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Angaben zur Veröffentlichung / Publication details:

Jacobeit, Jucundus, Joachim Rathmann, Andreas Philipp, and Philip D. Jones. 2009. "Central European precipitation and temperature extremes in relation to large-scale atmospheric circulation types." *Meteorologische Zeitschrift* 18 (4): 397–410. https://doi.org/10.1127/0941-2948/2009/0390.

Meteorologische Zeitschrift, Vol. 18, No. 4, 397-410 (August 2009)

Article

Central European precipitation and temperature extremes in relation to large-scale atmospheric circulation types

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(Manuscript received December 10, 2008; in revised form March 3, 2009; accepted March 19, 2009)

Abstract

There is increasing concern that precipitation and temperature extremes may be changing in frequency and character as a result of changing climate, and the latter is mostly linked with particular changes in the atmospheric circulation. Therefore the question arises – a key question in the climate change prospective – as to how precipitation and temperature extremes are related to large-scale atmospheric circulation types? To study such relationships over an extended period of more than one and a half centuries, we include daily precipitation and temperature time series compiled during the EU project EMULATE (European and North Atlantic daily to multidecadal climate variability) back to 1850 as well as daily mean SLP reconstructions from the same project for the same period. The latter data set has been used for classifying daily circulation types for each season using a simulated annealing clustering technique. Comparing each of these circulation types with their percentages among extreme days and among non-extreme days (with respect to precipitation or temperature) clearly reveals that in most cases only a few of the seasonal circulation types are conducive to the occurrence of daily extremes. This is shown for heavy precipitation and positive temperature extremes (beyond the 98th percentile in each case), related to the winter (DJF) and summer (JJA) seasons for a central European region. Different circulation patterns proved to be important in this context. Thus, in contrast to positive temperature extremes during winter being linked preferably to zonal circulation patterns (positive mode of the North Atlantic Oscillation, NAO), heavy winter precipitation in central Europe is distinctly associated with less zonal patterns characterized by an eastward or southeastward shift of the subpolar centre of low pressure implying only weak correlations with the NAO. Furthermore, particular indices reveal that changing frequencies of extremes are not only due to corresponding frequency changes of these conducive circulation types, but also to changes of their association to precipitation or temperature extremes (reflected by changes in the percentage of extremes related to the overall occurrence of the corresponding circulation type). These within-type changes of circulation types often govern the low-frequency variations in the overall incidence of extremes.

Zusammenfassung

Verbreitet wird damit gerechnet, dass Häufigkeit und Eigenschaften von Niederschlags- und Temperaturextremen sich ändern, wenn das globale Klima einem Wandel unterworfen ist. Da letzteres zumeist mit Änderungen in der atmosphärischen Zirkulation einhergeht, stellt sich die Schlüsselfrage, wie diese Extreme in Beziehung stehen zu großskaligen Zirkulationstypen. Um dies für den ausgedehnten Zeitraum seit Mitte des 19. Jahrhunderts zu untersuchen, wird auf Datensätze aus dem EU-Projekt EMULATE zurückgegriffen (European and North Atlantic daily to multidecadal climate variability), sowohl hinsichtlich täglich aufgelöster mitteleuropäischer Niederschlags- und Temperaturzeitreihen als auch rekonstruierter täglicher Bodenluftdruckfelder für den nordatlantisch-europäischen Großraum. Auf deren Basis sind während des genannten Projekts tägliche Zirkulationstypen für jede Jahreszeit mittels einer Clustermethode bestimmt worden, die auf sog. ‚simulated annealing' beruht. Vergleicht man für jeden dieser Zirkulationstypen seine Prozentanteile an den Extremtagen und an den nicht-extremen Tagen (bezüglich Niederschlag bzw. Temperatur), stellt sich klar heraus, dass in den meisten Fällen nur wenige der Zirkulationstypen begünstigend für das Auftreten von Extremen sind. Dies wird konkret für Starkniederschläge und positive Temperaturextreme (jeweils jenseits des 98 % Perzentils) im mitteleuropäischen Winter (DJF) und Sommer (JJA) gezeigt. Dabei ergeben sich folgende Differenzierungen: während positive Temperaturextreme im Winter vorwiegend mit zonalen Zirkulationsmustern verbunden sind, die der positiven Phase der Nordatlantischen Oszillation (NAO) entsprechen, sind winterliche Starkniederschläge in Mitteleuropa mit weniger zonalen Strömungskonfigurationen assoziiert, die durch eine ost- oder südostgerichtete Verlagerung des subpolaren Tiefdruckzentrums bei nur mehr geringen Korrelationen mit der NAO gekennzeichnet sind. Weiterhin zeigen spezifische Indizes, dass Häufigkeitsänderungen von Extremen nicht nur auf entsprechende Auftretensänderungen der begünstigenden Zirkulationstypen zurückzuführen sind, sondern auch auf typinterne Änderungen bei diesen Zirkulationstypen (erkenntlich an variablen Anteilen extremer Tage an der Gesamtzahl der Auftretenstage des betreffenden Zirkulationstyps). Diese zirkulationstypinternen Änderungen bestimmen sogar häufig die niederfrequenten Schwankungen im Gesamtauftreten von Niederschlags- bzw. Temperaturextremen.

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DOI 10.1127/0941-2948/2009/0390

0941-2948/2009/0390 $ 6.30

1 Introduction

Extremes in climatic parameters will always be proportionately more important in the media than changes in mean climate, since they have often strong impacts on ecosystems and society (DIAZ and MURNANE, 2008). As we have learned from historical climatology (e.g. JONES and LISTER, 1998; GLASER and STANGL, 2004; LUTERBACHER et al., 2004; GLASER et al., 2005; GLASER, 2008), the frequency and intensity of extreme events has changed with time, and therefore studies on extremes are a major emphasis in the context of climate change. Since changes in climate are mostly accompanied by changes in the atmospheric circulation, it is furthermore important to look at relationships between circulation and extremes. In view of the fact that the large-scale circulation is much better represented in climate models than extreme events, such relationships identified in observed data sets might also improve assessments on future changes in extremes provided that they are based on sufficiently long time-series to develop robust linkages. However, circulation-climate relationships are also changing with time, as for example YIOU et al. (2007) have shown for temperature during the last decade. This might be due to externally driven changes in climate that are not directly reflected in circulation changes (YIOU et al., 2007), or to changes in characteristics of particular circulation types (so-called within-type changes, BECK et al., 2007). Furthermore, temperature variability is also controlled by local feedbacks (e.g. FISCHER et al., 2007; VAUTARD et al., 2007) and remote teleconnections (e.g. CASSOU et al., 2005) which have modifying effects on atmospheric circulation variability. Besides these additional factors, relationships between large-scale circulation and regional climate constitute an important aspect for understanding variations in climate extremes since circulation patterns are able to explain spatial distributions, regional characteristics and long-term dynamics of extremes in a physically consistent way. This paper will contribute to such investigations after a short overview of selected works on extremes and their relation to the atmospheric circulation.

Due to requirements concerning sufficient data quality, many studies on extremes are restricted to relatively short periods (some decades or one century at the most). Analyses are based on monthly data (e.g. SCHÖNWIESE et al., 2003; TRÖMEL and SCHÖNWIESE, 2005) as well as on daily data (e.g. HUNDECHA and BÁRDOSSY, 2005; MOBERG et al., 2006; DELLA-MARTA et al., 2007a). In the compilation of FRICH et al. (2002), for the second half of the 20^{th} century, significant trends are identified for a number of extremes indices, such as the number of warm summer nights, the number of frost days or the intra-annual extreme temperature range. Indices based on daily precipitation data show a significant increase in the extreme amount derived from wet spells and in the number of heavy rainfall events for most regions outside the tropics. The last IPCC report (TRENBERTH et al., 2007) likewise indicated increasing contributions to total annual precipitation from very wet days (beyond the 95th percentile) during the last decades on a global scale.

