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Seasonality in secular changes and interannual variability of European air temperature during the twentieth century

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[1] A gridded terrestrial monthly surface air temperature (AT) data set for 1901–2000 from the Climatic Research Unit (CRU), University of East Anglia, is used to investigate seasonality in the long-term AT variability over Europe. Prominent seasonal differences are detected in all considered characteristics of AT variability. Significant warming trends over western and southern Europe are found during summer and fall. In winter, the largest positive trends are observed mostly in southern Europe, whereas during spring, they are detected over Scandinavia and northeastern European Russia. The spatial-seasonal differentiation of warming trends implies that, in different parts of Europe, different seasons play the role as major contributor to the warming trend. The first empirical orthogonal functions (EOF) modes of winter, spring, and fall AT over Europe are associated with the North Atlantic Oscillation (NAO) and explain about 50% of AT variability. For the summer season, the second EOF mode (explaining only 15% of AT variance) might be associated with the summer NAO but has a very different (compared to other seasons) spatial pattern and principal components. The second EOF mode of the winter AT might be linked to the East Atlantic/West Russia (EAWR) teleconnection pattern. Analysis of running correlations between the principal components of the leading EOF modes of AT and the NAO index has revealed nonstationarity of the links between European AT and the NAO and evident seasonality in their long-term changes. Subsequent singular value decomposition analysis performed for the climatic periods of strong/weak links to the NAO revealed considerable interdecadal changes both in the strength and the structure of the links between European AT and regional atmospheric circulation.

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1. Introduction

[2] There is a strong body of evidence that European climate variability in winter is largely dominated by the Atlantic Ocean and first of all by the North Atlantic Oscillation (NAO) [e.g., *Bjerknes*, 1964; *van Loon and Rogers*, 1978; *Rogers*, 1984; *Lamb and Peppler*, 1987; *Hurrell*, 1995; *Seager et al.*, 2000; *Hurrell et al.*, 2003] that determines the intensity and the location of the midlatitude jet stream. The latter steers the Atlantic heat and moisture transport to the European continent, largely explaining European temperature and precipitation conditions. It should be noted that Europe is a region of interaction between oceanic and continental climates characterized respectively by low and high seasonal temperature contrasts. The North Atlantic Ocean influence is stronger over western Europe, whereas features of continental climate are more pronounced over eastern Europe and European Russia. Many diagnostic and modeling studies [e.g., *Hurrell*, 1995; *Wibig*, 1999; *Rodwell et al.*, 1999; *Zveryaev*, 1999; *Cassou and Terray*, 2001; *Drevillon et al.*, 2001; *Gulev et al.*, 2002; *Jung et al.*, 2003] extensively analyzed mechanisms driving regional climate variability during the cold season, whose definitions, however, varied within the period from October to March [e.g., *Osborn et al.*, 1999] and were dependent on the data, key variables and methods of diagnostics applied. Considerably less has been done so far for the analysis of European climate variability during the other seasons (spring, summer and fall). However, the nonwinter anomalies in European temperature conditions may have as serious economic and societal impacts as the winter ones. For instance, the European heat wave during the period from June to September of 2003 [e.g., *Beniston*, 2004; *Schär et al.*, 2004; *Stott et al.*, 2004] resulted in the extremely hot weather, accompanied by deficient precipitation that caused extensive wildfires and increased human mortality in many European countries (e.g., France, Spain, Portugal).

[3] In the context of global warming considerable attention has been paid during the last decade to the analysis of long-term trends in air temperature (AT) both on global and regional scales [e.g., *Jones and Moberg*, 2003; *Polyakov et*

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al., 2003; *Trenberth et al.*, 2007]. It was revealed that during the twentieth century the global air temperature gradually increased, and this increase intensified during the last several decades. At the same time, most analyses demonstrate significant regional differentiation of the air temperature trends. These specific regional features of global warming are not well studied. Moreover, the majority of relevant studies focused on the analysis of annual mean air temperature, paying a little attention to the seasonality of the secular changes in air temperature. For example, *Jones and Moberg* [2003] analyzed spatial patterns of air temperature trends estimated for each calendar season for two climatic periods (1920–1944 and 1977–2001) that were characterized by the rapid air temperature increase. They revealed both essential seasonality of the trends and their significant difference between the two periods. However, these estimates reflect interdecadal variations of air temperature rather than secular changes. In particular, along with a general tendency of warming, *Jones and Moberg* [2003] found downward trends of the winter and spring air temperature over Europe in 1920–1944. We emphasize that global and hemispheric air temperatures demonstrated rapid increase during that period [see *Jones and Moberg*, 2003, Figure 6]. Earlier seasonality and spatial differentiation of air temperature signals were analyzed in the global context (Northern and Southern hemispheres) by *Angell* [1986]. Remarkably, the recent Fourth Assessment Report (AR4) of Intergovernmental Panel on Climate Change (IPCC) [*Trenberth et al.*, 2007] presented seasonal trends only for 1979–2005 whereas for the period 1901–2005 only trends in annual means were considered. Therefore seasonality in secular trends of air temperature (particularly, in European region) is not yet well quantified and requires further detailed analysis.

