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RECENT CLIMATE CHANGE IN THE NORTH ATLANTIC/EUROPEAN SECTOR

PETER C. WERNER[a,*], FRIEDRICH-WILHELM GERSTENGARBE[a], KLAUS FRAEDRICH[b] and HERMANN OESTERLE[c]

[a] *Potsdam-Institut für Klimafolgenforschung, Telegrafenberg, D-14473 Potsdam, Germany*
[b] *Meteorologisches Institut, Universität Hamburg, Bundesstrasse 55, D-20146 Hamburg, Germany*
[c] *Institut für Physik, Universität Potsdam, Am Neuen Palais 10, D-14469 Potsdam, Germany*

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ABSTRACT

The climate variability of the North Atlantic/European sector is characterized by large-scale circulation patterns measured in terms of a time series of two binary variables: the occurrence of a Grosswetter state and of a cluster set of meridional sea level pressure (SLP) gradients (characterizing the westerlies). An outlier test of the decadal behaviour of the residence time of these states identifies the decade 1981–1990 to be the first outlier. The climatological embedding and a possible stochastic/dynamical interpretation are presented. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: North Atlantic/Europe; time series; cluster analysis; Markov process; residence time; Grosswetter state; sea level pressure; air temperature

1. INTRODUCTION

The observation that global temperature has increased by about 0.3–0.6 K since the mid-nineteenth century (Intergovernmental Panel on Climate Change (IPCC), 1996) is not sufficient to answer the question whether this change does not exceed the natural variability. Other variables characterizing dynamical processes possibly associated with climate change need to be found, analysed and tested. In particular, such indicators that point to abrupt changes of the atmospheric circulation (Taylor *et al.*, 1993) are required because it may be expected that future climate changes will proceed at a similar speed as observed in the past. For example, the ice cores in Central Greenland reveal temperature changes of about 7°C within a few decades (Dansgaard *et al.*, 1989; Johnsen *et al.*, 1992; Grootes *et al.*, 1993). Although such abrupt temperature changes have not been observed so far, appropriate climatological parameters incorporating the atmosphere's complexity may show such a behaviour. For example, the North Atlantic Oscillation (NAO) reveals considerable change in the past decade (Hurrel, 1995), possibly affecting weather and climate in Europe (Wanner *et al.*, 1997). In this sense, the univariate NAO index time series, or similar parameters comprising highly complex dynamics, may be able to provide ideal measures to analyse and possibly identify a climate change signal.

That is, a systematic analysis of climate change requires identification of parameters characterizing climatologically relevant circulation patterns. Its subsequent time series analysis leads to reliable information on its frequency and persistence. In this paper, occurrence and residence time of weather states are chosen as such parameters that suitably characterize the statistics of large-scale circulation patterns (Grosswetter) effecting the North Atlantic/European sector. The outline is as follows: in the second section, the data and the method of analysis are presented, in the third section, a presentation and interpretation of the results are given.

* Correspondence to: Potsdam-Institut für Klimafolgenforschung, Telegrafenberg, D-14473 Potsdam, Germany.

2. DATA AND DATA ANALYSIS

Time series of binary circulation states are constructed from large-scale weather patterns (or Grosswetterlagen) to describe the variability associated with the zonality of the flow in the North Atlantic/European sector and to characterize the cross-Atlantic storm track. One state comprises similar patterns of westerly flow, the other is its complement and defines all remaining other circulation types. Both states are mutually exclusive. In addition, cluster analysis is applied to the meridional sea level pressure (SLP) gradients over continental Europe to obtain objectively defined patterns based on few parameters. Analogously, one cluster state can be identified comprising a subset of similar clusters comparable with the Grosswetter state; the other state contains the remaining other subset of clusters; again, both are mutually exclusive.

2.1. Grosswetter and clusters of sea level pressure

On a daily basis, the large-scale circulation of the North Atlantic/European sector has been described by Grosswetterlagen following Hess and Brezowsky (1977); see also Gerstengarbe and Werner, 1993; or Lamb and Jenkinson (Jones *et al*., 1993). Both catalogues provide subjectively estimated weather types. These datasets, for example, have been used to identify the response of far distant teleconnections, like the possible link between the El Niño–Southern Oscillation (ENSO) and Europe (Fraedrich, 1990; Wilby, 1993), regional influences of the sea surface temperature (SST) on large-scale processes in the northern hemisphere (NH) or Europe, climate trends, etc.