In accordance with the recent evolution of climate (cooling trend before the 1970s and a subsequent pronounced warming, KLEIN TANK et al., 2002), cold extremes have decreased and warm extremes have increased during the last quarter of the twentieth century. This has been shown for Europe (e.g. KLEIN TANK and KÖNNEN, 2003) as well as for various sub-regions (e.g. DELLA-MARTA et al., 2007b; BARTOLINI et al., 2008; PAVAN et al., 2008; TORETI and DESIATO, 2008). Furthermore, the general warming was accompanied by an increase not only in frequency but also in persistence of high temperatures in Europe (e.g. BENISTON and STEPHENSON, 2004; KLEIN TANK and KÖNNEN, 2003; MOBERG and JONES, 2005). For the summer season, DELLA-MARTA et al. (2007a) have shown that the length of heat waves over western Europe has doubled and the frequency of hot days has almost tripled since the late 19th century. The exceptional summer of 2003 has almost certainly been the hottest one since the year 1500 according to objective reconstructions of European temperatures (LUTERBACHER et al., 2004), and similar extreme events are likely to increase considerably in the future (BENISTON, 2004; SCHÄR et al., 2004). It is not just summers that have greater warm anomalies, other seasons have also been affected recently by exceptional anomalies (XOPLAKI et al., 2005; LUTERBACHER et al., 2007; YIOU et al., 2007; RUTISHAUSER et al., 2008).

Based on century-long daily temperature and precipitation data for Europe, MOBERG et al. (2006) have compiled an extensive set of extremes indices pointing to upward trends for all temperature indices. The same set of indices has further been extended back to the mid-19th century by CHEN et al. (2007). Changes in extreme temperatures for still longer time periods have been analyzed by YAN et al. (2002) using data from ten stations in Europe and China. They point out that additionally to the well-known recent trends there have also been changes of these extremes in the past: the 18th century warm period was followed by decreasing positive extremes especially for summer, whereas negative extremes have decreased since the late 19th century in winter.

Extreme temperatures have also been analysed by modeling studies, for present day climate as well as for climate change signals (e.g. KJELLSTRÖM et al., 2007). However, distinct conclusions are difficult to reach, if the difference in model predicted changes of extreme temperatures is larger than the natural variability during historical times. Another regional modeling study has been performed for the Mediterranean area (PAETH and HENSE, 2005), simulating present and future extreme climate conditions. Other numerical studies are focusing on mechanisms of extreme events, as for example the investigation on intense alpine precipitation by ROTUNNO and FERRETTI (2001). Such studies are useful in explaining physical processes during particular extreme events, but they could only be a starting point to deduce the long-term aspect of relations between extremes and atmospheric circulation.

YIOU and NOGAJ (2004) present an important study relating extreme events to the large-scale atmospheric circulation over the North-Atlantic-European region. Using data from 1958 to 2003, extreme events are defined by the exceedance of percentile-based thresholds for precipitation and temperature. Atmospheric circulation regimes, obtained by EOF (empirical orthogonal function) analysis of daily winter 500 hPa geopotential height anomalies and subsequent k-means clustering of the corresponding principal components, are identified as positive and negative NAO (North Atlantic Oscillation), Scandinavian blocking and an Atlantic ridge pattern. YIOU and NOGAJ (2004) highlight the importance of the atmospheric blocking regime for the occurrence of extreme climatic events in southern and northern Europe. Another approach to relate the large-scale atmospheric circulation to near-surface climate was used by DOMONKOS et al. (2003) analysing the variability of cold winters and hot summers in central and southern Europe based on 11 daily temperature time series for 1901–98. They applied the subjective Hess-Brezowsky classification (HESS and BREZOWSKY, 1952; GERSTENGARBE et al. 1999), found a strong increase (decrease) in the frequency of extremely warm (cold) events, and concluded that the residence times of circulation patterns over central Europe became longer both in winter and summer. KYSELÝ (2007) used a similar approach and demonstrated that the occurrence and severity of temperature extremes has become more pronounced in the context of more persistent circulation patterns. In the summer season, DELLA-MARTA et al. (2007b) have shown by Canonical Correlation Analysis that heat waves over western Europe are related to anomalous high pressure over Scandinavia and central western Europe, but they point out furthermore that other factors like Atlantic and Mediterranean SSTs (FEUDALE and SHUKLA, 2007) as well as soil moisture proxies are also important in the context of these kinds of extremes (see also SCHÄR et al. (1999), SENEVIRATNE et al. (2006), FISCHER et al. (2007) and SENEVIRATNE and STÖCKLI (2008) emphasising the amplifying effects of soil moisture feedbacks on climate extremes).

This paper takes up the objective of relationships between large-scale atmospheric circulation and climate extremes, in particular precipitation and temperature extremes in the region of Central Europe. In contrast to many of the previous studies (e.g. TRENBERTH et al., 2007) which are based on rather short time periods (due to the restricted availability and quality of data), the present study will use longer time series of more

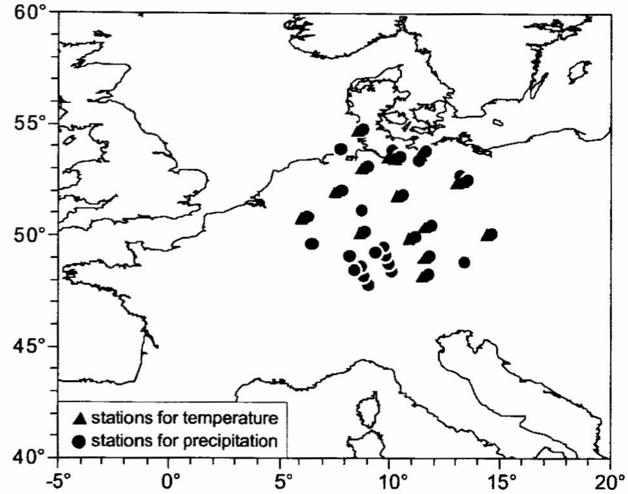

Figure 1: Locations of Central European stations used for precipitation and temperature analyses.

than one and a half centuries (see next section). Furthermore, the atmospheric circulation will be included in terms of a recently derived classification which optimizes the assignment of individual SLP fields to large-scale circulation types by a novel technique (section 2.2). Thus, we may contribute to an improved assessment of circulation-climate relationships with respect to Central European precipitation and temperature extremes.

2 Data and methods

2.1 Precipitation and temperature

A new database containing European long-term station data for precipitation and temperature with a daily resolution has been generated within the EMULATE project (European and North Atlantic daily to multidecadal climate variability, www.cru.uea. ac.uk/projects/emulate). The present study is based on Central European daily time series from this project going back to the year 1850. Therefore, early measurement problems as discussed by AUER et al. (2007) and also indicated by disagreements between measurements and proxy data (e.g. FRANK et al., 2007) have to be taken into account. However, a large part of original data deficiencies have been removed in the meanwhile justifying the following analyses. Furthermore, most homogeneity issues relate to low-frequency and thus will not be important in the present context. For details on various aspects of data quality see MOBERG et al. (2006).

