1990s (the 1910s and 1960s) (Figure 5(d)). The persistence has been higher than the long-term mean in all years since 1984, except for 1993.

Considering all CT together, a remarkable difference among individual seasons is that while in winter and spring the highest values were observed around 1990 (followed by a drop in the persistence and a slight increase in the late 1990s), in summer and autumn the main maximum appears in the late 1990s, after a temporary decrease in the first half of the decade.

4.2. Annual changes in the persistence of CT for groups of CT over 1881–2000

In annual data, the highest values of the mean lifetime of groups of CT occurred during the previous 20 years for the west (W), north (N), central European high (HM), south (S) and northeast (NE) types and values comparable to former maxima for the remaining groups of CT (Figure 6). For example, the mean

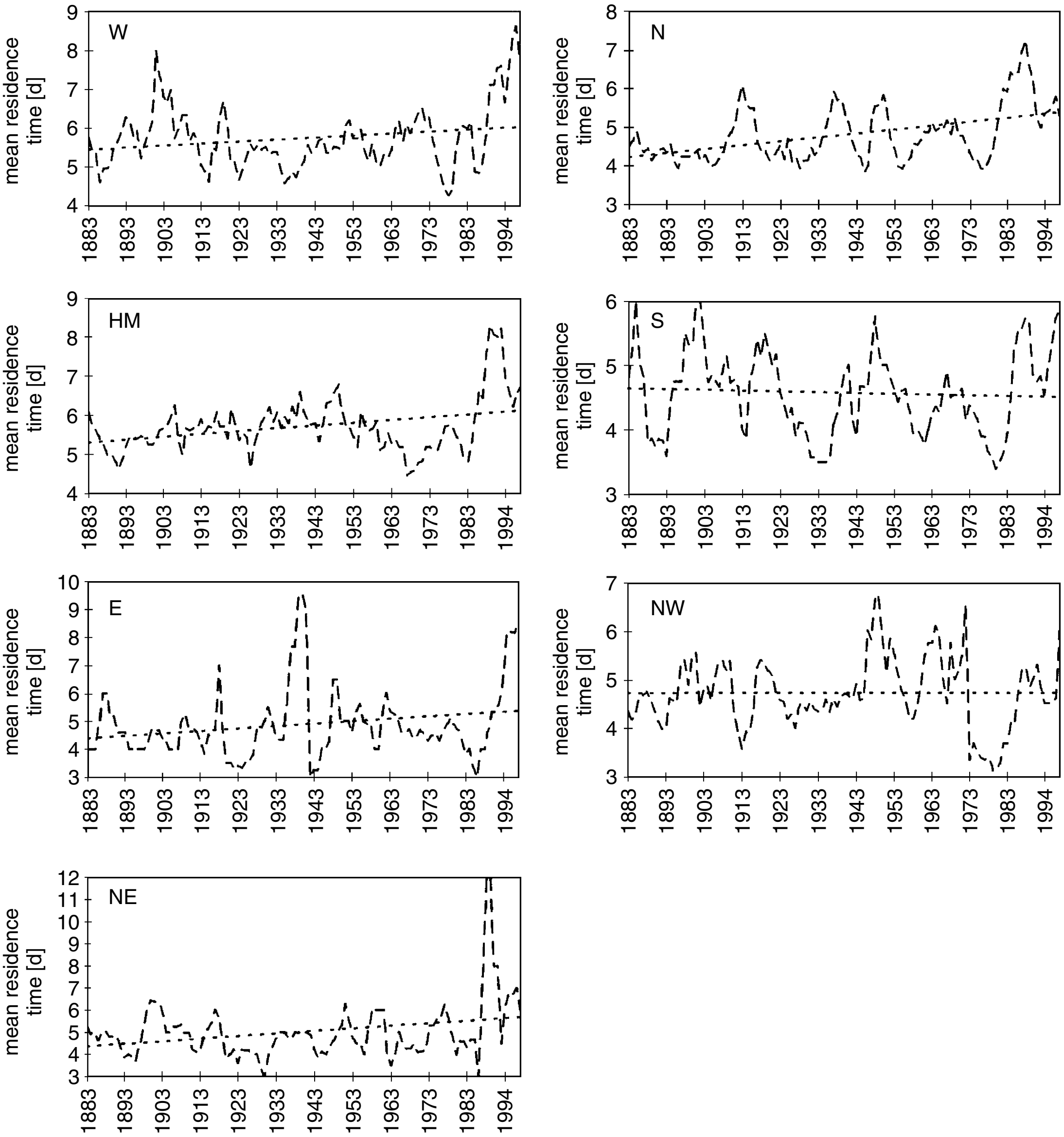


Figure 3. As in Figure 1 except for summer

duration of the zonal (west) types was 2 days longer in the 1990s than in any previous decade before 1980 (with the exception of a short period around 1900), and the mean lifetime of the south and north types was about 1 day longer in the 1980s and 1990s compared to all earlier decades.

Considering all CT together, the most pronounced positive (negative) anomalies appear in the 1980s and 1990s (the 1970s) (Figure 5(e)). The persistence has been above the long-term average by 0.5–2.2 days in all years since 1985.

4.3. Is the recent increase in the persistence of CT due to less frequent transitions between CT within the same group?

The rise in the persistence of CT in individual groups may be to some degree connected to a decreased frequency of transitions between CT *from the same group* (decreased within-group variability). Here, the