[4] Studies of the seasonality of European climate [*Shabalova and Weber*, 1998; *Portis et al.*, 2001; *Zveryaev*, 2004, 2006; *Casty et al.*, 2007; *Zolina et al.*, 2005, 2008] and of the leading modes of climate variability during the warm season [*Colman and Davey*, 1999; *Hurrell and Folland*, 2002] showed that during nonwinter months European climate variability is influenced by mechanisms other than the NAO. Predictability of the midlatitudinal climate for the nonwinter period shows generally lower skills than that for the winter period [e.g., *Johansson et al.*, 1998; *Colman and Davey*, 1999; *Dirmeyer et al.*, 2003]. *Colman and Davey* [1999] found quite low skill in the statistical predictability of European climate during summer on the basis of the North Atlantic sea surface temperature anomalies. *Dirmeyer et al.* [2003] investigated dynamical prediction of boreal summer climate, and found that predictability of interannual climate variations is low outside the deep tropics, and negligible over land. Thus a comprehensive study of both NAO-associated and non-NAO modes of European climate variability is needed during all seasons in order to explain the mechanisms of long-term variability in European temperature conditions throughout the year. On one hand, this analysis should involve advective processes exerted by the atmospheric circulation, controlling the regional air temperature variability as implied by the pioneering study of *Namias* [1948] and was shown in many other works (*Trenberth* [1990, 1995], *Hurrell* [1995], *Hurrell and van Loon* [1997], *Slonosky et al.* [2001], *Jacobeit et al.* [2001], *Pozo-Vázquez et al.* [2001], and others). On the other hand, the local mechanisms, intensifying during the nonwinter months, should be also accounted for. Moreover, NAO itself even during the winter season may experience quite strong changes of the regimes, that was shown by *Hilmer and Jung* [2000], *Kodera et al.* [1999], *Gulev et al.* [2001, 2002], and *Jung et al.* [2003]. For instance, *Jung et al.* [2003] argued that compared to the earlier period, the decades of 1980s and 1990s were characterized by the eastward shift of the NAO pattern that was also found by *Ulbrich and Christoph* [1999] in simulations of the greenhouse climate change.

[5] One goal of our study is to quantitatively describe the leading modes of European air temperature (AT) anomalies at different time scales during all seasons. Another goal is to depict the leading circulation modes, governing the AT variability during different seasons, and their changes during the last century. This will allow for the quantification of the extent to which the NAO-associated and non-NAO born processes are responsible for observed climate variability throughout the whole year. We will use centennial time series of European AT [*New et al.*, 1999, 2000; *Mitchell and Jones*, 2005], sea level pressure and the indices of regional teleconnection patterns such as North Atlantic Oscillation (NAO), East Atlantic/West Russia (EAWR) and other teleconnections [*Barnston and Livezey*, 1987], describing the leading circulation patterns in the Atlantic-European sector.

[6] The paper is organized as follows. The data used and analysis methods are described in section 2. Secular changes of seasonally averaged AT during 1901–2000 and leading modes of their interannual variability are considered in section 3. Links between leading modes of AT variability and sea level pressure (hereafter SLP) fields in the North Atlantic-European sector, and major teleconnection patterns are examined in section 4. Finally, concluding remarks and discussion are presented in section 5.

2. Data and Methods

[7] In the present study we use continuous and spatially homogeneous gridded monthly AT time series from the Climatic Research Unit (CRU) TS 2.1 data set of the University of East Anglia's CRU [*New et al.*, 1999, 2000; *Mitchell and Jones*, 2005]. This outstanding climate product is exclusively based on station observations and covers the period 1901–2000 with 0.5° by 0.5° spatial resolution. In our study the analysis domain is limited to latitudes 34°N–71°N and longitudes 11°W–50°E. To characterize NAO we use the NAO index based on the principal components (PCs) of the seasonal SLP anomalies as given by the Climate Analysis Section, NCAR, Boulder, USA [*Hurrell*, 1995] (http://www.cgd.ucar.edu/~jhurrell/nao.pc.html). In order to characterize the other modes of atmospheric variability we also use the indices of the major regional teleconnection patterns [*Barnston and Livezey*, 1987] which were obtained by applying rotated principal component analysis to standardized 500hPa height anomalies over the Northern Hemisphere. These indices are regularly updated by the NOAA Climate Prediction Center (CPC) at http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html and cover the period from 1950 onwards. Earlier similar (in terms of spatial structure) teleconnection patterns for the winter season were obtained by *Wallace and Gutzler* [1981]