For central Europe north of the greater Alpine region, 33 stations for precipitation and 16 stations for temperature are included in the EMULATE database (see Fig. 1 for the location of stations). This paper focuses on positive daily precipitation and positive temperature

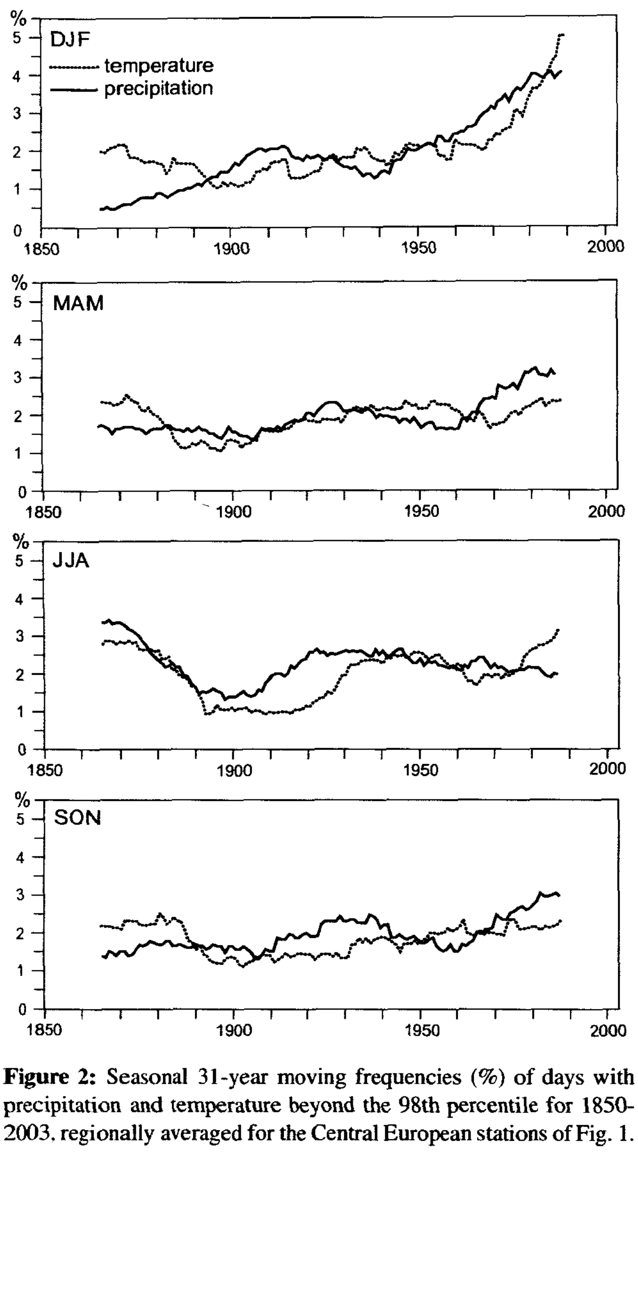

Figure 2: Seasonal 31-year moving frequencies (%) of days with precipitation and temperature beyond the 98th percentile for 1850-2003, regionally averaged for the Central European stations of Fig. 1.

extremes defined by the 98th percentiles of the corresponding seasonal time series 1850–2003. Fig. 2 depicts the 31-year moving frequencies of days with extreme precipitation and temperature that exceed the defined threshold, based on Central European time series for these variables averaged across the stations of Fig. 1. Obviously, an increase in heavy precipitation has taken place during the last decades except for summer (Fig. 2) with the earliest starting date for this increase during winter. Global warming in recent decades has also led to increasing frequencies of positive temperature extremes (Fig. 2), most pronounced during winter, but not discernible during spring and autumn. Some relationships to the atmospheric circulation will be discussed in the following sections.

2.2 Determination of large-scale atmospheric circulation types

A daily circulation type classification for the European-Atlantic domain has been developed using reconstructed mean sea level pressure (MSLP) data for the period 1850 to 2003. This reconstruction was based on a lot of homogenized station pressure time series which have been submitted to a reduced space optimum interpolation (RSOI) approach (ANSELL et al., 2006). The reference EOFs used to project station measurements onto a 5°x5° grid have been determined from NCEP/NCAR reanalysis (KALNAY et al., 1996; KISTLER et al., 2001). The reconstructed dataset is described in detail by ANSELL et al. (2006). In order to account for the spatially varying interpolation quality mainly caused by differences in the spatial station density, the reconstructed MSLP values have been weighted for further processing by the grid-point-specific mean interpolation error. Thus, the assignment to clusters (see below) will be dominated by pattern similarities in regions of low interpolation errors (central and western Europe) whereas regions with less reliable reconstructions (mainly at the margins of the domain) have a smaller impact on the classification results.

In order to achieve daily circulation types with minimized within-type pressure differences, non-hierarchical cluster analysis (NHCA) has been used as the classification method. The most common algorithm applied for NHCA is the k-means clustering technique for which the number of clusters has to be defined beforehand. Starting with an arbitrary initial partition of the individual daily circulation patterns (which represent the objects to be classified), they are stepwise shifted to another cluster if this reduces the overall within-cluster differences measured by the Euclidean distance between all objects and the corresponding cluster centroid pattern (commonly referred to as "within-cluster sum of squares" (WSS) of differences). Such a shift, in turn, alters the centroids of the two affected clusters and requires that all objects are tested again in additional iterations. Finally, a partition is achieved where no shift of single objects can further reduce WSS, i.e. the process has converged to an optimum solution with respect to within-cluster similarity of patterns. However, if there is no clearly inherent grouping in the dataset – as it is the case for daily MSLP data – there are more than one optimized partitions (referred to as local optima) differing considerably from the so-called global optimum. Moreover, depending on the starting partition and the ordering of objects to be classified, conventional k-means clustering converges to any local optimum by chance without any possibility to predict which one it might be (PHILIPP et al., 2007). In order to overcome this constraint and to approximate the global optimum, a more sophisticated NHCA algorithm has been developed using a Simulated ANnealing and Diversified RAndomisation (SANDRA) approach (PHILIPP et al., 2007). The only but decisive difference between simulated annealing and k-means is