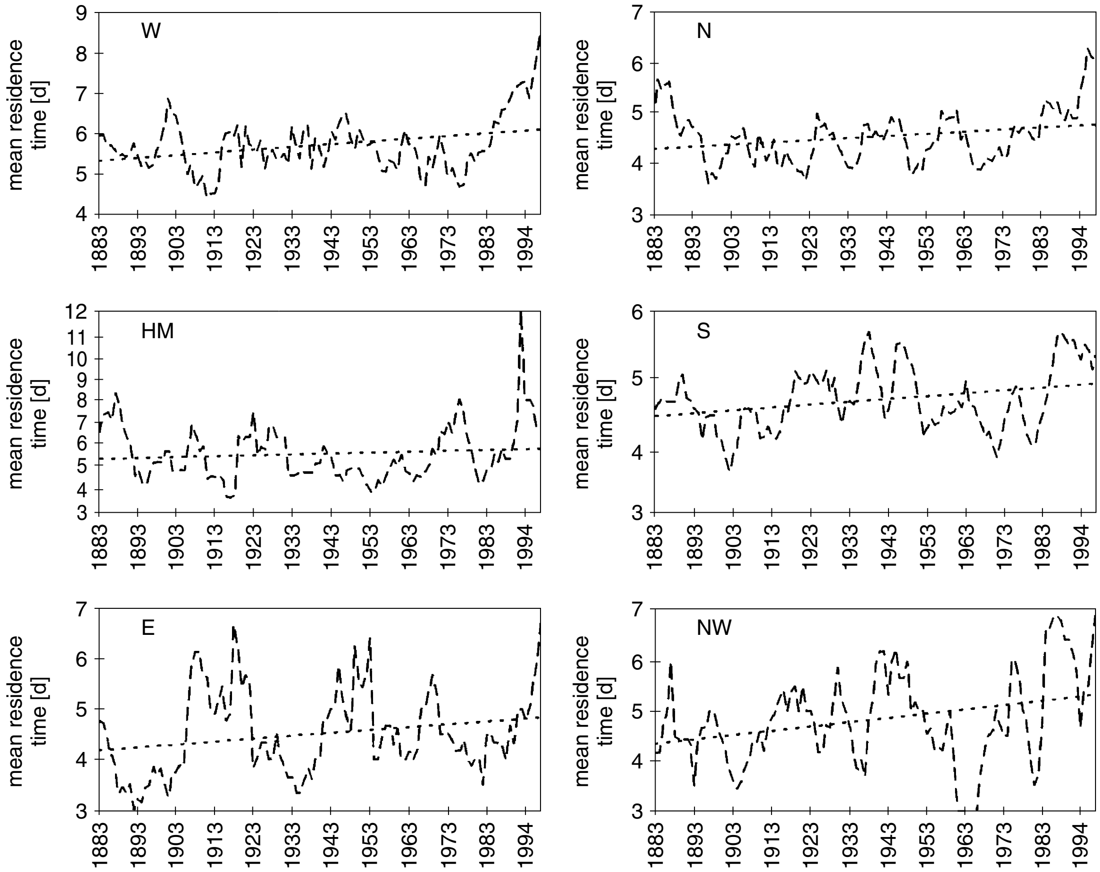


Figure 4. As in Figure 1 except for autumn

mean lifetime of a group of CT as a whole is calculated, disregarding the transitions between CT from the same group.

If all groups of CT are considered together, changes in the within-group variability cannot explain the recent increase in the persistence of CT in any season (see upper graphs in Figures 7 and 8 for winter and summer), and the persistence of the groups of CT is still above the long-term average in the 1980s and 1990s. In winter, it is obvious for most groups of CT, e.g. for the most frequent zonal weather state (W) as well as the east types (E) and central European high (HM) (Figure 7). In summer, the figure looks somewhat different (Figure 8). The reduced within-group variability is partly responsible for the recent increase in the persistence of some groups of CT; e.g. the recent mean residence time of the zonal type (W) is not higher than around 1950 and 1970. In spring and autumn, the patterns are more similar to winter than summer (not shown). Hence, for some groups of CT, a part of the recent rise in their persistence (calculated over all occurrences of CT from the group) may be attributed to a reduced frequency of within-group transitions, mainly in summer. Differences between the two definitions of the persistence are addressed also in Sections 5.1 and 5.3.

5. EVALUATION OF THE RECENT INCREASE IN THE PERSISTENCE OF CIRCULATION TYPES BY TESTING THE STATISTICAL SIGNIFICANCE OF CHANGE POINTS, TRENDS AND OUTLIERS

All examinations in this section are performed for 39 'group of CT–season' pairs, considering eight individual groups of CT and all CT taken together, four seasons and the whole year and omitting NE type in DJF and SON and TM in all individual seasons from the analysis because of their low frequencies.