In the following, both catalogues are used but only the Grosswetterlagen of Hess and Brezowsky, especially the Grosswetter state W (west), will be analysed in more detail. The Grosswetter state W comprises the following Grosswettertypes: WA, west anticyclonic; WZ, west cyclonic; WS, west south; WW, west angular.

The catalogue of the Grosswetterlagen of Hess and Brezowsky was revised recently (Gerstengarbe *et al*., 1999). The test of homogeneity showed that artificial disturbances do not exist within the dataset. So the Grosswetterlagen represent the typical circulation patterns over Central Europe between 1881 and 1998.

It is supplemented by an objectively computed circulation index provided by clusters of a pair of daily north–south SLP differences at grid points over Europe (45°N/0°E–55°N/0°E, or the line Bordeaux–Newcastle; 45°N/20°E–55°N/20°E, or Belgrade–Kaliningrade). These two SLP differences are classified by a non-hierarchical cluster analysis (see Gerstengarbe and Werner, 1997). With this analysis, eight clusters are separated. Similarity with the Grosswetter W is achieved by combining all three (of the eight) clusters associated with the westerlies, into a single cluster set CW (west).

As the atmospheric circulation in the North Atlantic/European sector occurs in the Grosswetter state (W) or the cluster set (CW) for almost 30% of the time, the subsequent statistical analysis will be confined to a time series that is dichotomous (binary), consisting of two circulation regimes. One is the Grosswetter state $\mathrm{W}(t)$, and the other is its complement (no W), $\mathrm{N_W}(t)$; both states are mutually exclusive. Analogously, the cluster set process consists of two similar states, $\mathrm{CW}(t)$ and $\mathrm{N_{CW}}(t)$.

The following analysis of the daily binary datasets focuses on statistical parameters derived from the time series on an annual basis counted from $i = 1881–1882$ to 1997–1998:

(i) The mean occupation time of the Grosswetter state W during the days of winter (December–February), t_i, in frequencies per season is

$$O_{\mathrm{W}}(i) = \sum_{t_i} \mathrm{W}_i(t_i)$$

(ii) The residence times of the Grosswetter in state W (their frequencies and means) are

$$R_{\mathrm{W}}(i) = \frac{\sum_{j=1}^{m_i} H_{ij} j}{\sum_{j=1}^{m_i} H_{ij}}$$

where H_{ij} is the absolute frequency of the residence time j and m_i is the value of the longest residence time for the season i.

The time series of the new state variables (winter mean occurrence and residence time) is transformed to sample means of ten consecutive winter seasons (from December to February, DJF) which are constructed by sliding a decadal window over the time series.

2.2. Time series analysis of outliers

The time series of the seasonal residence time (distributions and means) and the mean occupation time are tested for outliers following the Thompson rule (Mueller *et al.*, 1973). This test defines outliers as follows:

$$t_i = (X_i - \langle X \rangle)/s^*, \quad \text{for } i = 1, \ldots, n$$

where $\langle x \rangle$ and s* are means and standard deviations of the samples (decadal windows). Outliers are all values x_i ($i = 1, \ldots, n$) for which $|t_i| > t_{m;\alpha}$ holds, with $m = n - 2$ ($t_{m;\alpha}$ = critical value, m = degree of freedom; α, statistical table). In this sense, the Thompson rule is a two-sided test to examine the hypothesis

H0:
The sample has no outliers for a chosen level of significance

The time series of the frequency distributions is tested by the Kolmogorov–Smirnov test.

3. CLIMATE CHANGE IN THE NORTH ATLANTIC/EUROPEAN SECTOR

To substantiate a possible change in climate and climate variability, the decadal mean residence times in winter (attached to the first year of the decade in all figures) of both the Grosswetter and the cluster state, W and CW, are analysed; their frequency distributions and their occupation times are also considered. Analysis of relations to other variables of the climate system are confined to the cluster state or CW time series, which shows a very similar statistical behaviour and is objectively derived.