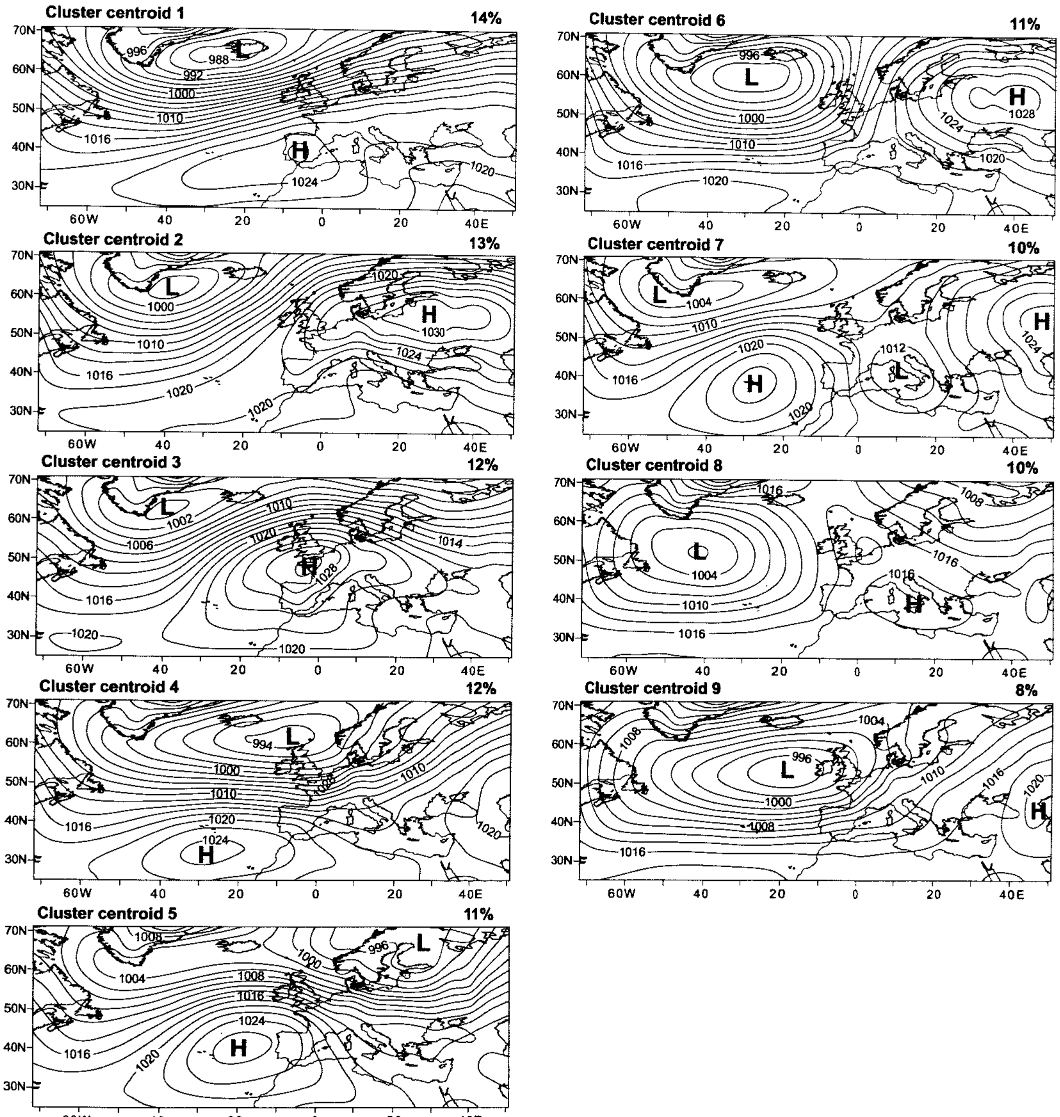

Figure 3: Centroid patterns (hPa) resulting from a SANDRA cluster analysis (see text) of daily SLP fields for winter (DJF) 1850–2003 (from PHILIPP et al., 2007).

the following: the reduction of WSS is not irreversible for simulated annealing, so that local optima can be left again if there is another optimum with further reduced WSS. This is achieved by allowing shifts of objects between clusters not only if they lead to further reductions in WSS, but also (with a certain probability) if this is not the case. This probability is slowly reduced during the iterative process leading to a slow approximation of the global optimum (for further details see PHILIPP et al., 2007).

Unfortunately it is neither analytically nor numerically possible to prove whether a particular optimum represents the global optimum. Therefore the procedure is repeated 1000 times with randomly diversified starting partitions as well as randomly diversified orderings of objects and clusters. Finally, the best solution from these runs is selected representing the best approximation of the global optimum. The SANDRA algorithm has been extensively compared to conventional k-means and outperformed it in all cases concerning the resulting WSS. This was even true when k-means has been repeated 10^5 times with diversified starting partitions and SANDRA only 10^3 times. Furthermore, comparisons of resulting partitions show that there are large impacts on the actual assignment of objects to particular circulation types reflecting the different performance of clustering (PHILIPP et al., 2007).

Since there is no unambiguous way to define the appropriate number of clusters, the number of independent T-mode PCA (Principal Component Analysis) patterns fitting into the dataset has been used. T-mode analysis (see RICHMAN, 1986) processes spatial fields of a particular quantity (MSLP in this case) for a number of time units (days of a season in this case) in such a way that the time units enter as variables and the spatial units (grid points) as cases (JACOBEIT et al., 2003a). Resulting T-mode scores define the basic circulation patterns whose time coefficients (often called amplitudes) are given in terms of T-mode loadings. A crucial question is the way to determine an appropriate number of principal components for such analyses. In the present context this number has been determined by applying particular dominance criteria for the extraction of orthogonal modes. These criteria ensure that each of the PC circulation patterns has at least one significantly correlated correspondent among the original MSLP patterns thus excluding artificial PC patterns. For further details on these criteria see JACOBEIT (1993) and PHILIPP et al. (2007). They indicate 9 patterns for winter and 6 patterns for summer defining the numbers of seasonal SLP clusters prescribed to the SANDRA algorithm. Resulting circulation types are represented by the cluster centroid patterns which differ from the above-mentioned PC patterns due to the calculation of mean values from the cluster members instead of deriving dynamical modes. For the analysis of relationships between circulation and daily precipitation/temperature extremes such circulation types – allowing for unambigious assignments of all days within the study period to one particular circulation type – have been preferred against multivariate modes or regimes of the atmospheric circulation (see STEPHENSON et al., 2004) being widely used for studying large-scale dynamics of the climate system.

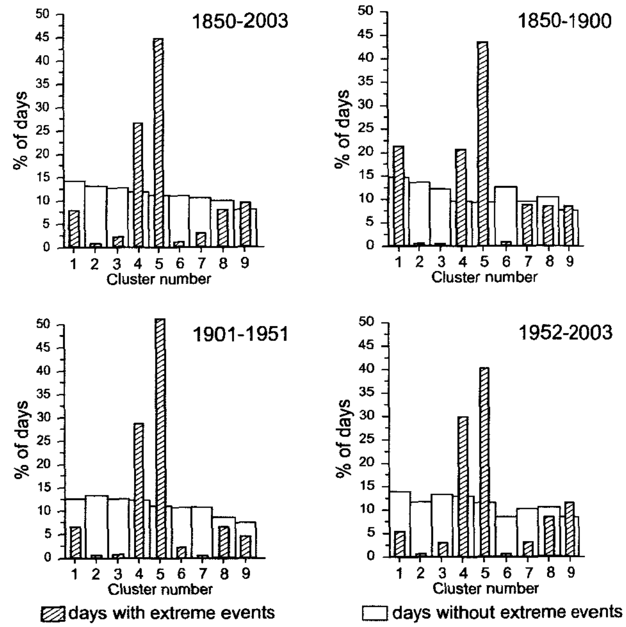

Figure 4: Percentages of days with extreme Central European precipitation (beyond the 98th percentile) and without such extremes for each of the wintertime SLP clusters of Fig. 3, related to the overall occurrences within the indicated time periods. Clusters with ratios between these percentages significantly greater than 1 (0.01 level according to Monte-Carlo resampling of 1000 circulation type time series) are discussed in the text.

2.3 Relating precipitation/temperature extremes to circulation types

In a first step the number of days with extreme Central European precipitation or temperature (beyond the corresponding 98th percentile) and the number of days without such extremes has been calculated for each of the seasonal SLP clusters. These are then related to the overall seasonal occurrences of extreme days and non-extreme days, respectively. Those circulation types for which the ratio between these percentages is significantly greater than 1 (with significance testing based on Monte-Carlo resampling of 1000 circulation type time series), are considered to be conducive to the corresponding extremes. This ratio is slightly different from the efficiency coefficient of KYSELÝ (2007) which relates the frequency of a circulation type within the extremes sample to its long-term mean frequency. The latter includes the extreme cases for the particular circulation type once more whereas the ratio defined above relates disjoint quantities to each other.

In a second step SLP composites are calculated for each seasonal SLP cluster from days with extreme Central European precipitation or temperature and from days without such extremes. To maintain equal sample sizes for these composites (otherwise the degree of smoothing would differ too strongly), the members of the non-extreme one have been randomly sampled up to the same sample size as given for the extreme composite. Using another random sampling has proved to have no discernible effects on the main results.