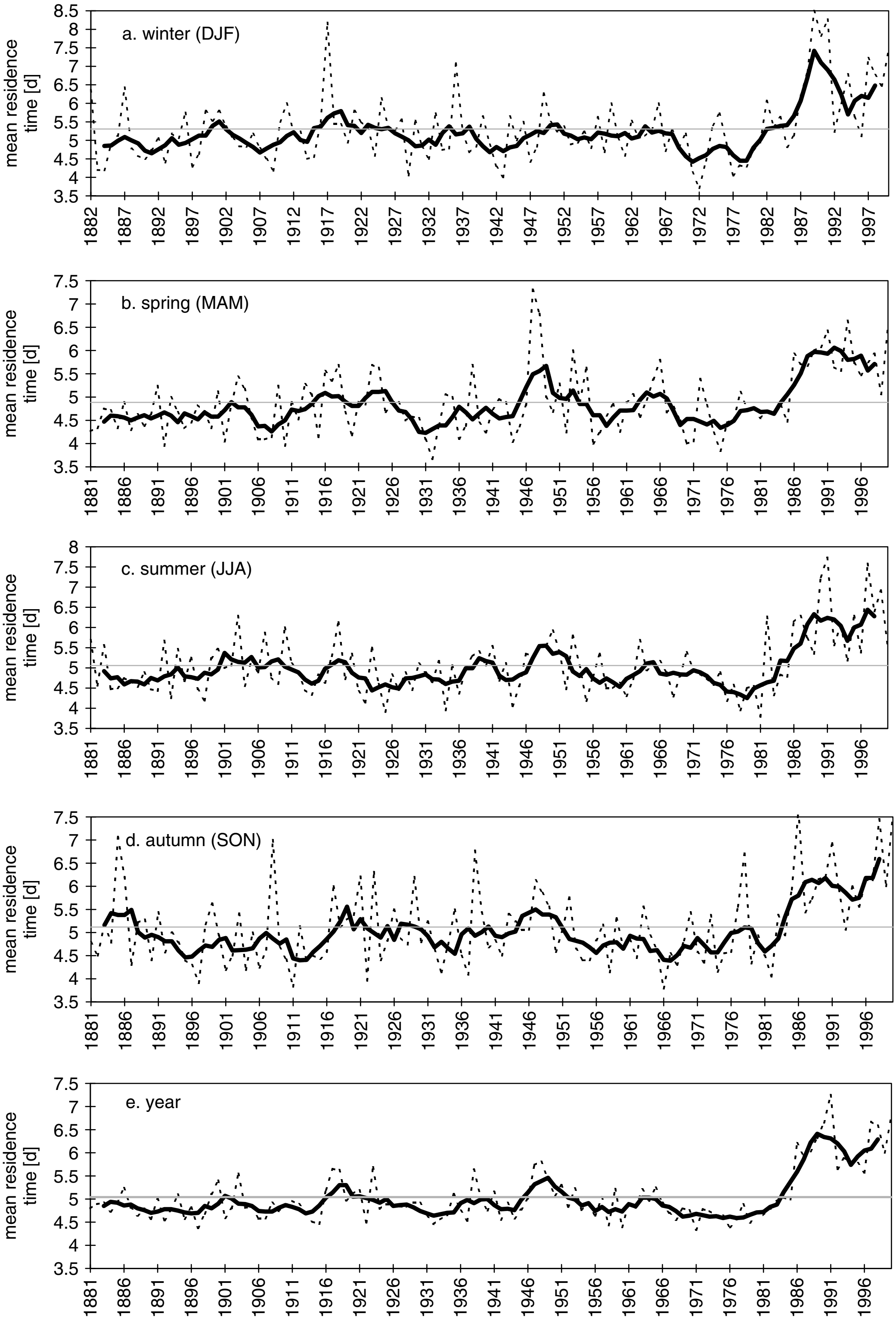


Figure 5. Long-term changes in the mean residence time of all CT in 1881–2000 in individual seasons (a-d) and annual data (e). The solid curve shows 5-year running means; the horizontal line denotes the long-term (1881–2000) mean

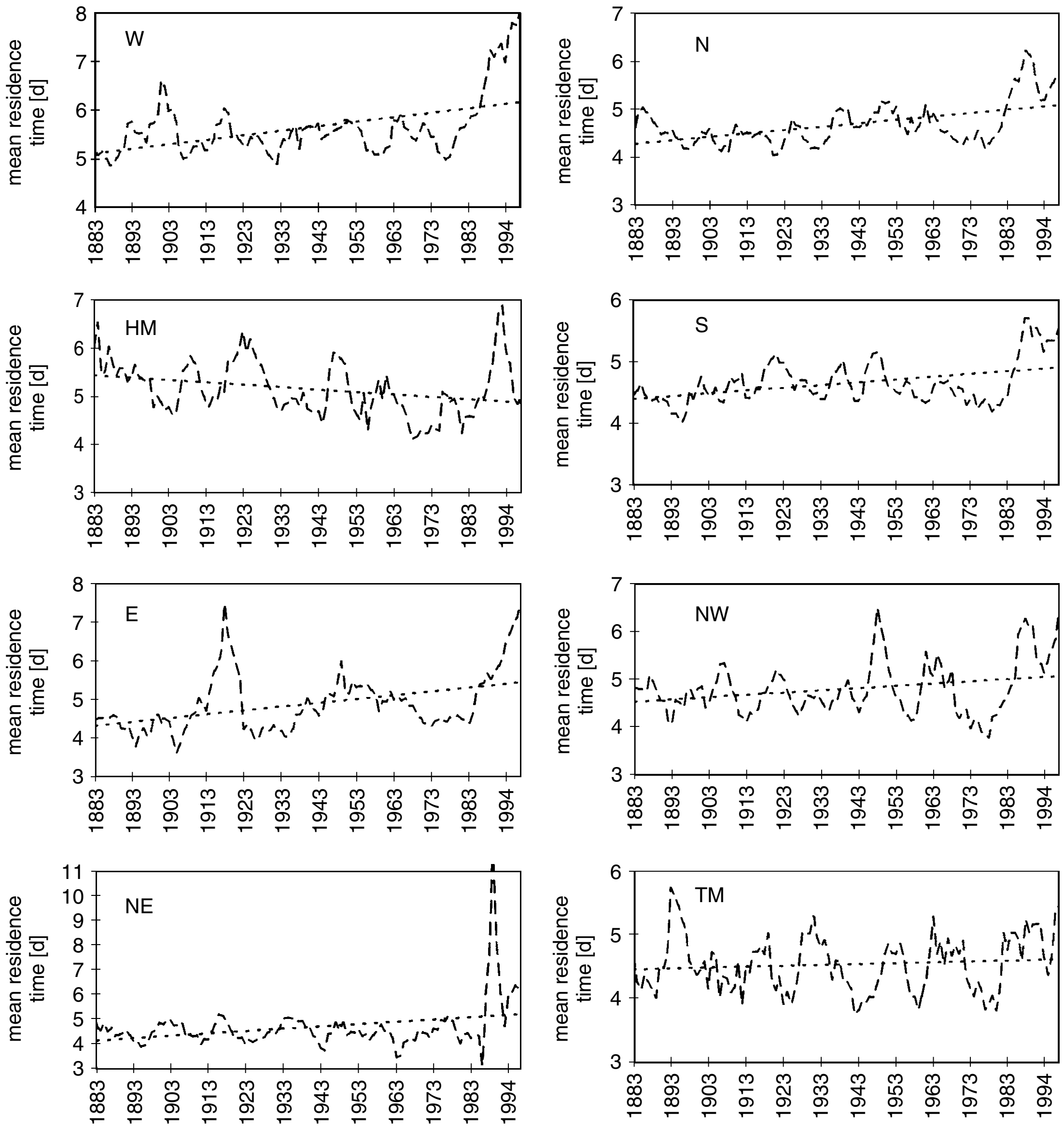


Figure 6. As in Figure 1 except for whole year

5.1. Tests for detection of change points

Results of the Pettitt test, SNHT and t-test are shown in Table III and summarized in Table IV. Since the tests focus on various characteristics of time series, slight differences in their performance are not surprising. Notwithstanding, all types of tests indicate a significant and widespread shift in the persistence of CT during the 1980s. This feature is most pronounced in the SNHT results. According to the SNHT, 0 or 1 change point is detected in 38 out of 39 examined cases; a change point between 1980 and 1990 is found in 67% of the 'group of CT–season' pairs, and 90% of all the detected discontinuities appear in the 1980–1990 period. The Pettitt test yields 0 to 2 change points (with two exceptions when 3 change points are detected); a change point between 1980 and 1990 is found in 46% of the examined 'group of CT–season' pairs, and 56% of the detected change points lie within the 1980–1990 period. The t-test leads to slightly more detected change points compared to the Pettitt test and the SNHT (1.1 per time series on average, with a maximum of 4), but