3.1. Grosswetter and cluster states

3.1.1. Residence and occupation time. A qualitative inspection of Figure 1(a) shows an abrupt increase of the decadal means of residence times and its frequencies near the beginning of the 1970s. More support comes from an analysis of Central European Grosswetter, precipitation, and temperature (Bardossy and Caspary, 1990). The outlier analysis of the means reveals that, commencing with the decadal window 1981–1990 (from the winter 1981–1982 through to 1990–1991) they leave the level of the peaks observed so far and do not belong to the previous centennial sample (1881–1980) on the 99% significance level (denoted by triangles in all figures). The mean residence times of the cluster state CW show very similar behaviours (Figure 1(b)). Comparing the distributions of the residence times of the state W of 1971–1997 with the preceding reference period (1881–1970) demonstrates their difference with an error probability for the χ^2 test at a level of $\alpha = 0.01$ (Figure 2(a)). Figure 2(b) shows the same comparison for CW.

Applying the same analysis to the Lamb/Jenkinson circulation patterns, i.e. the type 16 (west) plus 26 (cyclonal west), leads to the same results (not shown). Note that the mean occupation times of the circulations states (W and CW) reveal an analogous time evolution, but there are no statistically safe outliers on the required level of significance.

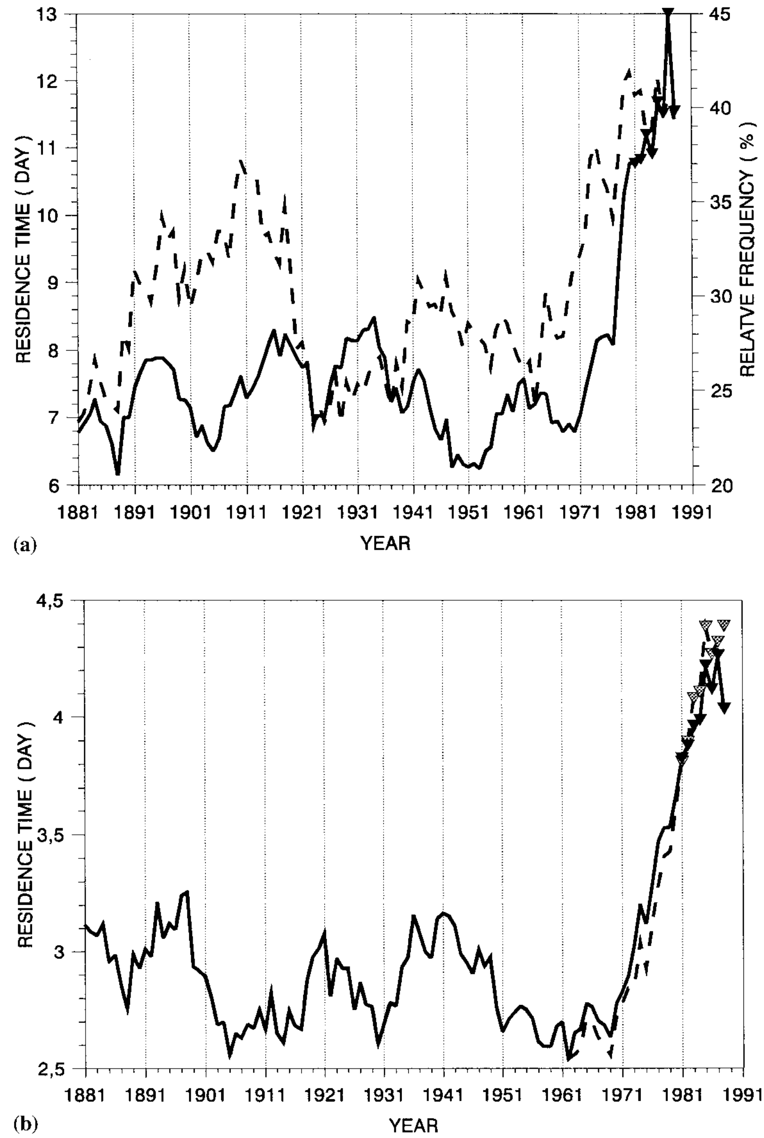

Figure 1. Time series of the decadal mean residence times (full line) and occupation time (dashed line) of the Grosswetter state W (a) and of the cluster state CW (b) in winter (1881–1882 to 1997–1998); triangles define statistically safe outliers ($\alpha = 0.05$) Discarding contributions from winter seasons affected by ENSO warm events since 1972 is shown by the dashed line

