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Interdecadal changes in the links between European precipitation and atmospheric circulation during boreal spring and fall

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ABSTRACT

A gridded monthly terrestrial precipitation from the Climatic Research Unit (CRU), University of East Anglia data set and the UK Met Office Northern Hemisphere mean sea level pressure data are used to investigate interdecadal changes in the relationships between precipitation variability over Europe and atmospheric circulation in the Atlantic–European sector during boreal spring and fall.

Singular value decomposition (SVD) analysis, performed for the climatic periods of strong/weak links to the North Atlantic Oscillation (NAO) during spring and fall, revealed considerable interdecadal changes both in the strength and the structure of the links between European precipitation and regional atmospheric circulation. During periods of strong links to the NAO, the leading SVD mode is characterized by the NAO-like meridional dipole in sea level pressure (SLP) fields and associated opposite precipitation variations over northern/southern Europe. When the links to the NAO are weak, the leading SVD mode is represented by the tripole pattern in SLP fields over the North Atlantic–European region, driving regional precipitation variability both in spring and fall. Further correlation analysis has shown that this mode is associated with the Scandinavian teleconnection pattern (SCA). Thus, for the considered seasons during periods of weak NAO influence, the SCA plays a role of major driver of the regional precipitation variability.

1. Introduction

During boreal winter, the European climate variability is mainly driven by the North Atlantic Oscillation (hereafter NAO, e.g. Jones et al., 1997; Wunsch, 1999; Seager et al., 2000; Mills, 2004). The NAO determines the position and strength of the mid-latitudinal jet stream, providing the heat and moisture transport from the Atlantic to Europe and forming European climate and its variations (e.g. Hurrell, 1995; Hurrell and van Loon, 1997). Although it is supposed that the NAO is one of the most prominent teleconnection patterns in all seasons (Barnston and Livezey, 1987), its relative role in the variability of European climate during non-winter months is not as clear as for the winter season. Several recent studies (e.g. Pauling et al., 2006; Zveryaev, 2006; Casty et al., 2007; Zolina et al., 2008) investigated and intercompared characteristics of regional climate variability during all calendar seasons and revealed their substantial seasonality. Nevertheless, we should admit that major mechanisms driving European climate variability during non-winter seasons are not well understood. Moreover, these mechanisms might vary from one climatic period to another, and also might be different for different climatic variables (e.g. air temperature, precipitation, etc.).

De Jongh et al. (2006) analysed high-quality 105-year precipitation time-series at Uccle, Belgium, and found significant interdecadal changes in the character of precipitation variability during the 20th century. Recently, using long (1901–2000) time-series of precipitation data from the Climatic Research Unit (CRU), University of East Anglia data set (New et al., 1999, 2000; Mitchell and Jones, 2005), the seasonality in interannual variability of European precipitation and its links to regional atmospheric circulation was investigated (Zveryaev, 2006). Along with evident seasonal differences, our analysis revealed essential non-stationarity in the links between regional precipitation and the NAO. In particular, prominent interdecadal changes in the strength of such links have been found for the spring and fall seasons. During winter and summer, interannual variability of the strength of links between regional precipitation and the NAO is dominated by the upward linear trends. That is why, our present analysis is focused on the spring and fall seasons. The present study expands and complements the analysis of Zveryaev (2006). On the basis of conventional singular value decomposition (SVD) analysis (e.g. Bretherton et al., 1992), we investigate the structure of the leading modes of

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covariability between regional spring and fall precipitation and sea level pressure (SLP) fields during earlier detected (Zveryaev, 2006) climatic periods of the strong/weak links to the NAO. Further, by means of correlation analysis, we examine possible links to the leading modes of regional atmospheric circulation.

The paper is organized as follows. The data used in the present study and analysis methods are described in Section 2. Section 3 examines leading modes of covariability between precipitation over Europe and atmospheric circulation in the Atlantic–European sector. Finally, concluding remarks are presented in Section 4.