The third approach derives characteristic daily SLP pattern sequences from 4 days before an extreme event by performing extended T-mode PCA of all corresponding sequences during a particular season. This approach, also called "Principal Sequence Pattern Analysis" (COMPAGNUCCI et al., 2001), extends the time-scale from one individual pattern being linked with an extreme event to a whole sequence of daily patterns before this event thus enabling identification of particular developments in flow configurations linked to the occurrence of such extreme events (JACOBEIT et al., 2006).

The fourth step addresses the temporal variation in relationships between circulation types and extreme events by calculating particular indices: a first one describes, in terms of 31-year moving frequencies separately for each seasonal circulation type, how many days from each 31-year window have experienced extreme precipitation or temperature in connection with the occurrence of the corresponding circulation type thus indicating its decreasing or increasing representation in connection with extreme events. A second index relates the number of days with extremes occurring together with a particular circulation type to the overall number of days

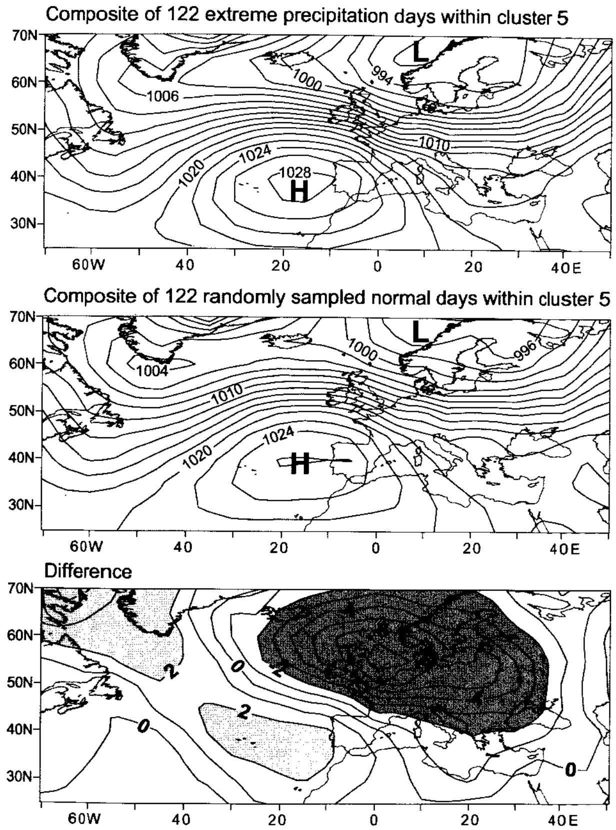

Figure 5: SLP composites (hPa) of days with extreme Central European precipitation (beyond the 98th percentile) and without such extremes (randomly sampled with the same sample size) for SLP cluster 5 (see Fig. 3) during winter (DJF) 1850–2003. Light and dark grey shading in the difference map is for positive and negative significant values (0.05 level according to Mann-Whitney test), respectively.

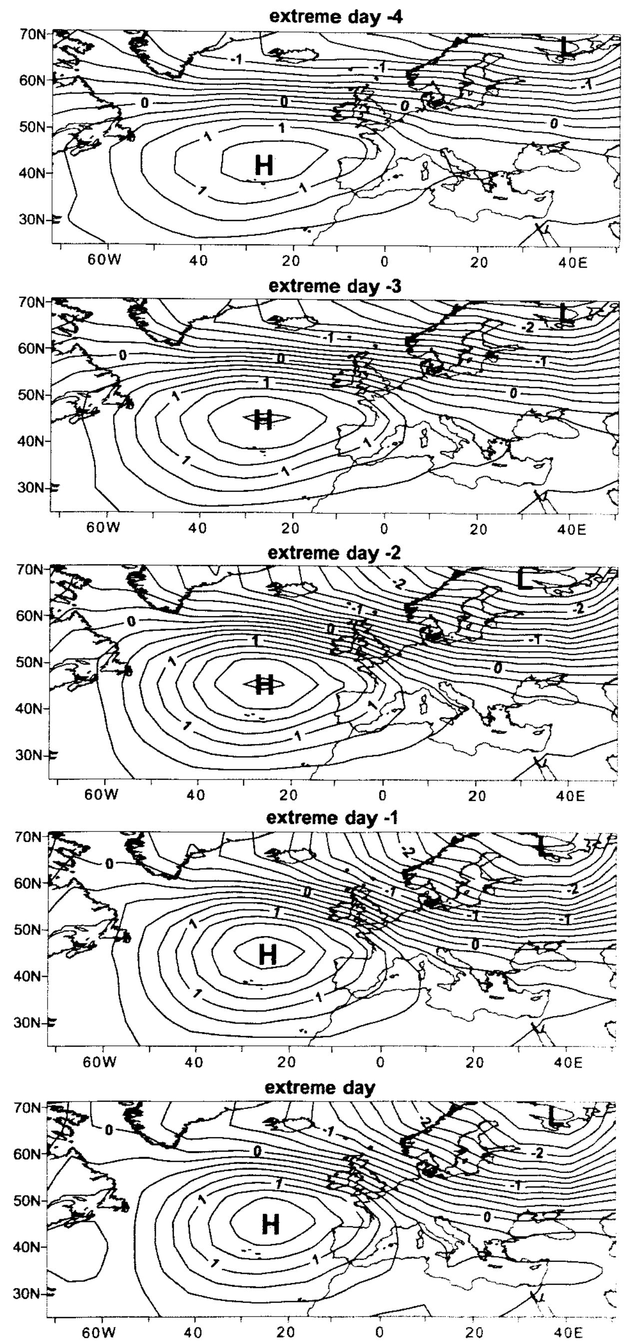

Figure 6: Normalized SLP pattern sequence from 4 days before an extreme Central European precipitation event (beyond the 98th percentile) resulting as first mode from an extended T-mode PCA of all corresponding sequences during winter (DJF) 1850–2003.

of this circulation type (again for moving time-windows) thus indicating the varying extremes-association of this type (higher or lower percentages of its total occurrence being linked with extreme events). Similar indices have also been used in the context of circulation-flood investigations (JACOBEIT et al., 2003b). The window size of three decades has proved to be favorable among variants between 20 and 50 years in terms of an appropriate smoothing for multi-decadal analyses.

The results section will focus on the winter (DJF) and summer (JJA) seasons giving selected examples.

3 Results

3.1 Winter (DJF) 1850–2003

Fig. 3 reproduces the SLP cluster centroid patterns from PHILIPP et al. (2007) derived by the SANDRA technique explained in the previous section. Circulation patterns are described in detail in the same paper and will only be discussed in the present context as far as they prove to be important for climate extremes (see below). Overall seasonal frequencies of these cluster circulation patterns vary in a rather narrow range between 14 and 8 % (compared, for example, to much greater differences in variances explained by PCA-derived circulation patterns).

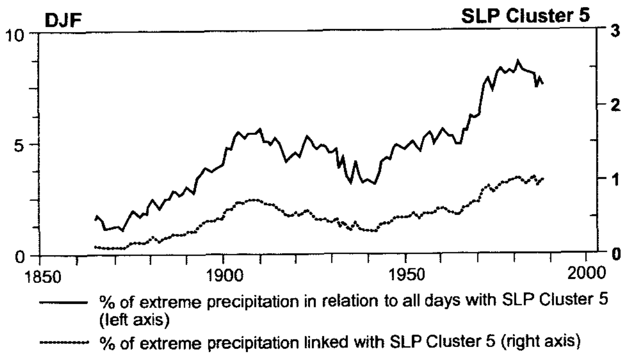

Figure 7: 31-year moving frequencies (%) of days with extreme Central European precipitation (beyond the 98th percentile) in connection with SLP cluster 5 (see Fig. 3) and in relation to all days with SLP cluster 5 during winter (DJF) 1850–2003.