3.2. Climatological embedding

The observed climate change signal in the time evolution of the decadal mean residence time of both the Grosswetter state W and cluster state CW (and their frequency distributions) requires supporting analysis of its relations to other parameters: is it a regional effect, related to teleconnections or connected to an overlying global process? Accordingly, the subsequent analysis concentrates on the relation with (a) the North Atlantic SST (obtained from the Hadley Centre, 1998), (b) the ENSO, (c) the NH winter mean surface temperature (Jones *et al.*, 1998), and (d) the evolution of the continental surface temperature anomalies. In the following, the decadal variability of the large-scale circulation patterns will be compared with the more objectively defined cluster state W (Figures 1(b) and 3(a) and (b) for the decadal mean residence times).

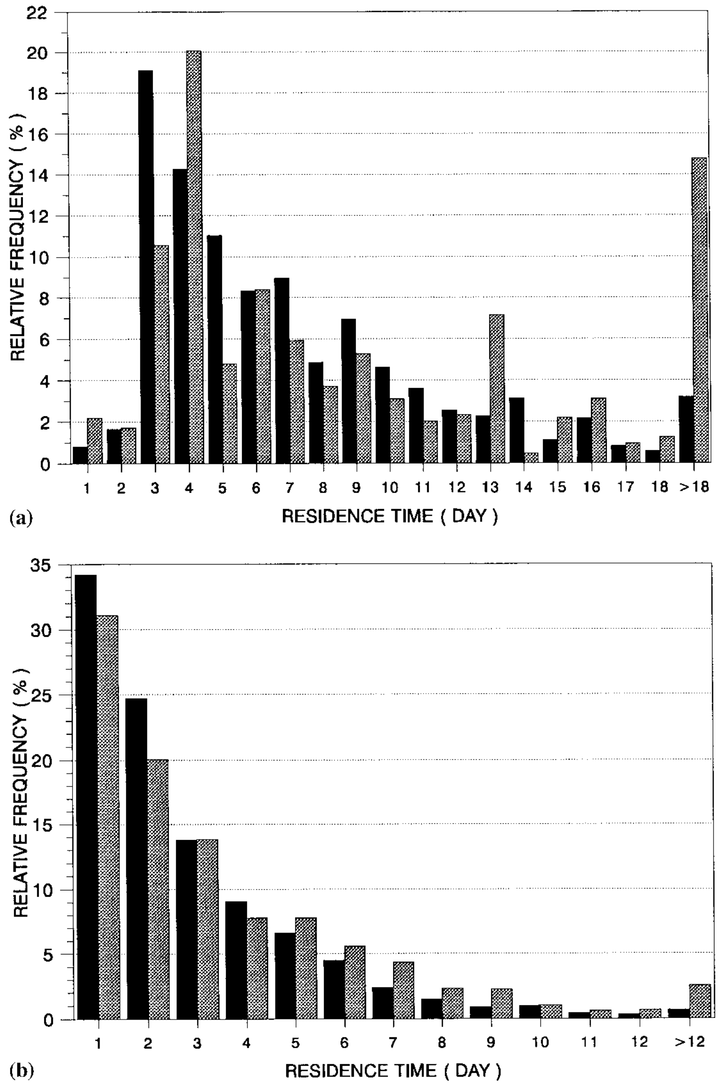

Figure 2. Distribution (relative frequencies) of the residence time of the Grosswetter state W (a) and of the cluster state CW (b) for the time periods 1881–1970 (black columns) and 1971–1997 (grey)

3.2.1. (a) North Atlantic SST. Figure 3(a) shows the time series of the decadal mean of the residence time of the cluster state CW and the north–south gradient of the North Atlantic SST between 60.5°N and 40.5°N at 30.5°W. Both graphs reveal the same strong rise since the early 1970s. However, the time series of the SST gradient is without any significant outlier. Comparing the two time series from 1971–1972 to 1996–1997 on a annual basis shows that the correlation coefficient is only $r = 0.3$ without subtracting the trend. The low correlation indicates only a weak control of the SST gradient on the evolution of the cluster state CW and its variability.