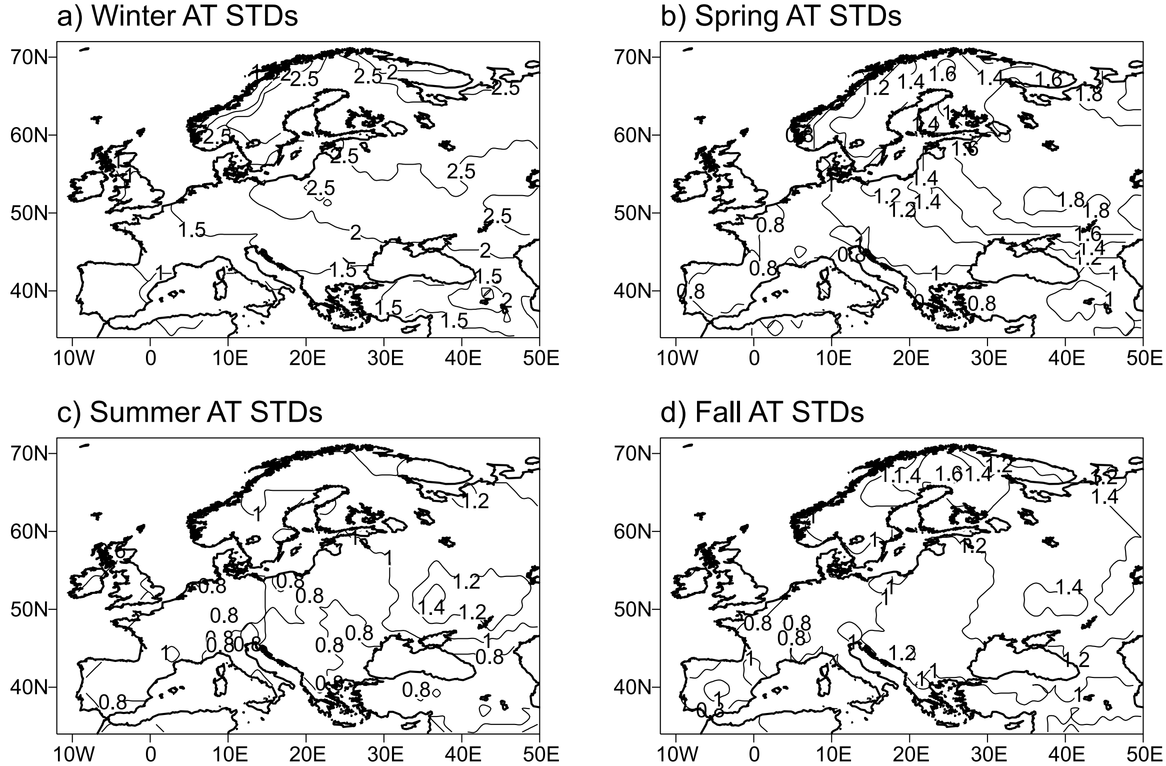

Figure 1. Standard deviations (in degrees centigrade) of the (a) winter, (b) spring, (c) summer, and (d) fall seasonal mean air temperature (1901–2000).

on the basis of correlation analysis. To examine the dynamical context of the AT variability, we used the UK Met Office Northern Hemisphere Mean Sea Level Pressure Data [*Basnett and Parker*, 1997]. This data set holds monthly and daily 5° by 10° Mean Sea Level Pressure (MSLP) fields north of 15°N and covers the period from 1873 onwards.

[8] The analysis was performed for the winter (DJF), spring (MAM), summer (JJA) and fall (SON) seasons. Long-term linear trends were estimated by least squares at each grid point. Statistical significance of trend estimates was assessed according to a Student *t* test [*Bendat and Piersol*, 1966]. Structure of the long-term nonsecular variations was quantified through the empirical orthogonal functions (EOF) analysis of the detrended seasonal anomalies [*Wilks*, 1995; *von Storch and Navarra*, 1995]. In order to account for the latitudinal distortions, each grid point value 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]. In order to associate AT variability with atmospheric circulation we use the correlation and singular value decompositions (SVD) analyses [*Bretherton et al.*, 1992; *von Storch and Navarra*, 1995].