2. Data and methods

In the present study, we used the CRU TS 2.0, 0.5° latitude–longitude gridded monthly precipitation data set (Mitchell and Jones, 2005) which is a revised and extended version of the earlier constructed data set (New et al., 1999, 2000). This data set has been constructed at the CRU, University of East Anglia. The data set presents terrestrial surface climate for the 1901–2000 period. It has higher spatial resolution than other data sets of similar temporal extent, and longer temporal coverage compared to other products of similar spatial resolution. The precipitation data for the European region used in this study were interpolated directly from station observations. Station records from which the data set was constructed, were obtained from seven sources (see table 1 in Mitchell and Jones, 2005). The data were checked for inhomogeneities in the station records using an automated method that improves earlier used Global Historical Climatology Network (GHCN) method of homogenization (e.g. Peterson and Easterling, 1994) by using incomplete and partially overlapping records and by detecting inhomogeneities with opposite signs in different seasons. The method includes the development of reference series using neighbouring stations. More details on data construction method can be found in Mitchell and Jones (2005). In the present study, the domain of analysis is limited to latitudes 34°N–71°N and longitudes 11°W–50°E.

Another key data set for the present study is the UK Met Office (UKMO) Northern Hemisphere mean SLP (MSLP) data (Basnett and Parker, 1997) provided by the British Atmospheric Data Centre. This data set holds gridded (5° latitude × 10° longitude grid) Northern Hemisphere (north of 15°N) monthly and daily series of MSLP fields. The monthly series data are available for the period 1873 to the present. The series has been made up from a number of different sources (for details see table 2 in Jones, 1987). Some data are missing, primarily before 1930. Another MSLP data set having similar length (starting from 1899) and spatial resolution is the National Center for Atmospheric Research (NCAR) data set described by Trenberth and Paolino (1980). The UKMO and NCAR data sets are essentially the same between 1899 and 1939 as they are both based on the U.S. Historical Weather Map Series. During later period (i.e. after 1939), different data sources were used to construct the UKMO and NCAR data sets. However, major differences between these data sets for that period have been found over the Himalayan and Rocky mountain ranges (Williams and van Loon, 1976), whereas reasonably good agreement has been revealed over North Atlantic–European sector.

We also used indices of the major teleconnection patterns that have been documented and described by Barnston and Livezey (1987). The patterns and indices were obtained by applying rotated principal component analysis to standardized 500 hPa height anomalies over the Northern Hemisphere. These indices are regularly updated and available from the Climate Prediction Center (CPC) website (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html). The data cover the period 1950 to the present. Details on the teleconnection pattern calculation procedures can be found in Barnston and Livezey (1987).

To examine relationship of the leading modes of seasonal mean precipitation to variations of the regional atmospheric circulation, we performed the SVD of the covariance matrix between precipitation fields over Europe and the SLP fields in the North Atlantic–European sector. SVD is a fundamental matrix operation, a generalization of the diagonalization method that is performed in principal component analysis to matrices that are not square or symmetric. The SVD of a cross-covariance matrix identifies, for instance, from two data fields, pairs of spatial patterns that explain as much as possible of the mean-squared temporal covariance between the two fields. Detailed descriptions of SVD analysis can be found in Bretherton et al. (1992) and von Storch and Navarra (1995). Before the SVD analysis, the annual cycle was removed from all gridpoint time-series by subtracting each season's long-term mean from the respective seasonal value. After that the time-series has been linearly detrended. To account for the latitudinal distortions, each gridpoint of the large-scale field anomalies was weighted by the square root of cosine of latitude to ensure that equal areas are afforded equal weight in the analysis (North et al., 1982). It is known that SVD analysis has some drawbacks (e.g. Newman and Sardeshmukh, 1995; Cherry, 1996). SVD has a potential to produce spurious spatial patterns. In particular, when the time-series analysed are relatively short, interpretation of the results of SVD analysis needs to be treated with caution. Newman and Sardeshmukh (1995) show that SVD analysis is useful when time-series of the expansion coefficients are highly correlated and there is strong similarity between SVD patterns and respective empirical orthogonal functions (EOF) patterns. Therefore, we verified results of the present analysis in two ways. We performed SVD analysis on the monthly spring and fall time-series (seasonal cycle removed), thus getting essentially longer time-series. Results of this additional analysis were very close (both in terms of spatial patterns and squared covariance fractions, SCFs) to those obtained from analysis of seasonal means. To discern geophysical relevancy of the SVD coupled patterns, Cherry (1997) suggested a comparison of the SVD results with those from the EOF analysis. Therefore, we performed EOF analysis of regional precipitation for selected climatic periods, and subsequently estimated correlations between principal components of the leading EOF modes of precipitation and SLP fields in the North Atlantic–European sector. Obtained EOF patterns of precipitation and correlation patterns (not shown) appeared very similar to the respective patterns from the SVD analysis. Thus, results of our SVD analysis depict the real relationship between regional precipitation and SLP fields during considered climatic periods. To assess links to teleconnection patterns, we used conventional correlation analysis. Statistical significance of the correlations was estimated according to Student *t*-test (Bendat and Piersol, 1966).