3.2.2. (b) El Niño–Southern Oscillation (ENSO). Figure 1(b) shows the time series of the mean SLP cluster residence time with and without warm event ENSO years, commencing with the decade 1961–1970. There is almost no difference between the two graphs, which demonstrates that the enhanced ENSO activity of the last decades has no influence on the cluster state statistics.

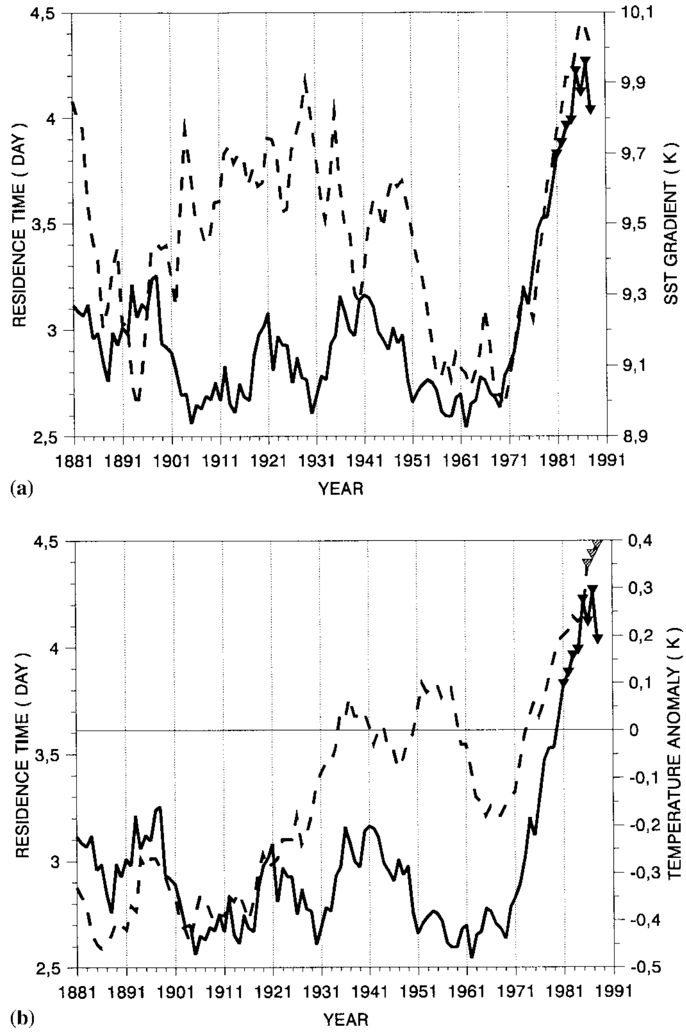

Figure 3. (a) Time series of the decadal mean residence times of the cluster state CW in winter (1881–82 to 1997–1998); triangles define statistically safe outliers ($\alpha = 0.05$). The winter mean of the SST gradient is indicated by the dashed line. (b) Time series of the decadal mean residence times of the cluster state CW in winter (1881–82 to 1997–1998); triangles define statistically safe outliers ($\alpha = 0.05$). The dashed line shows northern hemispheric temperature anomalies (winter means)

3.2.3. (c) NH surface temperature. Figure 3(b) shows the time series of the mean SLP cluster residence time in comparison with the NH surface temperature. Since 1881 up to the 1970s there is almost no simultaneous development of both variables. However, it appears that in the 1980s and 1990s both surface temperature and mean residence time increase in the same manner. Note that the first outlier of the SLP cluster occurs during the decade 1981–1990, which, in a qualitative sense, coincides with the NH surface temperature leaving its range of variability. Applying the same test to the NH surface temperature the last three winter decades from 1986–1995 to 1988–1997 are statistically safe outliers.