3. Secular Changes and Interannual Variability of the Seasonal Mean Air Temperature

3.1. Standard Deviations and Linear Trends

[9] As a background information for the further analysis of the AT variability, we present in Figure 1 the interannual standard deviations (STDs) of the seasonal mean AT. The STD patterns (Figures 1a, 1b, 1c, and 1d) demonstrate the general southwest to northeast increase of the magnitudes of AT variability. The AT climatologies (not shown) reflect the opposite tendency (i.e., decrease of AT) in the same direction. The range of spatial STD changes is from 1°C over the Iberian Peninsula to 2.5°C over eastern Scandinavia and northeastern European Russia during winter and from 0.8°C over Mediterranean to 1.2°C over northern Scandinavia in summer. Thus the general decrease in the magnitudes of interannual variability of regional AT is evident from winter to summer season. Linear trends demonstrate significant upward changes in DJF AT during 1901–2000 (Figure 2a) only over southern Europe (e.g., Spain, Italy, Greece) and the southern part of European Russia (about 0.02°C per year), being insignificant over most central and northern Europe. Contribution of the trend signal to the total variance of DJF AT (not shown) amounts to 10% over southern European Russia, and up to 30% over Iberian Peninsula.

[10] During spring (MAM) the intensity of interannual AT variability (Figure 1b) is somewhat weaker than in winter (STDs are lower by 0.2°C over western Europe and by 0.9°C over northern Scandinavia). Compared to the winter season, spring AT trends (explaining 10 to 25% of the total variance) are statistically significant over essentially larger European area (Figure 2b) with the strongest trends (>0.02°C per year) detected over the southern European Russia. Interannual AT variability in summer (Figure 1c) is generally lower than that during winter and spring. Positive linear trends of JJA AT are significant over western and southern Europe (Figure 2c), being about 0.01°C per year, and contributing 20%–30% to the total variance. The STD pattern for the fall (SON) AT (Figure 1d) is structurally similar to that obtained for spring and summer seasons

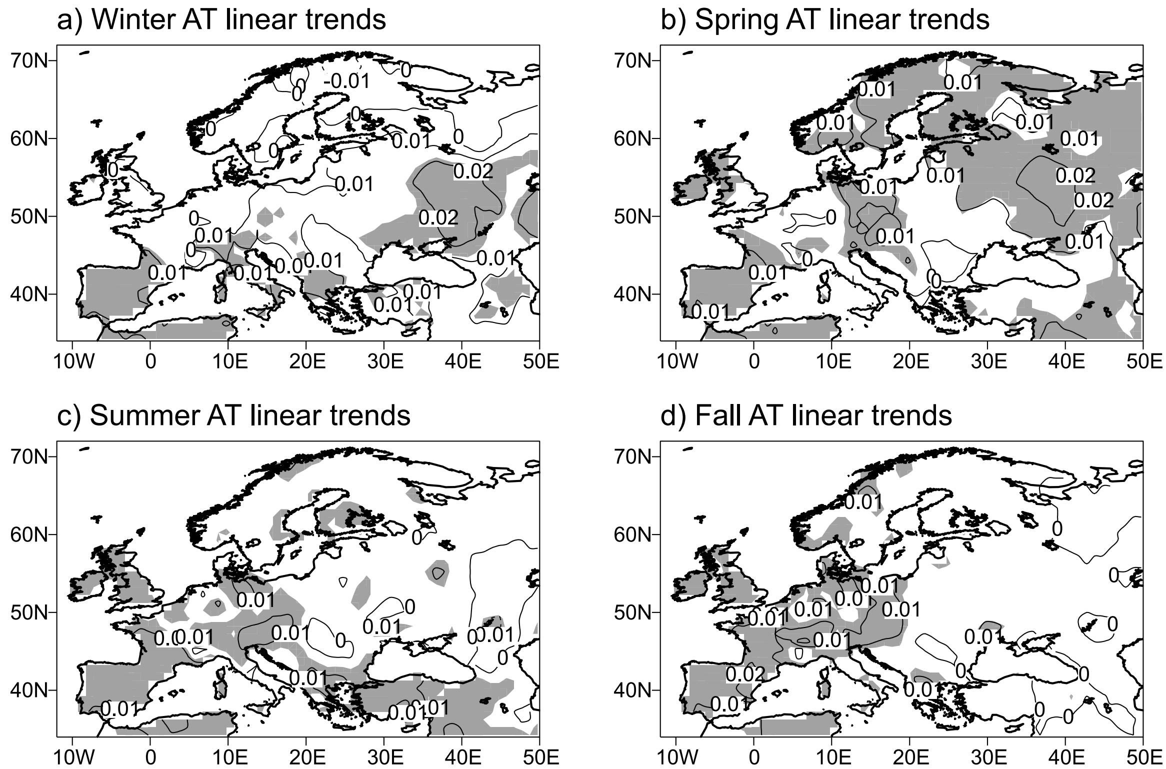

Figure 2. Linear trends of the (a) winter, (b) spring, (c) summer, and (d) fall seasonal mean air temperature (1901–2000). Linear trends are presented in degrees centigrade per year. Shaded areas indicate 95% significance level.