3. Leading SVD modes between precipitation and SLP

3.1. Spring

To explore links between spring and fall precipitation variability over Europe and regional atmospheric circulation during different climatic periods, we performed conventional SVD analysis (e.g. Bretherton et al., 1992) on the detrended seasonal mean precipitation and SLP data. Linear coupled dominant modes between fields of yearly sampled seasonally averaged (spring or fall) precipitation over Europe and SLP in the North Atlantic–European sector were defined for spring and fall periods of strong/weak links between regional precipitation and the NAO. These climatic periods have been selected based on the running correlations between the principal components of the leading EOF modes of regional precipitation and the NAO index for the respective season (see fig. 5 in Zveryaev, 2006). We limit our analysis to consideration of the first SVD mode only since each of the subsequent modes explains very small fractions of the total covariance of precipitation and SLP. Spatial patterns of the first SVD mode and their expansion coefficients for spring and fall are shown, respectively in Figs. 1 and 2. Estimated SCFs and correlations between expansion coefficients are present in Table 1.

The first SVD mode (SVD-1) between spring precipitation and SLP fields, estimated for the period of weak links to the NAO (1950–1969) explains 45% of the total covariance. The SVD-1 spatial pattern for the SLP (Fig. 1a) is characterized by the three action centres. The strongest action centre with the largest loadings is located over Scandinavia and northern European Russia, the second centre with opposite SLP variations is revealed over the northern North Atlantic and the third centre, showing relatively weak SLP variations of the same sign as over Scandinavia, is detected over the subtropical North Atlantic. Evidently, the obtained pattern is not the NAO pattern which is characterized by the meridional dipole of SLP over the North Atlantic. The associated SVD-1 spatial pattern for precipitation (Fig. 1c) is mostly affected by the first two action centres in Fig. 1a, and shows opposite precipitation variations over Mediterranean region and over the rest of Europe. Time-series of expansion coefficients of SLP and precipitation patterns (Fig. 1e) are strongly linked (correlation is 0.91) to each other and to the spring index of the Scandinavian (hereafter SCA) teleconnection pattern (Barnston and Livezey, 1987). In particular, correlation between expansion coefficients for SVD-1 precipitation pattern and spring SCA index is 0.75, implying that during this climatic period (1950–1969) characterized by the weak links between regional precipitation and the NAO, the SCA was the major driver for the spring precipitation variability over Europe. This teleconnection pattern has been earlier referred to as the Eurasia-1 pattern by Barnston and Livezey (1987). The positive phase of this pattern is characterized by the positive height anomalies, reflecting major blocking anticyclones, over Scandinavia and western Russia.

During period of strong links to the NAO (1971–1990), the SVD-1 explains 49% of the total covariance between seasonal mean precipitation and SLP fields. As expected, its spatial pattern for the SLP (Fig. 1b) shows a meridional dipole with opposite SLP variations over region extending from Greenland to Scandinavia (first action centre), and over subtropical North Atlantic–Mediterranean region (second action centre). The pattern reflects positive phase of the NAO which is characterized by below normal SLP in the wide region around Iceland, and above normal SLP in the extensive region around the Azores. This SLP pattern results in enhanced atmospheric moisture advection into the region and excessive (deficient) precipitation over northern (southern) Europe (e.g. Hurrell, 1995; Zveryaev, 2004). The SVD-1 pattern for precipitation (Fig. 1d) shows its opposite variations over northern and southern Europe, thus, being consistent with the 'classic' NAO-associated precipitation pattern over Europe. As expected, expansion coefficients of this pattern are strongly ($R = 0.82$) correlated to the spring NAO index.

3.2. Fall

Fall precipitation over Europe was strongly linked to the NAO for the period 1925–1944 (Zveryaev, 2006). The SVD-1 estimated for that period explains 57% of the total covariance between European precipitation and SLP fields over North Atlantic–European sector. The SVD-1 spatial pattern for the fall SLP (Fig. 2a) is characterized by the meridional dipole with the strong SLP variations over Iceland and Scandinavia (first action centre) and opposite (relatively weak) SLP variability over region around the Azores (second action centre). Though the pattern is basically the NAO pattern (negative phase), it is evident that the northern (first) action centre played the dominant role in the regional atmospheric circulation during considered period. The associated SVD-1 spatial pattern for fall precipitation (Fig. 2c) shows opposite precipitation variations over northern and southern Europe, thus being consistent with the earlier described (e.g. Hurrell, 1995) NAO-associated variability of