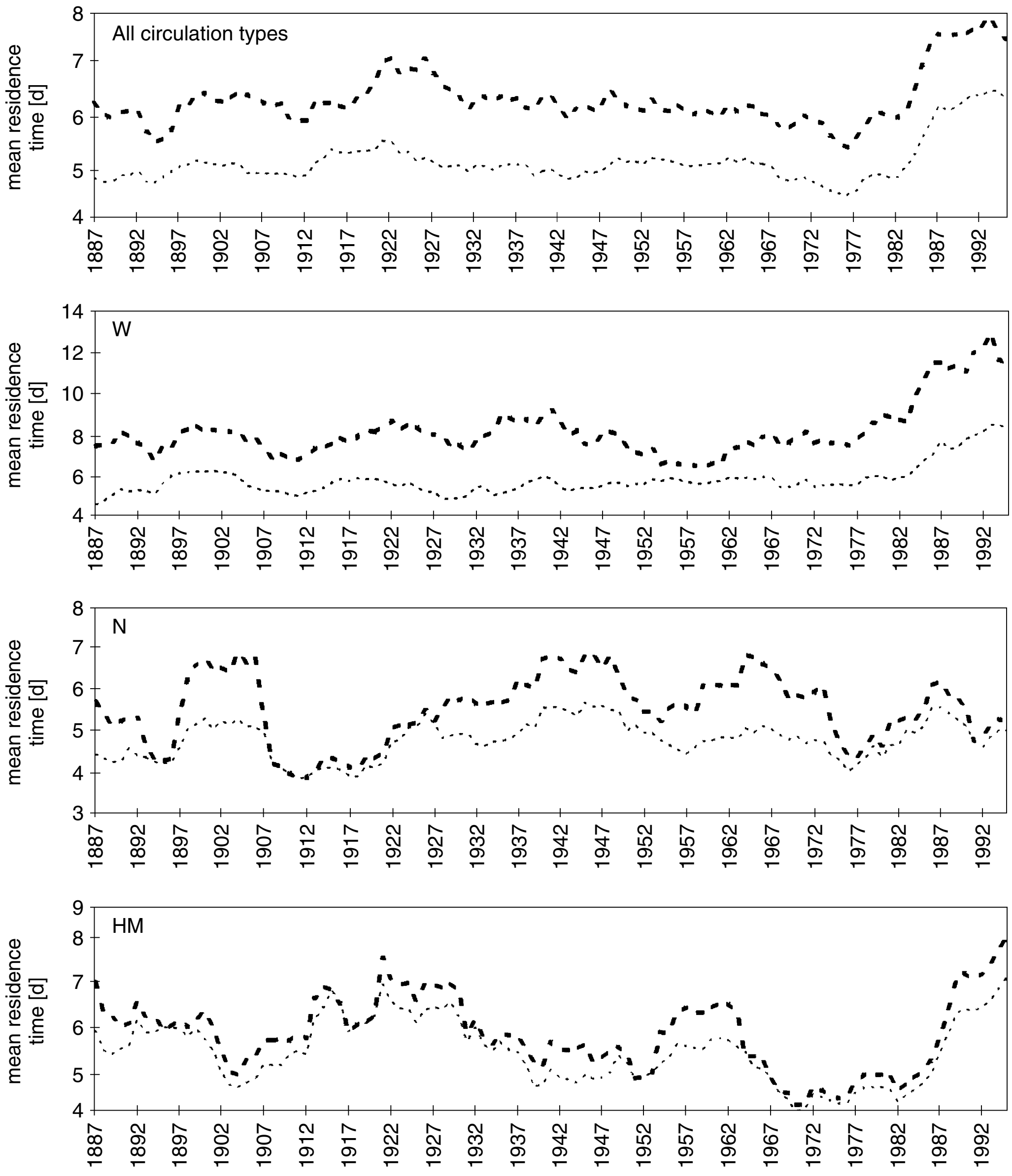


Figure 7. Long-term changes in the mean residence time of groups of CT in winter in 1881–2000. The mean residence time is defined for a group of CT as a whole (upper black curve) and over individual CT in a group (bottom grey curve). Values are computed as averages over 10-year periods

the ratio between dates in and out of the 1980s is similar to that of the Pettitt test. In the t-test results, 54% of the cases show a discontinuity between 1980 and 1990, and 55% of the detected change points appear in the 1980–1990 period.

All groups of CT and all seasons are involved in the persistence shift in the 1980s, although in winter, significant change points are detected only for the W types and all CT in this decade (according to the t-test, a significant change point is found also for HM). For all CT considered together, a significant discontinuity in the 1980s is revealed in all seasons and by all tests with the exception of autumn and the t-test.

The general accordance of the test results in the 1980s confirms a shift towards higher values of the persistence since the mid-1980s (*cf* Figure 5). The detected change points (Table III) have an outstandingly