(Figures 1b and 1c). During fall the AT trends are statistically significant only over western Europe (Figure 2d), contributing from 10 to 35% to the total variance of AT.

[11] Linear trends in AT show evident seasonality in the magnitude and spatial structure. Significantly positive trends in summer and fall AT are detected mostly over western and southern Europe (Figures 2c and 2d) in contrast to spring (Figure 2b) when significantly positive trends are observed over Scandinavia, European Russia and some western European regions. In winter (Figure 2a) positive trends of AT are significant over the Mediterranean region and the southern part of European Russia. Linear trends estimated for each calendar month from the regionally averaged ATs for the two regions in France and in European Russia (not shown) demonstrate opposite seasonal tendencies in these regions. The seasonal march of AT linear trends over France is characterized by stronger (weaker) trends during warm (cold) season, whereas the AT trends over European Russia are stronger (weaker) during the cold (warm) season. This implies, besides seasonality of the AT trends, also essential regional differentiation of this seasonality. *Briffa and Osborn* [2002] and *Jones et al.* [2003] showed that between 1861 and 2000 the winter (DJF) season has warmed by 1.05°C, while during the summer (JJA) season the warming was only 0.31°C for the whole Northern Hemisphere. Although above mentioned features of seasonality might be true for the spatially averaged AT, our results show significant spatial/seasonal differentiation of the warming trends. In particular, it is evident that the findings of *Briffa and Osborn* [2002] do not hold for western Europe, where the warming trends are the most pronounced during summer and fall.

3.2. Leading Modes of Interannual Variability of Air Temperature

[12] To analyze the nonsecular variability we used the leading EOFs of the seasonal detrended time series of AT (Figure 3). For all four seasons the first EOF mode is represented by the monopole pattern, accounting for 48%–54% of the total variance during winter, spring and autumn, and for an essentially smaller (37.2%) fraction in summer. The largest local loadings of the first EOF are observed over central European Russia (Figures 3a, 3c, 3e, and 3g) with, however, the winter loadings over this region being twice as large as the summer ones.

[13] Time series of the corresponding principal components (hereafter PCs) (Figures 4a, 4c, 4e, and 4g), show that the winter PC1 is highly correlated with NAO index (r = 0.70) reflecting the association of the high (low) NAO index with anomalously warm (cold) conditions over Europe [*Hurrell*, 1995]. Although the correlation of the spring PC1 with NAO (r = 0.49) is significant at the 99% level, it is considerably smaller than in winter. Summer PC1 implies long-term multidecadal AT variability with the maxima during the 1930s and 1990s and minima in the 1920s and 1970s. This mode is not linked to the summer NAO. The fall PC1 reveals again the NAO-associated (r = 0.53) variability, showing strong decadal scale positive anomalies during the late 1920s and 1930s, and predominantly short-term interannual variability during the later period.