3.2.4. (d) Continental surface temperatures. Annual mean temperatures from 1901 to 1995 on a 2° × 2° grid (New and Hulme, 1997) on the continents serve as a basis for a global analysis of decadal temperature utilizing cluster analysis. Five clusters (Figure 4(a)) of the sequence of 10 year temperature anomalies at each grid point, which are associated with a time evolution of the centroids (Figure 4(b)), are determined. The temporal courses of each of the five centroids differ in the period between 1901 and 1970. However, after 1970, all graphs are similar, revealing upward trends of varying intensity demonstrating global warming.

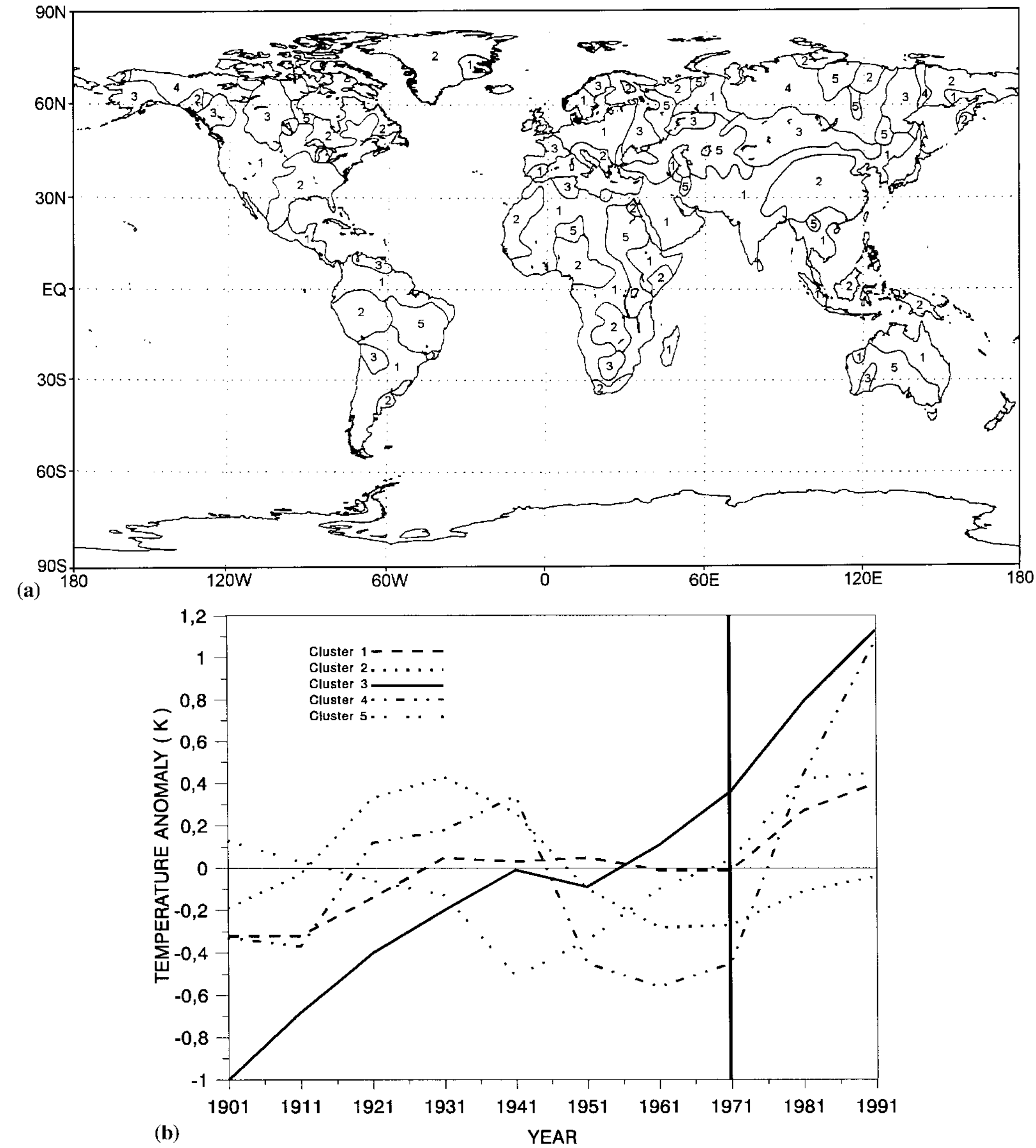

Figure 4. (a) Global distribution of clusters characterizing the time evolution of decadal mean temperature anomalies (1901–1991) over continents; no observations exist in white areas. (b) Time evolution (1901–1991) of the decadal mean temperature anomalies over continents represented by the five clusters