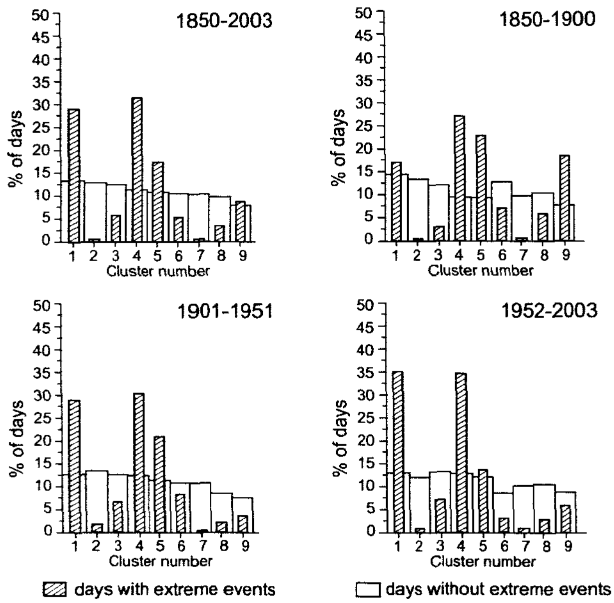

Figure 8: Percentages of days with extreme Central European temperature (beyond the 98th percentile) and without such extremes for each of the wintertime SLP clusters of Fig. 3, related to the overall occurrences within the indicated time periods. Clusters with ratios between these percentages significantly greater than 1 (0.01 level according to Monte-Carlo resampling of 1000 circulation type time series) are discussed in the text.

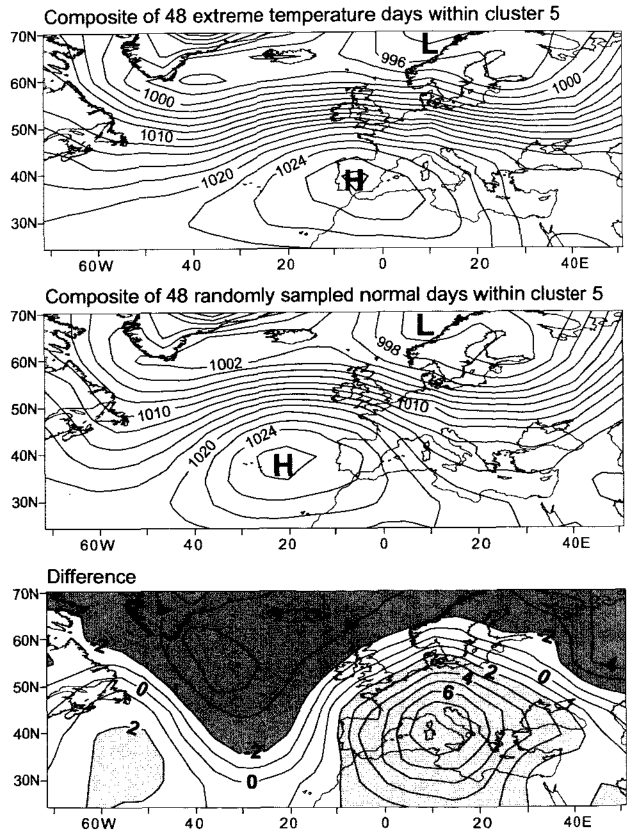

Figure 9: SLP composites (hPa) of days with extreme Central European temperature (beyond the 98th percentile) and without such extremes (randomly sampled with the same sample size) for SLP cluster 5 (see Fig. 3) during winter (DJF) 1850–2003. Light and dark grey shading in the difference map is for positive and negative significant values (0.05 level according to Mann-Whitney test), respectively.

3.1.1 Precipitation results

Fig. 4 clearly points out that just two out of the nine circulation patterns reproduced in Fig. 3 are conducive to heavy winter precipitation in Central Europe (significantly (0.01 level) higher percentages of extreme days than of non-extreme days). Only during the subperiod 1850–1900 a third pattern (Cluster 1) exceeds this threshold in addition, but at this time larger interpolation errors for the reconstructed SLP fields (ANSELL et al., 2006) also imply a lower degree of reliability in pattern classification than for more recent times. The two circulation patterns being primarily conducive to heavy precipitation (Clusters 4 and 5, see Fig. 3) include essentially zonal patterns, but with eastward or southeastward shifted domains of the cyclonic centre of action in subpolar latitudes compared to Cluster 1 which represents the pattern with highest similarity to common NAO patterns. This difference is also reflected by different correlation coefficients between the NAO index time series and seasonal cluster frequencies of these circulation patterns (0.76 for Cluster 1 in contrast to 0.31 and 0.38 for Clusters 4 and 5). This indicates that it is not the pronounced positive phase of the NAO which favours heavy winter precipitation in Central Europe, but particular modifications of zonal circulation as represented by Cluster centroid patterns 4 and 5 which only have much less variance in common with NAO indices.

The characteristics of these patterns especially when linked directly to heavy precipitation events, are underlined by comparing SLP composites of days with and without such extremes (see Fig. 5 as an example

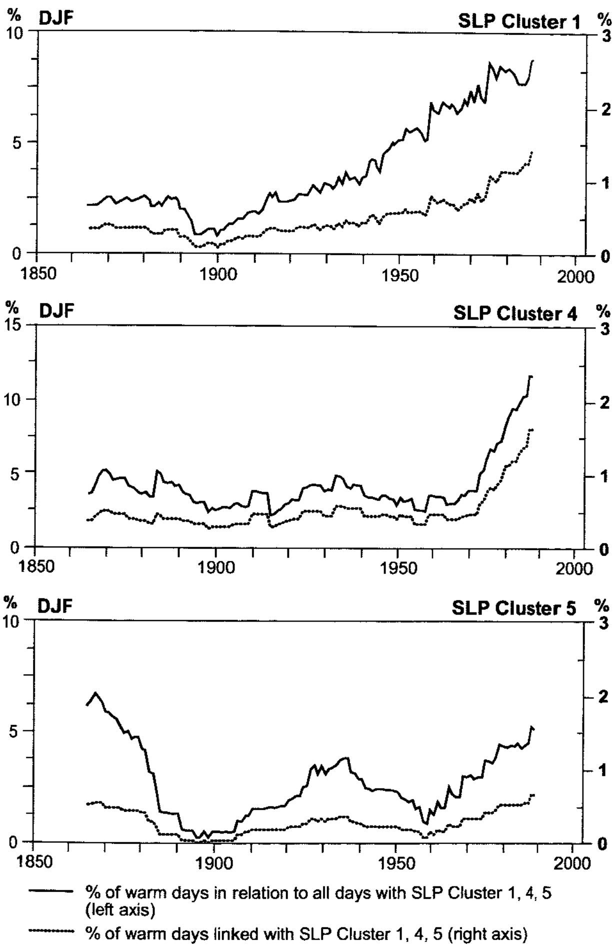

Figure 10: : 31-year moving frequencies (%) of days with extreme Central European temperature (beyond the 98th percentile) in connection with SLP clusters 1, 4 and 5 (see Fig. 3), respectively, and in relation to all days of SLP clusters 1, 4 and 5, respectively, during winter (DJF) 1850–2003.

for SLP Cluster pattern 5, the most important one for extreme precipitation). In contrast to the more zonal configuration for non-extreme days, this pattern reveals some wave amplification with increasing and southward advancing cyclonicity for the extremes-composite (see also the difference map in Fig. 5). Such a change from a zonal configuration to an intensifying and southward advancing cyclonic wave can also be seen from the daily pattern sequence in Fig. 6 which represents the leading mode (27 % of explained variance) of an extended T-mode PCA of all daily SLP sequences starting 4 days before an extreme precipitation event during winter. Obviously this most important pattern sequence develops towards a circulation pattern as reflected by the extremes-composite of Cluster 5 (Fig. 5).