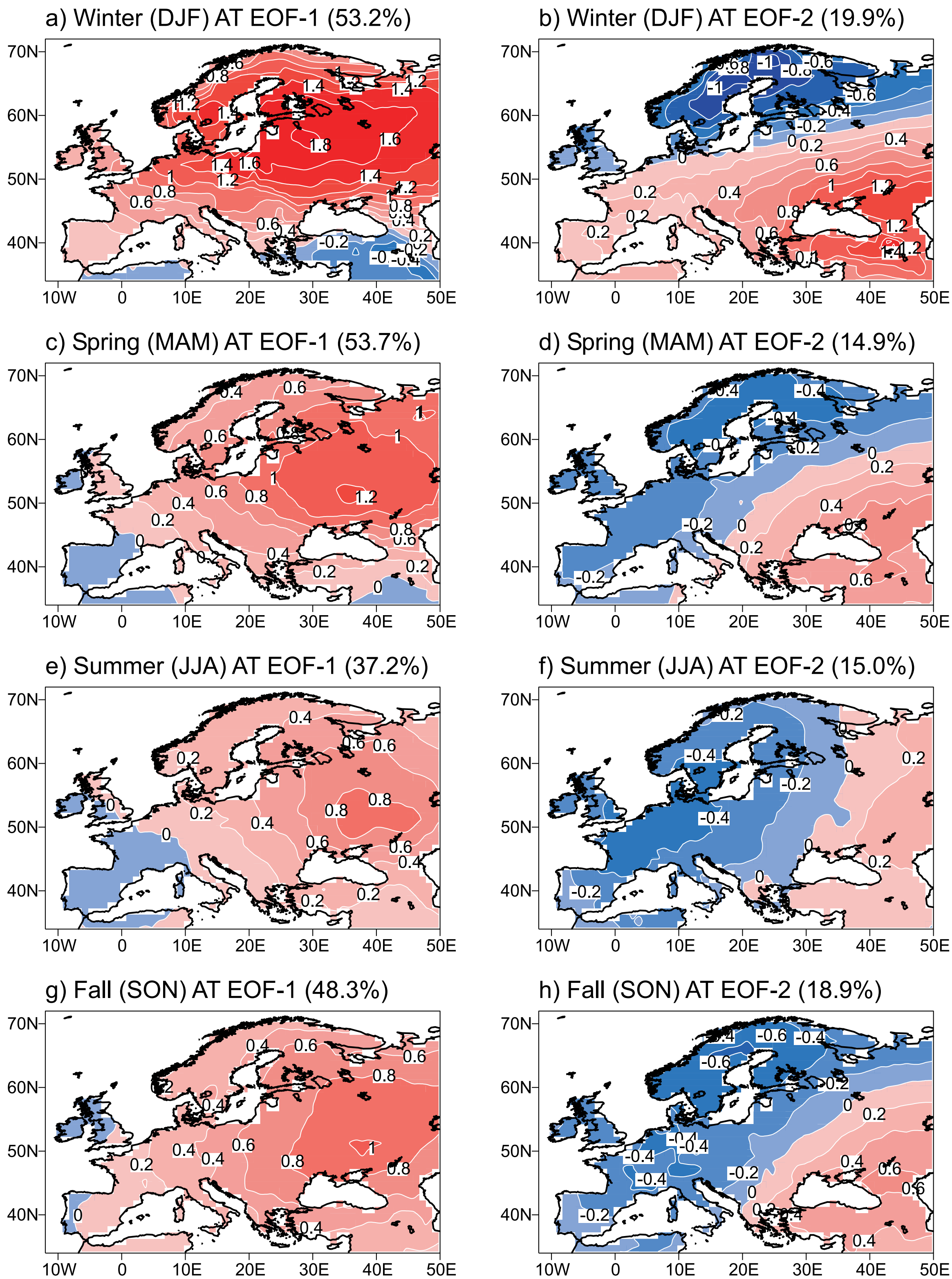

Figure 3. Spatial patterns of the first two EOF modes of the (a, b) winter, (c, d) spring, (e, f) summer, and (g, h) fall air temperature (1901–2000). Red (blue) color indicates positive (negative) values.