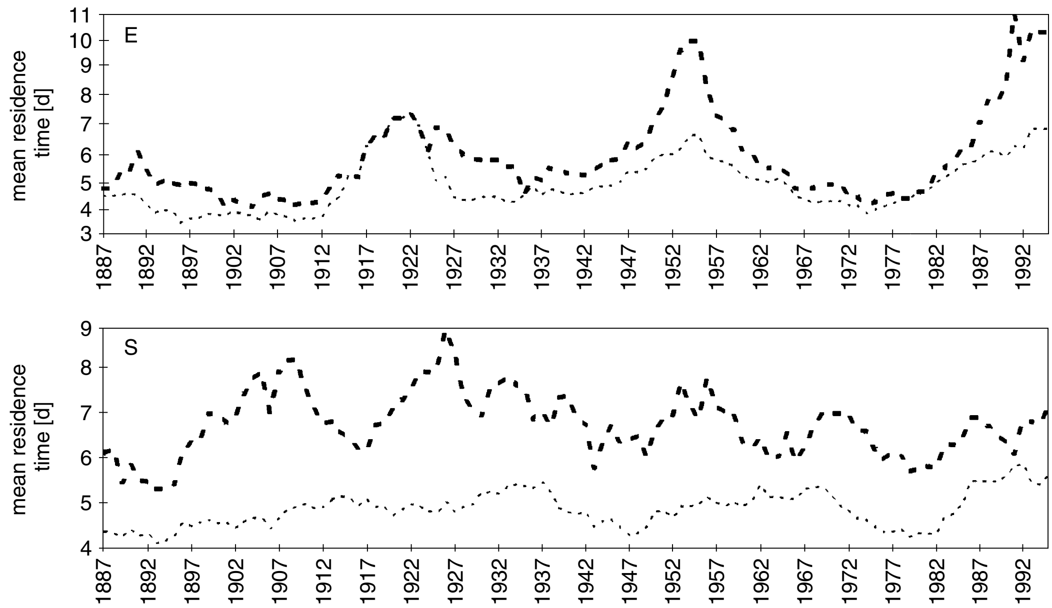


Figure 7. (*Continued*)

high frequency in the 1980s, but they are relatively rare and their dates are scattered in other periods. There is no sign of another seasonally and climatologically coherent discontinuity than the one observed in the mid-1980s. Allowing slightly more change points to be detected by the t-test is advantageous since it proves that there is no other discontinuity that would appear simultaneously for more groups of CT and/or more seasons than the one in the 1980s.

In order to examine whether the reduced within-group frequency of transitions from one CT to another influences the findings, the tests were also performed in a mode in which the persistence is defined over groups of CT instead of individual CT (*cf* Section 4.3). Results of these tests (not shown) also prove the shift of the persistence in the 1980s, but with a lower significance compared to the results in Tables III and IV. Significant change points in the 1980s are detected in 23 (31, 41)% of the examined 'group of CT–season' pairs for the Pettitt test (the SNHT, the t-test).

5.2. *Tests for trend*

Over the whole period of 1881–2000, 16 (17) out of 39 examined 'group of CT–season' pairs show a statistically significant increase in the persistence of CT according to the t-test (the Mann–Kendall test) at $p = 0.05$ (Table V); particularly for W in winter, spring and year, S in spring, autumn and year, N in spring, summer and year, E in winter and year and NW in autumn. There are no significant negative trends. In annual data, the trends are statistically significant for all groups of CT with the exception of HM and the least frequent NE and TM types. If all CT are treated together, the trends are significant in spring and in annual data.

If the analysis is confined to the period of the last 40 years, the trends are significant for a large majority of the groups of CT in all seasons (not shown).

5.3. *Tests for outliers*

The results demonstrate again that the persistence of CT was unprecedentedly high in 1986–2000 compared to earlier periods; the increase is a general feature over all groups of CT and all seasons (Table VI). The mean lifetimes in 1986–2000 are significantly enhanced in 87% of the 39 examined 'group of CT–season'

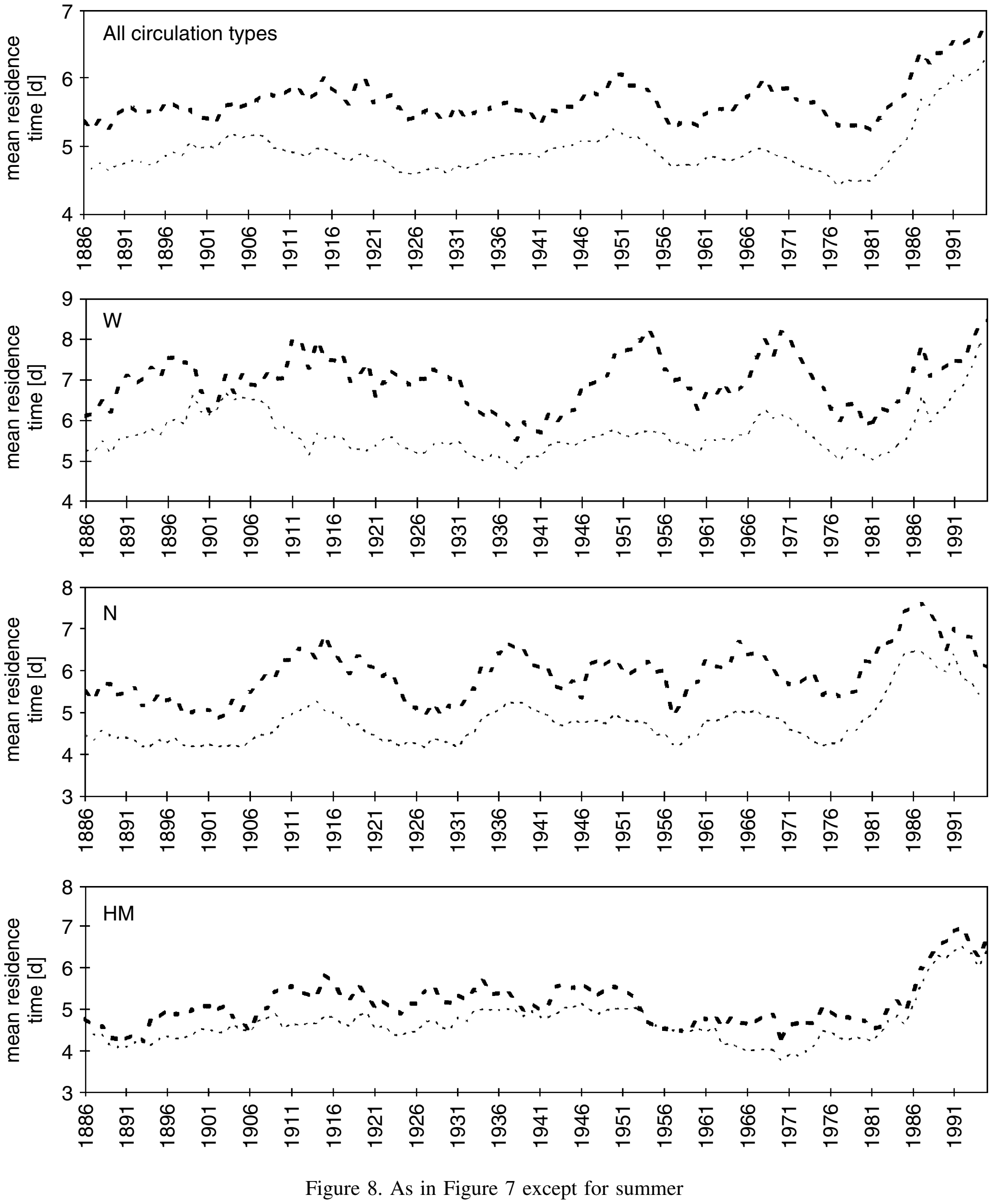
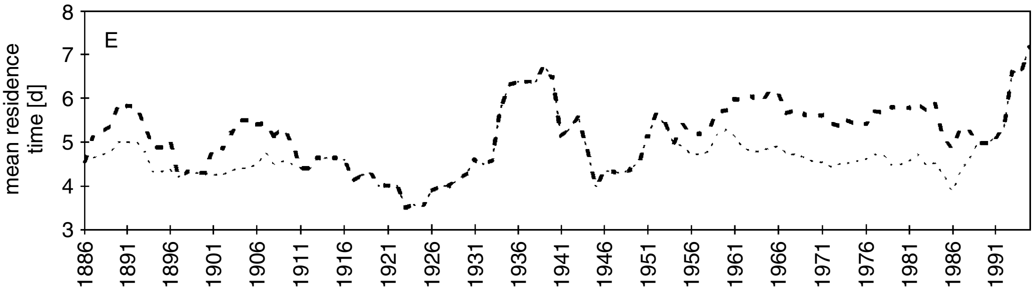