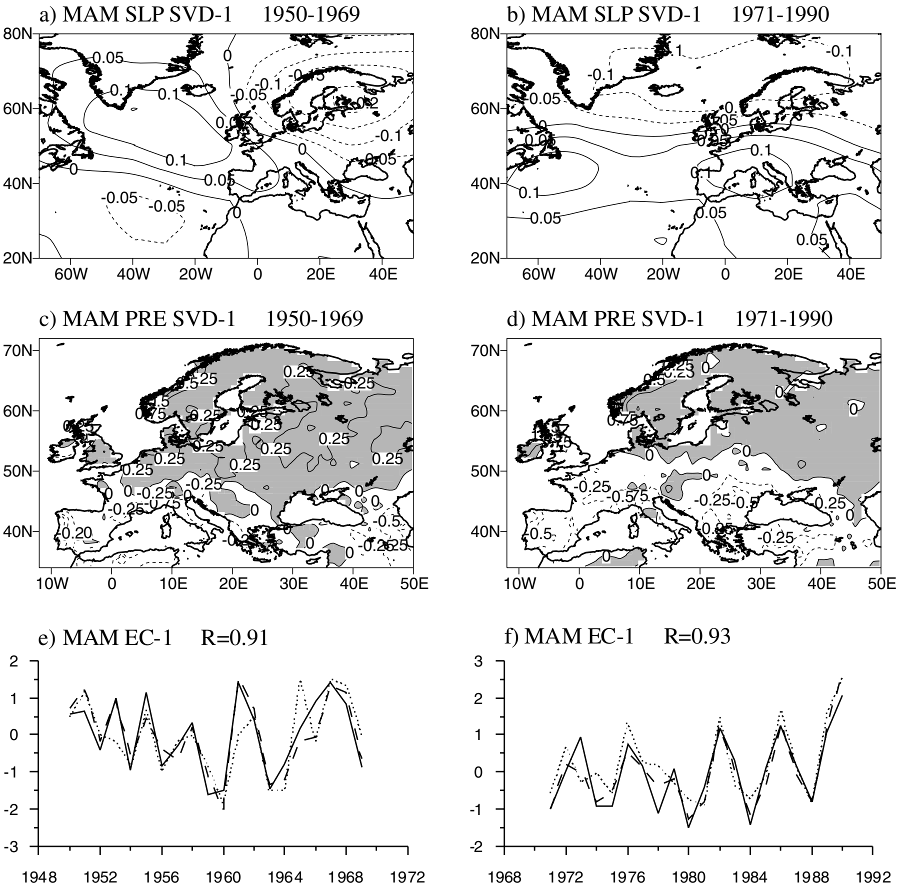

Fig. 1. The SVD-1 spatial patterns (a–d) and the expansion coefficients (e and f) obtained for pairs of the spring precipitation and sea level pressure (SLP) fields for 1950–1969 (a, c and e) and 1971–1990 (b, d and f). The expansion coefficients were normalized by their standard deviations. The dashed curves in (a–d) indicate negative values. The solid curves in (e and f) denote variation of precipitation, and the dashed curves, variation of SLP. The dotted curve in (e) denotes the SCA index, whereas the dotted curve in (f) shows the NAO index.

regional precipitation. Correlation between expansion coefficients of this pattern and the fall NAO index is high ($R = 0.83$) and statistically significant at the 99% level according to Student *t*-test (Bendat and Piersol, 1966).

During period of weak links to the NAO (1971–1990), the SVD-1 between fall precipitation and SLP fields accounts for 69% of the total covariance. Note this explained covariance is substantially larger than that obtained for the SVD-1 in 1925–1944. The SVD-1 spatial pattern for the SLP (Fig. 2b) depicts three action centres. Two strong action centres with opposite SLP variations are located over the British Isles and eastern Scandinavia. The third (substantially weaker) centre is revealed over subtropical North Atlantic. The obtained pattern is structurally similar to that for the spring SLP in 1950–1969 (Fig. 1a). The associated SVD-1 pattern for precipitation (Fig. 2d) is mostly affected by the first two action centres in Fig. 2b, and shows opposite precipitation variations over the western Europe–Mediterranean region and over the rest of Europe. These precipitation variations are associated with anticyclonic (cyclonic) anomalies of SLP over the British Isles (eastern Scandinavia). Time-series of expansion coefficients of SLP and precipitation patterns (Fig. 2f) are strongly linked (correlation is 0.91) to each other and to the fall SCA index. Particularly, correlation between expansion coefficients of precipitation pattern and fall SCA index is 0.79. Thus, similar to the spring season, during period of the weak links between regional precipitation and the NAO, the SCA was the major driver for the fall precipitation variability over Europe.