Looking at temporal changes in the context of circulation dynamics of extremes, Fig. 7 depicts the moving frequencies of particular indices explained in the methods' section, shown for the example by SLP Cluster 5 (Cluster 4 gives similar but less pronounced results). At first an increase – interrupted between 1910 and 1940 – can be seen for heavy precipitation events in connection with Cluster 5 (stippled curve). In general this might be linked to corresponding changes in the frequency of Cluster 5, however, neither the insignificant long-term trend in seasonal cluster frequency nor the phasing in multi-decadal variations (see PHILIPP et al., 2007) do support this suggestion. On the other hand, the continuous line in Fig. 7 indicates that a growing percentage of days when Cluster 5 occurs, are connected with heavy precipitation. This means a within-type increase in association to such extremes: Cluster 5 occurrence is more often linked with heavy precipitation. Within-type changes of circulation types are a major factor in low-frequency climate variability (JACOBEIT et al., 2003a; BECK et al., 2007), including dynamical as well as climatic properties of circulation types. Also with respect to extreme events, changes for example in relative vorticity, pressure gradients, type-specific temperature and precipitable water may well affect climatic impacts of circulation types and in particular their relative association to extreme events. Such investigations are still in progress concerning the EMULATE data bases, but even the simple indices in Fig. 7 already point to such internal changes of circulation types. Furthermore, the phasing of both indices not only corresponds with each other, but also with that of the overall moving frequencies of heavy winter precipitation (Fig. 2) thus indicating that changing characteristics of SLP Cluster 5 (and to a lesser degree also of Cluster 4) are decisive for frequency (and probably also intensity) changes of extreme winter precipitation in general.

3.1.2 Temperature results

Similar investigations for positive temperature extremes during winter confirm the significance (0.01 level) of only a few of the circulation types reproduced in Fig. 3, in this case mainly all of the more or less zonal patterns already discussed (Clusters 1, 4, and 5, see Fig. 8), but with some pecularities: during the first 50-year period (1850–1900) Cluster 9, a monopole pattern with southwesterly flow towards Central Europe, becomes conducive to positive temperature extremes instead of the NAO-like Cluster 1, but again constraints in reliability have to be considered for this earliest period of the MSLP reconstruction. During the most recent subperiod (1952–2003) Cluster 5 – the most important one for heavy winter precipitation – looses its significance for extremely warm days, probably due to its sharp increase in association to extreme precipitation (Fig. 7, continuous line) which is realised in terms of more wave-like than zonal patterns (see extremes-composite in Fig. 5). The opposite is true for positive temperature extremes (Fig. 9): now the flow configuration of Cluster 5 becomes more zonalised in contrast to normal conditions (see also the maxima in the composite-difference

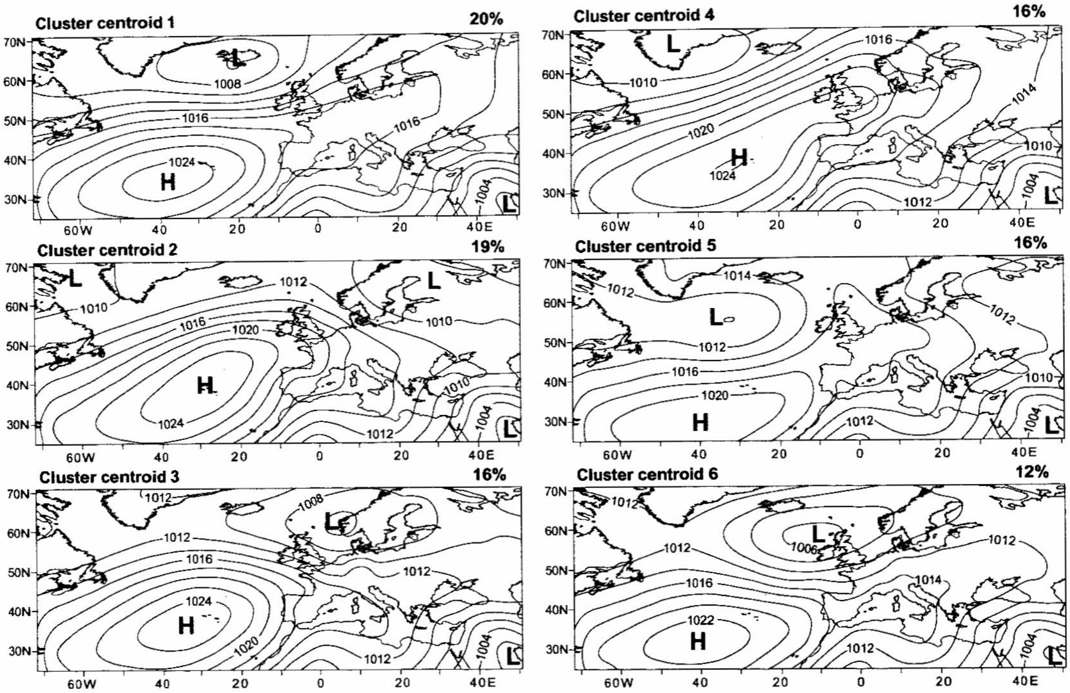

Figure 11: Centroid patterns (hPa) resulting from a SANDRA cluster analysis (see text) of daily SLP fields for summer (JJA) 1850–2003 (from PHILIPP et al., 2007).

map being shifted to the west (east) in comparison with the cyclonic (anticyclonic) centre of the centroid pattern in Fig. 3). Thus, circulation patterns being conducive to positive temperature or precipitation extremes are different in terms of flow characteristics: temperature extremes are linked preferably to zonal patterns in relation with the positive mode of the NAO (including in particular the NAO-like Cluster pattern 1), whereas heavy winter precipitation is distinctly associated with less zonal, more wave-like patterns implying only weak correlations with the NAO (see previous sub-section).

Looking at circulation impacts on the temporal development of positive temperature extremes, all relevant SLP Clusters depict increases in association to such extremes (continuous lines in Fig. 10), but on different time scales: Cluster 1 – the NAO-like pattern – starts already at the beginning of the 20th century (Fig. 10) leading to a moderate tendency for increasing frequencies of such extremes in general (Fig. 2). But only after the 1960s when the association of Clusters 4 and 5 to extremes begins to rise distinctly (Fig. 10), the overall frequencies in Fig. 2 change to an accelerated increase. Even Cluster 5 – the most important one for heavy winter precipitation – is involved in this change, but with its zonalized subtype (see extremes-composite in Fig. 9) and at a considerably lower level compared not only with Clusters 1 and 4 (Fig. 10) but also with its own increase in association to precipitation extremes (Fig. 7). Thus, in terms of preferred linkages to extremes, Cluster 5 has to be considered primarily with respect to heavy precipitation, Cluster 1 with respect to positive temperature extremes, and Cluster 4 as an intermediate actor in accordance with the corresponding circulation patterns reproduced in Fig. 3.

3.2 Summer (JJA) 1850–2003

Fig. 11 reproduces the six SLP cluster centroid patterns from PHILIPP et al. (2007) for the summer season. They are mainly characterized by different extensions of the Azores' high pressure centre and some of them by cyclonic influence in different regions of the higher latitudes.