Figure 8. As in Figure 7 except for summer

pairs and in all pairs without seasonal distinction and/or without distinction according to the group of CT. (For several 'group of CT–season' pairs, there are no occurrences of $g > m$ among the 10 000 simulations at all.) The insignificant cases are mostly found in 'group of CT–season' pairs with a low number of events.

If within-group CT transitions are not considered, the percentage of significant differences is slightly lower (74%), which is in accord with the results presented in Sections 4.3 and 5.1.

Results in Table VII confirm these findings and show that the period 1986–2000 is an outlier. The percentage of significant differences in 1986–2000 is 85% (the small deviation compared to the values in Table VI is due to the change in the reference period); this is a much higher value than in any other 15-year-long period examined.



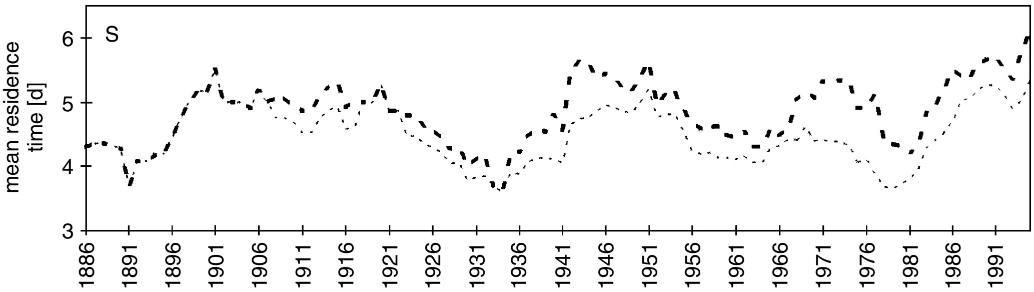


Figure 8. (*Continued*)

The same simulations were carried out also for the case when all events are weighted with their durations (both in the calculation of the observed and simulated values; not shown). (The weighting leads to a higher mean lifetime relative to the non-weighted one when the residence times are more variable.) In this mode, the percentage of significant differences in 1986–2000 was 64%, a value still much higher than in any other 15-year-long period.

6. DISCUSSION

6.1. Enhanced persistence of the atmospheric circulation in the 1980s and 1990s: Comparison with other studies

Variations in the mean residence times of CT over Europe have been examined in several papers recently, following the work of Bárdossy and Caspary (1990) who found no significant changes in the persistence of CT over 1881–1989. A rise in the mean lifetime of the Hess–Brezowsky CT around 1990 was reported for zonal types in winter (Werner *et al*., 2000) and for all groups of CT in summer (Kyselý, 2000, 2002). Changes in the persistence of the atmospheric circulation over Europe were dealt with also by Stefanicki *et al*. (1998) who concluded that the average length of convective (advective) Schüepp's weather types in the Alpine region rose (fell) in 1970–1994 compared to 1945–1969, mainly in winter. Kyselý and Huth (2005) examined an objective classification of CT over 1958–1998 in addition to the Hess–Brezowsky catalogue; a slight increase in the persistence during the 1990s was observed for some groups of the objectively defined CT too, although it was less pronounced (mainly in summer) than for the subjective types.

The present analysis demonstrates that the rise towards higher mean lifetimes of the Hess–Brezowsky CT from the 1970s to the late 1980s and 1990s appears in all seasons and in most groups of CT, and that it was a more general event than shown by the previous studies confined to individual seasons and/or groups of CT (Werner *et al*., 2000; Kyselý, 2002). The rise is significant for many groups of CT and seasons according to statistical tests; the 1986–2000 period is an outlier for most groups of CT and seasons, and the change point detection methods locate the most conspicuous change point of the time series to the 1980s.