The robustness of the considered SVD modes was accessed by the Monte Carlo technique, as suggested by Barnett and Preisendorfer (1987). We conducted 500 sets of SVD analyses between the seasonal precipitation and temporally shuffled seasonal SLP fields. When the observed squared covariance is larger than the top 5% of the surrogate squared covariances, the SVD mode is regarded to be significant at the 95% confidence level. Both in spring and fall, the Monte Carlo test shows that the first SVD modes are significant during all considered climatic periods. As we already mentioned, we also examined spring and fall precipitation by an EOF analysis, and found that the first EOF modes of precipitation are statistically significant and well

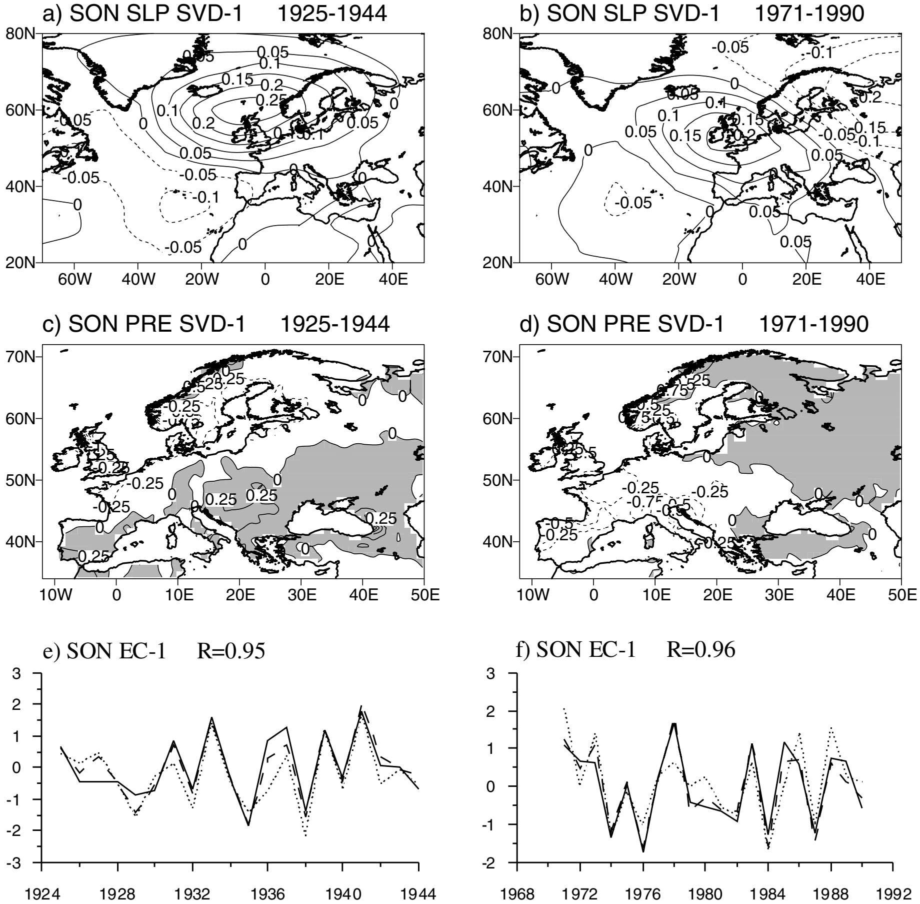

Fig. 2. The SVD-1 spatial patterns (a–d) and the expansion coefficients (e and f) obtained for pairs of the fall precipitation and sea level pressure (SLP) fields for 1925–1944 (a, c and e) and 1971–1990 (b, d and f). The expansion coefficients were normalized by their standard deviations. The dashed curves in (a–d) indicate negative values. The solid curves in (e and f) denote variation of precipitation, and the dashed curves in (e and f) variation of SLP. The dotted curve in (e) denotes the NAO index, whereas the dotted curve in (f) shows the SCA index.