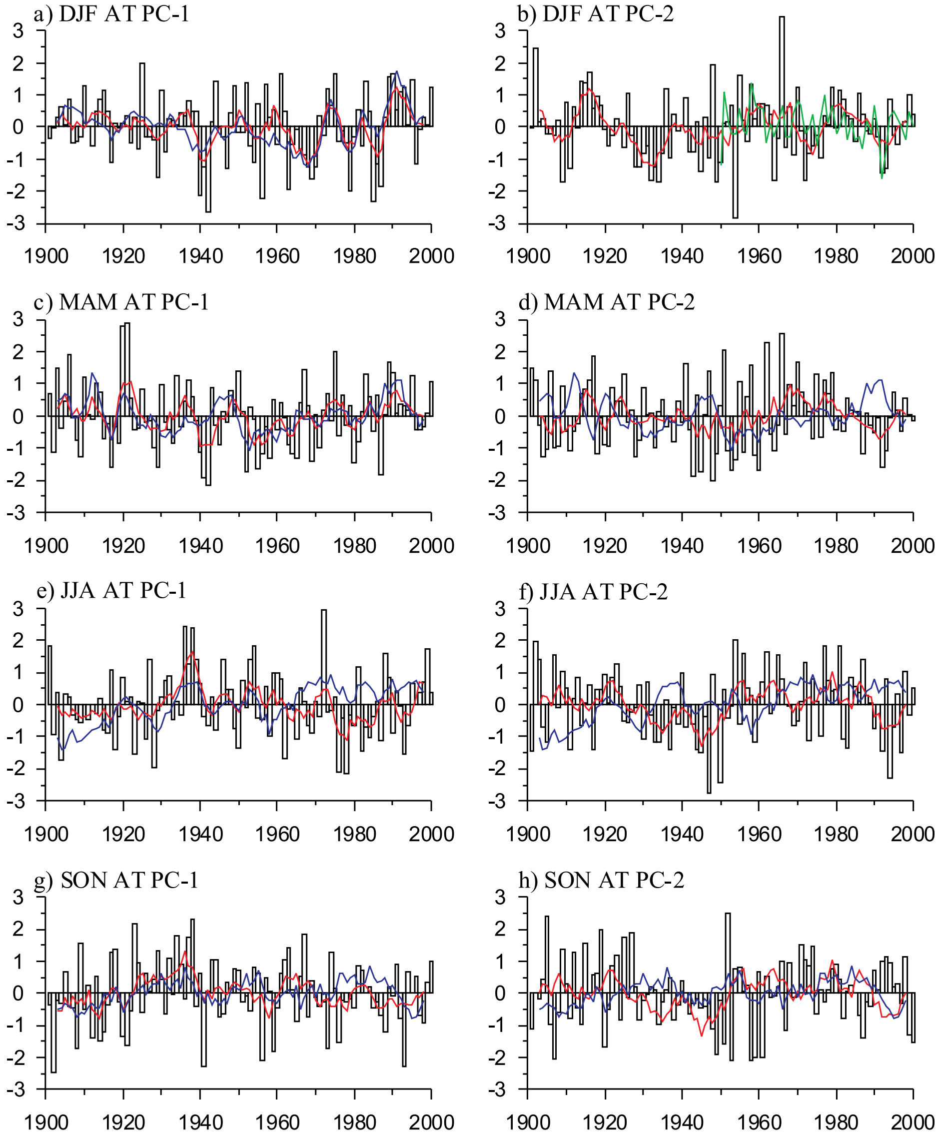

Figure 4. Principal components of the first two EOF modes of the (a, b) winter, (c, d) spring, (e, f) summer, and (g, h) fall air temperature (1901–2000). Red curves indicate 7-a running means. Blue (green) curves indicate NAO (EAWR reversed) index.

[14] The second EOFs explain 15%–20% of the total variance of AT with the largest contributions in winter and fall and the smallest in summer. During all seasons the second mode is represented by the dipole-like pattern with, however, quite different locations of the centers of action (Figures 3b, 3d, 3f, and 3h). In particular, the north-south dipole is observed in winter (Figure 3d), while in summer the second EOF pattern is represented by the east-west dipole (Figure 3f). During spring (Figure 3d) and fall (Figure 3h) the second EOF is represented by the north-west-southeast oriented dipole, which is intermediate between winter and summer patterns. The winter PC2 (Figure 4b) is significantly correlated ($r = -0.49$) with the East Atlantic/West Russia (hereafter EAWR) teleconnection pattern [*Barnston and Livezey*, 1987], one of the three prominent patterns that affect European climate during most of the year. The EAWR has been referred to as the Eurasia-2 pattern by *Barnston and Livezey* [1987]. This pattern consists of four major action centers. Its positive phase is associated with positive height anomalies located over Europe and northern China, and negative height anomalies located over the North Atlantic and north of the Caspian Sea. The spring PC2 (Figure 4d) shows significant negative correlation ($r = -0.52$) with the spring NAO index. During summer and fall the second PCs (Figures 4f and 4h) do not show significant links with the major regional modes of atmospheric circulation.

[15] From the EOF analysis (Figures 3 and 4) we conclude that the leading PCs for different seasons show significant correlation with the major atmospheric circulation indices in the Atlantic-European sector, such as NAO and EAWR. However, linear correlation analysis implies that the wide spectrum of variability of European AT cannot be totally explained by just these two modes in their classical sense. Moreover, the quantified links vary significantly from season to season, potentially implying the

change of the role of different circulation modes throughout the year [e.g., *Peng and Fyfe*, 1996]. In the next section we will quantify the circulation patterns responsible for the described modes of the AT variability by analyzing correlations between considered PCs and SLP anomalies.