Although the recent change is unlikely to stem from potential artificial inhomogeneities in the subjective Hess–Brezowsky catalogue, it cannot be excluded that some methodological changes might have contributed

Table III. Statistically significant ($p = 0.05$) change points in the time series of the persistence of CT for groups of CT. The change points detected are ordered according to their significance; the change points between 1980 and 1990 are marked in bold. – indicates no significant change point. Note that the NE and TM types were omitted in some seasons because of their low frequency of occurrence

Group of CT	Season	Pettitt test	SNHT	t-test
W	DJF	1973 **1987**	**1987**	1985 1891
	MAM	–	–	–
	JJA	–	**1989**	**1988**
	SON	1979	**1990**	**1984**
	Year	**1981 1989**	**1987**	**1985** 1893
N	DJF	–	–	–
	MAM	1932	**1987**	1962 **1988**
	JJA	1934 **1980**	**1980**	**1981**
	SON	**1983**	**1983**	1894
	Year	**1982** 1936 1965	**1982**	**1981**
HM	DJF	–	–	**1989** 1909 1964
	MAM	–	–	1945 **1983**
	JJA	**1983**	**1987**	**1986**
	SON	–	**1985**	–
	Year	**1983** 1964	**1985** 1964	**1983** 1965 1977 **1989**
S	DJF	–	–	1972
	MAM	1977	**1988**	–
	JJA	**1985** 1958	**1985**	**1985**
	SON	**1983**	**1983**	–
	Year	**1985**	**1985**	**1985**
E	DJF	1946	1914	1946 1916 1926
	MAM	–	**1985**	1913 1923
	JJA	–	**1990**	–
	SON	–	–	–
	Year	1946 **1986** 1968	1991	**1990** 1913 1926
NW	DJF	–	–	–
	MAM	–	**1987**	**1987**
	JJA	–	–	**1983** 1970
	SON	**1985**	**1985**	–
	Year	**1985** 1963	**1985**	**1985** 1979
NE	MAM	–	–	–
	JJA	–	–	–
	Year	–	**1986**	–
TM	Year	–	–	–
All	DJF	**1982** 1929	**1988**	**1982 1988**
	MAM	**1986** 1945	**1986**	**1986**
	JJA	**1986**	**1986**	**1986**
	SON	**1985**	**1986**	–
	Year	**1982**	**1986**	**1986**

to the observed rise in the mean lifetime of groups of CT. Particularly, the decreased frequency of within-group transitions that explains a part of the recent increase in the persistence, mainly in summer, may be an artefact resulting from the subjective approach to the classification. This point needs further investigation.

Table IV. Evaluation of statistically significant change points detected by various methods in the time series of the persistence of CT for groups of CT

	Pettitt test	SNHT	t-test
Number of examined series	39	39	39
Number of series with ≥1 change point	22	28	25
Number of series with ≥2 change points	10	1	12
Total number of change points	34	29	42
Number of change points in 1980–1990	19	26	23
Percentage of examined series with a change point in 1980–1990	46	67	54

6.2. Methodological issues

Various statistical methods (change point detection methods, Monte Carlo simulations and tests for trends) were utilized so that a comprehensive view of the past changes in the mean residence times of CT over Europe would be obtained. Besides well-established methods, two methodological modifications for the detection of climatic shifts were introduced. The SNHT is a frequently used tool for correcting inhomogeneities of observed data series, and despite the strong relation between the detection of inhomogeneities and climatic shifts, it has not yet been applied to locate the latter. The method has a sophisticated theoretical basis, and test results on artificial series (not shown) indicate that it is superior to other change point detection methods (*cf* Ducré-Robitaille *et al*., 2003). A new development utilized for the identification of discontinuities or climatic shifts is the modified sequential t-test. Its advantages are that it can be applied to any kind of time series without restricting to statistical qualities of the data (this is not true for the standard t-test) and that an examination of changes in a time window is unaffected by quality of data outside that window (and, thus, results for different parts of the series are independent).

6.3. Implications for the occurrence of extremes

Since stable atmospheric circulation usually supports anomalies of surface air temperature (as well as some other climatic variables) in one direction, the enhanced persistence of the circulation patterns may have been one of the causes of the increased frequency of climatic extremes observed in Europe in the 1990s and early 2000s (e.g. Heino *et al*., 1999; Kyselý, 2002; Domonkos *et al*., 2003; Beniston, 2004; Moberg and Jones, 2005; Trigo *et al*., 2005). Western and central European heatwaves of summer 2003 as well as central European floods on river Elbe and its tributaries in August 2002 may be examples of recent severe impacts of the enhanced residence times of particular circulation patterns favourable for extreme events. The fact that the higher persistence of the atmospheric circulation has been reflected mainly in the occurrence of positive temperature extremes in central Europe in summer is supported also by an increase in frequencies of anticyclonic CT at the expense of cyclonic ones (Kyselý, 2002; Jacobeit *et al*., 2003). This issue deserves further investigation.

6.4. Possible links with global warming

In all seasons, the atmospheric circulation over Europe has shifted towards a higher persistence around 1985, and the long-term perspective shows that this change is unprecedented since 1881. A decline in the frequency of cyclones observed over large parts of the northern hemisphere mid-latitudes (30–60 °N), including the North-Atlantic-European area, in the 1980s and 1990s (Serreze *et al*., 1997; McCabe *et al*., 2001; Paciorek *et al*., 2002; Zhang *et al*., 2004) seems to be consistent with the increase in the residence times of CT, since the generation of baroclinic instabilities reduces the persistence of the atmospheric circulation. If global warming is associated with a decrease in the baroclinicity over northern hemisphere mid-latitudes (likely related to a decrease of meridional temperature gradient, *cf* Geng and Sugi, 2003) and a northward shift of areas with the highest baroclinic activity (storm tracks) as indicated by a number of GCM and synoptic climatological

Table V. Trends in the persistence of CT for groups of CT over 1881–2000. Levels at which the null hypothesis (no trend) is true are shown for the t-test of the linear regression and the Mann–Kendall test. – indicates an insignificant trend at $p = 0.10$. Note that the NE and TM types were omitted in some seasons because of their low frequency of occurrence