Table 1. Squared covariance fractions (SCFs) and correlation coefficients (R) between expansion coefficients of the first SVD mode between precipitation over Europe and SLP fields in the North Atlantic–European sector

Spring			Fall		
Period	SCF (%)	R	Period	SCF (%)	R
1950–1969	45	0.91	1925–1944	57	0.95
1971–1990	49	0.93	1971–1990	69	0.96

separated from the other modes according to North et al. (1982) criteria. We also found that these EOF modes are essentially the same as the respective modes obtained by the SVD analysis.

4. Concluding remarks

In the present study based on observational data, we examined interdecadal changes in the relationships between precipitation over Europe and atmospheric circulation over the North Atlantic–European region during spring and fall seasons. We performed SVD analysis on the time-series of seasonal mean precipitation and SLP for climatic periods characterized by the strong/weak links to the NAO. These periods were earlier detected in Zveryaev (2006) using running correlations between leading principal components of the regional precipitation and the NAO index.

Our analysis revealed considerable structural differences in covariability between regional precipitation and SLP fields during periods of strong and weak links to the NAO. The revealed differences are prominent both in spring and fall season. More specifically, during period of strong links to the NAO both precipitation and SLP patterns of the first SVD mode are the ‘classic’ NAO-associated patterns (e.g. Hurrell, 1995; Zveryaev, 2004). Namely, the SLP pattern depicts a north-south meridional dipole with intensive interannual variations over wide region around Iceland and opposite SLP variations over extensive region around the Azores. This pattern drives zonal atmospheric moisture transport into the European region, resulting in variability of regional precipitation. The SVD-1 pattern for precipitation reveals NAO-associated opposite precipitation variability over northern and southern Europe. It should be emphasized that the structures of the obtained SVD patterns for both SLP and precipitation are somewhat expected since they are related to the period characterized by the strong links to the NAO.

The structure of the first SVD mode obtained for the climatic periods of weak links to the NAO is principally different. The SLP pattern of this mode is characterized by the large-scale tripole over the North Atlantic–European region with most intensive variations over Scandinavia, the British Isles and northeastern North Atlantic. This SLP pattern results in opposite variability of precipitation over southwestern and northeastern Europe. The SVD-1 SLP pattern is structurally similar to the Scandinavian teleconnection pattern earlier revealed and described by Barnston and Livezey (1987). Moreover, correlations between respective expansion coefficients and the SCA index appeared very high and statistically significant. Thus, for the first time, results of our analysis clearly indicate that during climatic periods of weak links to the NAO (both in spring and fall) precipitation variability over Europe was mainly driven by the SCA teleconnection pattern, implying considerable interdecadal changes in the character of links between regional precipitation and atmospheric circulation.

It is important to emphasize that in our analysis, 1971–1990 is a period during which variability of spring precipitation over Europe was driven by the NAO, whereas variability of fall precipitation was driven by the SCA teleconnection pattern. Hence, our results do not suggest any seasonal persistence in relationships between regional precipitation and atmospheric circulation even during the same climatic period. It is well known that starting from the late 1960s, the NAO index showed a strong upward trend (Hurrell, 1995). Therefore, strong links between spring precipitation over Europe and the NAO during 1971–1990 are expected. It is not clear at this stage why the fall precipitation variability during that period was dominated by the SCA. And more widely speaking, major mechanisms that form interdecadal changes in the analysed links are not currently evident. We can speculate about possible impact of the so-called Atlantic Multidecadal Oscillation (AMO, Delworth and Mann, 2000; Kerr, 2000). For instance, Sutton and Hodson (2005) showed that the AMO had an important role in modulating European climate on multidecadal time scales. Recently, Baines and Folland (2007) provided evidence for a rapid global climate shift in the late 1960s, characterized by the prominent changes in the different climatic variables. However, results of the mentioned studies are mostly related to the summer season. Also, they usually analyse interdecadal changes in the mean characteristics but not differing interannual variability during particular climatic periods.

In summary, results of the present study highlight essential non-stationarity and seasonality in precipitation variability over Europe and its links to atmospheric circulation. Considerable interdecadal changes in the structure and character of the above links have been detected. Moreover, the present study reveals differing physical mechanisms driving interannual variability of regional precipitation during certain climatic periods. While the NAO and the SCA are the major drivers for both spring and fall precipitation, during particular climatic period driving mechanisms can be different for spring and fall seasons, indicating absence of seasonal persistence in the links between precipitation variability over Europe and regional atmospheric circulation. In general, better understanding of mechanisms driving interannual variability of regional climate could advance its seasonal forecasting and climate change modelling. Altogether present results imply that rather complex and yet not well-understood variability of regional precipitation during boreal spring and fall deserves further investigation.

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