3.3. *A conceptual model: Markov properties*

Further insight into the process underlying the observed climate variability may be gained from an analysis of the Markov properties of the daily dichotomous (CW, N_{CW}) time series associated with the SLP cluster. These properties are represented by a two-state Markov chain, which describes the dynamics of the probabilities attached to the occurrence of CW and N_{CW}. These two events can be regarded as the outcome of a trial at time t that depends on the outcomes of the directly preceding trials at $t-1, t-2, \ldots, t-n$, where n denotes the order of the process. This order is the measure of the deterministic contribution to the process and describes its memory. In this sense, it can be compared with an autoregressive process; e.g. a first-order system describes exponential (or geometrical) decay and a second-order process allows oscillatory behaviour. It is plausible that a change of the order n of the process is an indication of a qualitative change in the underlying dynamics; no order change may be attributed to a change of the intensity of the process measured in terms of the associated distributions of, say, residence or exit times. Estimating the order after the χ^2 test (Anderson and Goodman, 1958; see also Fraedrich and Müller, 1983) proceeds as follows: starting with the order $o = 1$, neighbouring Markov chains are compared. For the test statistics, the following equation is used:

$$Z = \sum_{i,j,\ldots,k,l} \frac{n_{i,j,\ldots,k,l}(P_{i,j,\ldots,k,l} - P_{j,\ldots,k,l})^2}{P_{j,\ldots,k,l}}$$

with $i, j, \ldots, m$ conditions and $n_{i,j,\ldots,k,l}$ transition numbers. Z follows a χ^2 distribution. The degree of freedom can be calculated from

$$F = m^{o-1}(m-1)^2$$

The order o of the Markov process is defined as that point on which the test value Z changes from 'significant' (= order o) to 'non-significant' (= order $o + 1$).

Estimating the parameters of the Markov chain based on sliding decadal samples, and applying the Anderson–Goodman test yields a third-order process. This order remains unchanged for the whole time series from 1881 to 1997. This indicates that the transition in climate variability commencing with the outliers of the 1971–1980 decade may not be associated with a change in the underlying dynamics, but merely a change of intensity.

4. CONCLUSIONS

The climate variability of the North Atlantic/European sector in winter is characterized by large-scale circulation patterns measured in terms of time series of binary variables: the occurrence of a Grosswetter state (comprising a set of weather patterns) and a cluster set of meridional SLP gradients is used to describe the zonality of the flow. Time series of these statistics define the climate signal. It is associated with the behaviour of circulation patterns in terms of their residence times during which the circulation remains in the state of zonality. The results of the analysis are summarized below.

An *outlier test* of the decadal behaviour of the climate state signal (the mean and distribution of the residence time of circulation patterns) identifies the decade 1981–1990 as the onset of climate change in the North Atlantic/European sector with a trend commencing in the beginning of the 1970s.

A stochastic/dynamical interpretation is based on an *order test* of the two-state Markovian properties of the binary time series. As a third-order process characterizes the complete time series from 1881 to 1997 as well as the period from 1971 to 1997; the transition in climate variability starting with the outliers of the 1971–1980 decade, may not be associated with a change in the underlying dynamics but merely a change of the intensity.

The clusters of the decadal global surface temperature anomaly sequences 1901–1997 over the continents show a simultaneous rise from 1971–1980 onwards. This provides the climatological embedding for the observed climate variability identified in the statistics of circulation patterns in the North Atlantic/European sector. Other parameters (ENSO variability, North Atlantic SSTs, NH temperatures) have been excluded to be significantly related to the observed climate change.

With the indicated relation between global and regional circulation changes one can not conclude that a general global circulation change exists. To substantiate this hypothesis a full set of circulation indices over the globe needs to be assessed. In case that a significant number of them are characterized by significant circulation changes, evidence for a real signal is visible. This will be the task of a further analysis.

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