Group of CT	Season	Trend (days/100 years)	p (t-test)	p (Mann–Kendall test)
W	DJF	1.5	<0.001	<0.001
	MAM	0.9	<0.05	<0.05
	JJA	0.3	–	–
	SON	0.7	<0.1	<0.05
	Year	1.0	<0.001	<0.001
N	DJF	0.2	–	–
	MAM	0.8	<0.01	<0.05
	JJA	0.9	<0.01	<0.01
	SON	0.5	–	<0.05
	Year	0.7	<0.001	<0.001
HM	DJF	−0.4	–	–
	MAM	0.4	–	<0.1
	JJA	0.6	–	–
	SON	0.1	–	–
	Year	0.1	–	–
S	DJF	0.5	<0.1	<0.1
	MAM	0.7	<0.01	<0.01
	JJA	0.4	–	–
	SON	0.6	<0.05	<0.05
	Year	0.5	<0.001	<0.01
E	DJF	1.5	<0.01	<0.01
	MAM	0.6	–	–
	JJA	0.7	–	–
	SON	0.9	<0.1	<0.05
	Year	0.9	<0.001	<0.001
NW	DJF	−0.3	–	–
	MAM	1.4	<0.01	–
	JJA	0.0	–	–
	SON	1.3	<0.01	<0.05
	Year	0.5	<0.05	–
NE	MAM	−0.2	–	–
	JJA	0.4	–	–
	Year	0.3	–	–
TM	Year	0.1	–	–
All	DJF	0.4	–	–
	MAM	1.1	<0.001	<0.001
	JJA	0.5	–	–
	SON	0.6	–	<0.1
	Year	0.7	<0.01	<0.05

studies (Hall *et al*., 1994; Schubert *et al*., 1998; Knippertz *et al*., 2000; Gulev *et al*., 2001; Geng and Sugi, 2003; Zhang *et al*., 2004), the increased persistence of the atmospheric circulation over mid-latitudes may be a concomitant event.

Table VI. Monte Carlo simulations of mean residence times of CT for groups of CT. P denotes the relative frequency of simulated mean residence times from the 1881–1985 data higher than the mean residence time in 1986–2000, * stands for values lower than 0.05. Note that the NE and TM types were omitted in some seasons because of their low frequency of occurrence

Group of CT	Season	Mean lifetime in 1881–1985 [days]	Mean lifetime in 1986–2000 [days]	P	
W	DJF	5.3	8.0	0.000	*
	MAM	4.8	6.2	0.000	*
	JJA	5.8	7.0	0.013	*
	SON	5.6	7.2	0.000	*
	Year	4.9	7.3	0.000	*
N	DJF	4.5	4.9	0.211	
	MAM	4.8	6.0	0.000	*
	JJA	4.8	5.8	0.000	*
	SON	4.4	5.6	0.000	*
	Year	4.7	5.6	0.000	*
HM	DJF	5.3	6.5	0.032	*
	MAM	5.9	5.6	0.071	
	JJA	4.6	6.5	0.000	*
	SON	5.8	6.8	0.002	*
	Year	5.1	6.2	0.000	*
S	DJF	4.8	5.6	0.014	*
	MAM	4.2	5.5	0.000	*
	JJA	4.7	5.6	0.000	*
	SON	5.0	5.7	0.000	*
	Year	4.4	5.5	0.000	*
E	DJF	4.5	6.8	0.002	*
	MAM	4.5	6.7	0.001	*
	JJA	4.3	6.2	0.001	*
	SON	5.3	5.9	0.020	*
	Year	4.4	6.5	0.000	*
NW	DJF	4.8	5.6	0.092	
	MAM	4.3	6.9	0.000	*
	JJA	4.8	4.8	0.396	
	SON	4.5	6.6	0.000	*
	Year	4.6	6.0	0.000	*
NE	MAM	4.0	5.8	0.081	
	JJA	6.1	7.0	0.012	*
	Year	5.0	5.8	0.003	*
TM	Year	4.4	5.2	0.028	*
All	DJF	5.2	6.4	0.000	*
	MAM	4.7	6.0	0.000	*
	JJA	5.1	6.1	0.000	*
	SON	5.3	6.3	0.000	*
	Year	4.9	6.2	0.000	*

Table VII. Percentage of simulated mean residence times of CT for 39 'group of CT–season' pairs significantly different in a given subperiod from the mean residence times over 1881–2000. $P < 0.05$ ($P > 0.95$) stands for the percentage of significantly high (low) values

Period	$P < 0.05$ (%)	$P > 0.95$ (%)
1881–1895	0	28
1896–1910	0	23
1911–1925	8	5
1926–1940	0	23
1941–1955	5	0
1956–1970	0	15
1971–1985	0	31
1986–2000	85	0

7. CONCLUSIONS

Temporal changes in the persistence of the large-scale atmospheric circulation over Europe were investigated using the Hess–Brezowsky catalogue of CT over 1881–2000. Trends, change points and outliers in the time series of the persistence (measured by the mean residence time of CT) of groups of CT were analysed. The main findings are as follows:

1. The most remarkable change in the persistence of the atmospheric circulation since 1881 is a general sharp increase from the 1970s to the late 1980s and 1990s. It is observed in all seasons and in most groups of CT and is a more general event than previous studies (confined to individual seasons and/or particular groups of CT) reported. It cannot be explained by a reduced within-group frequency of transitions between similar CT; if all CT in a given group are treated as one 'supertype', its mean lifetime is still enhanced for most groups of CT and in most seasons at the end of the twentieth century compared to earlier decades. However, a part of the recent increase is due to a decreased frequency of transitions between CT from the same group. Whether this is an artificial disturbance in the series of CT or not remains open.
2. The recent increase in the persistence of the atmospheric circulation is statistically significant in most groups of CT and most seasons. Different statistical tools applied here show various features of the long-term changes, but a shift towards a higher persistence in the 1980s is confirmed by all of them. The 1986–2000 period is a clear outlier and the change point detection methods locate the most conspicuous discontinuity of the series to the 1980s. The post-1985 values of the lifetimes of CT cannot be considered to be drawn from the same sample as the pre-1985 values; this finding is significant at the 0.01 level.

The change towards a higher persistence of the atmospheric circulation over Europe in the 1980s and 1990s may be related to the global warming, since the observed decrease in the cyclonic activity over the North Atlantic mid-latitudes as well as a northward shift of storm tracks (which are likely to be associated with the anthropogenic climate change) support more stable circulation conditions over central Europe.

The increase in the persistence of CT, in connection with other circulation changes such as the enhanced frequency of anticyclonic types at the expense of cyclonic ones in summer (Kyselý, 2002; Jacobeit *et al*., 2003), may have supported the more frequent occurrence of temperature and other climatic extremes observed in Europe in recent years.

ACKNOWLEDGEMENTS

Our thanks are due to F.-W. Gerstengarbe, Potsdam Institute for Climate Impact Research, Germany, for providing the revised dataset of the Hess–Brezowsky Grosswetterlagen. Part of the study was supported by Grant Agency of AS CR under project no A300420506.

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