3.2.1 Precipitation results

Once again, only a few of these patterns prove to be conducive to extreme events. According to Fig. 12 addressing heavy summer precipitation, SLP Clusters 2 and 3 become evident as conducive patterns, both, however, showing different properties: Cluster 3 is represented by a reduced high pressure extension and a cyclonic centre over southern Scandinavia; this pattern is also included in the leading mode of an extended T-mode PCA of all daily SLP sequences starting 4 days before extreme summer precipitation (not shown). Cluster 2, on the other hand, is at the same time the only pattern conducive to negative summer temperature extremes (not shown) so that its cold front steering might also be responsible for its importance in favouring heavy precipitation.

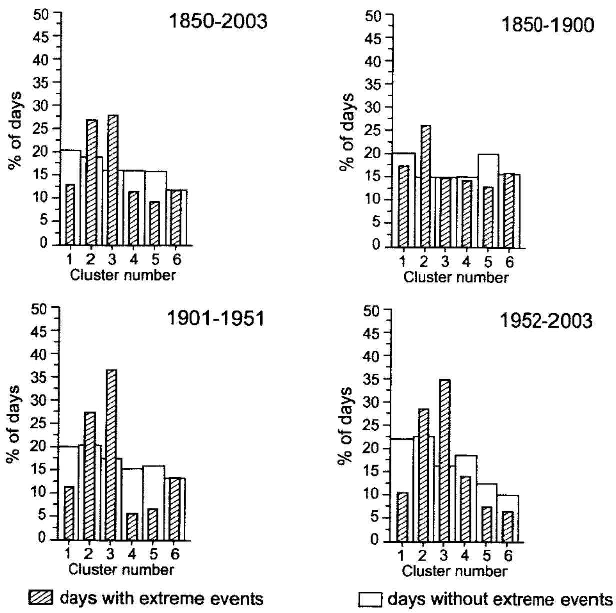

Figure 12: Percentages of days with extreme Central European precipitation (beyond the 98th percentile) and without such extremes for each of the summertime SLP clusters of Fig. 11, related to the overall occurrences within the indicated time periods. Clusters with ratios between these percentages significantly greater than 1 (0.01 level according to Monte-Carlo resampling of 1000 circulation type time series) are discussed in the text.

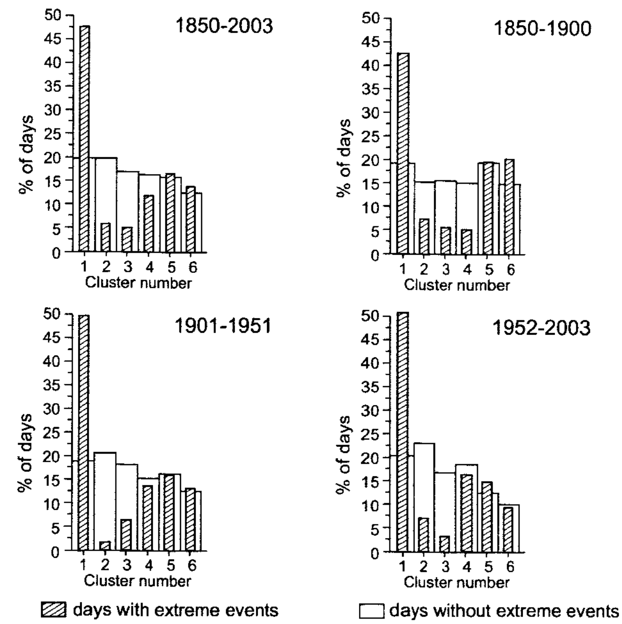

Figure 13: As Fig. 12 but for extreme temperature (beyond the 98th percentile).

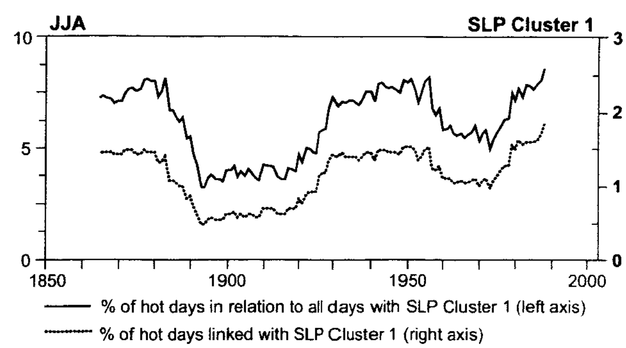

Figure 14: 31-year moving frequencies (%) of days with extreme Central European temperature (beyond the 98th percentile) in connection with SLP cluster 1 (see Fig. 11) and in relation to all days of SLP cluster 1 during summer (JJA) 1850–2003.

3.2.2 Temperature results

According to Fig. 13 the only significant (0.01 level) circulation pattern for positive temperature extremes is SLP Cluster centroid 1 being characterized by an extended high pressure ridge towards Central Europe and southern Scandinavia (Fig. 11). Further Cluster centroids with modified ridges (Clusters 4 and 5) imply that Central Europe is in front of these ridges thus not being conducive to hot extremes. In contrast to this, composite patterns for Cluster 1, calculated from extremely hot and from normal days (not shown), reveal that hot extremes related to this circulation pattern mainly result from positive pressure anomalies still further to the east (roughly between 20 and 30° E). Finally, the time series showing changes in the association of Cluster 1 to hot extremes (Fig. 14) again depict a similar phasing as known from the overall frequencies of extremely high temperatures (Fig. 2) thus pointing to the major importance of changes within particular circulation types (e.g. as indicated by the above-mentioned extremes-composite) for the general dynamics of extremes.

4 Conclusions

Extracting the most important indications from the selected results of section 3 leads to five major conclusions:

– Extreme events in precipitation and temperature on a daily time-scale are not randomly distributed with respect to large-scale atmospheric circulation types. In most cases there are only a few types which are conducive to a particular type of extremes (indicated by the ratio of percentages for each circulation type among the days with and without such extremes).

– Despite this low number of conducive circulation patterns, positive precipitation and temperature extremes during winter are not confined to the positive phase of the NAO. The latter is important for positive temperature extremes which also take place, however, in connection with zonal circulation patterns characterized by eastward shifted centres of action and reduced correlations with the NAO. In contrast to that, heavy winter precipitation in Central Europe is distinctly associated with less zonal circulation patterns revealing an eastward or southeastward shift of the subpolar centre of low pressure and implying only weak correlations with the NAO.

– During summer only one circulation pattern is conducive to hot extremes: that with the most extended high pressure ridge towards the northeast, implying some resemblence to the positive phase of the summer NAO (time series correlations, however, do not exceed 0.5). Heavy summer precipitation is mainly linked to patterns with a strong cyclonic centre to the north or to that SLP cluster which is the only one being conducive to negative summer temperature extremes (cold fronts mainly from the northwest).

– Circulation types are also changing with time their association to precipitation or temperature extremes (reflected by changes in the percentage of extremes related to the overall occurrence of the corresponding circulation type). Such within-type changes – due to internal variations of dynamic or climatic parameters – are especially important with respect to those circulation types conducive to extreme events: their varying association to a particular kind of extremes often governs the low-frequency variations in the overall incidence of these kinds of extremes.

– The distinct relationship between circulation types and precipitation or temperature extremes will allow for conditional assessments of future changes in extremes. Large-scale circulation types are better represented by numerical models of the climate system and can be estimated with respect to frequency and within-type changes taking place in various scenario model simulations. These empirically established relationships between conducive circulation types and corresponding extremes may then be transferred to possible future conditions thus giving indications about changing dynamics of extremes. The present study is just an initial step towards this sequence of investigations.

Acknowledgments

This work was part of the EU-funded project EMULATE under contract EVK2-CT-2002-00161.

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