4. Links to Atmospheric Circulation

4.1. Correlations With Sea Level Pressure Fields

[16] Figure 5 shows the correlations between the leading PCs of AT for different seasons and the seasonal SLP anomalies in the North Atlantic-European sector for 1901–2000. Winter PC1 correlation pattern forms a typical NAO pattern [*Hurrell*, 1995] with the largest positive correlations over the Mediterranean (0.5) and the largest negative correlations of −0.7 over Scandinavia (Figure 5a) implying the enhanced advection of the warm air from the Atlantic to Europe that results in the anomalously high European AT. Not surprisingly the DJF PC1 is highly correlated with the NAO index (Figure 4a and Table 1). Even when NAO dominates the leading mode of European temperature variability in a particular season, there might be some regions (characterized by the low AT EOF's loadings) where this influence is quite weak or hardly detectable. For instance, this is clearly seen for Iberian Peninsula for some seasons (e.g., Figures 3c and 3e). Earlier studies [*Sáenz et al.*, 2001; *Castro-Diez et al.*, 2002] did not find clear relationships between the NAO and air temperatures over Iberian Peninsula. Correlation between the PC2 and DJF SLP (Figure 5b) represents northwest-southeast dipole with the largest negative correlations (−0.6) over eastern Europe, and the largest positive correlations (0.4) over Greenland. High correlation between DJF PC2 and the EAWR index (Figure 4b and Table 1) suggests that this mode is associated with the EAWR teleconnection pattern that has some structural similarity to the NAO [*Barnston and Livezey*, 1987].

[17] During spring the PC1 correlations form a northeast-southwest dipole over the North Atlantic (Figure 5c). In the previous section we noted that PC1 of MAM AT shows rather strong correlations with the NAO index, implying that this mode of spring AT can be linked to the NAO. Correlations between PC2 of spring AT and SLP (Figure 5d) show the largest negative values over eastern Europe (−0.5), and somewhat weaker negative correlations over the southwestern North Atlantic (−0.3). The largest positive correlations of 0.5 are detected over the southern tip of Greenland. Although Figure 4d and Table 1 imply rather strong negative correlation of the PC2 of spring AT to the spring NAO index, the pattern in Figure 5d differs significantly from the typical NAO pattern [e.g., *Hurrell*, 1995].

[18] Correlations between PC1 of summer AT and SLP anomalies (Figure 5e) display a zonal dipole with negative correlations (reaching −0.3) around Iceland, and large positive correlations (reaching 0.6) over eastern Europe, Scandinavia and European Russia. This pattern implies that an anticyclonic anomaly over a large portion of Europe leads to intensive heating of the land surface, resulting in anomalously high temperatures in the region. This pattern is not associated with any known regional teleconnections [*Barnston and Livezey*, 1987]. Summer PC2 correlations (Figure 5f) form a dipole with the largest negative correlations (−0.5) over Scandinavia, and the largest positive correlations (0.4) southeast of Greenland. Significant correlation with the NAO index (Table 1) implies that during summer the second EOF mode might be associated with the NAO. The NAO-associated AT patterns (Figures 3a and 3f) and SLP correlation patterns (Figures 5a and 5f) are very different for winter and summer. During summer the respective patterns are characterized by zonal dipoles, whereas during winter we obtained a monopole pattern for temperature and a meridional dipole for SLP. This implies significant reduction (relative to winter) of the role of air advection from the Atlantic into Europe in the regional AT variability during summer.

[19] During fall, correlations between PC1 of AT and SLP anomalies (Figure 5g) form the pattern similar to that for the PC1 of spring AT (Figure 5c). This is in agreement with the strong positive correlation between PC1 and the fall NAO index (Table 1). The PC2 correlation pattern (Figure 5h) displays significant negative correlations over southeastern Europe (−0.4 to −0.5) and the largest positive correlations of 0.4 in the region between the southern tip of Greenland and Iceland, resembling the pattern for the PC2 of spring AT (Figure 5d).

[20] To examine the robustness of the revealed links between leading modes of the European AT and regional atmospheric circulation, we derived linear coupled dominant modes between AT and SLP seasonal time series using conventional SVD analysis [e.g., *Bretherton et al.*, 1992]. Since the spatial patterns of the leading SVD modes are very similar to the above considered EOF patterns of AT (Figure 3) and associated correlation patterns in SLP fields (Figure 5) we do not show here the leading SVD modes. However, we show in Table 2 the squared covariance fractions (SCF) for each SVD mode and correlation coefficients between the corresponding expansion coefficients. The first SVD mode explains the major portion (more than 70%) of the total covariance of AT and SLP during winter, spring and fall, whereas it explains only 57% of the total covariance of AT and SLP during summer. The second SVD modes explain less than 20% of AT and SLP covariance during all seasons, indicating a relatively weak association of the second EOF modes of European AT with atmospheric circulation.

4.2. Running Correlations Between Leading PCs and the NAO Index

[21] Although Figures 3, 4, and 5 imply that variability in European AT is dominated by the NAO, we can hypothesize that the interdecadal persistence of the NAO impact on European AT variations changed during the last century. We computed the running correlations, based on 21-a overlapping periods, between the leading PCs of seasonal AT and the NAO index (Figure 6). For the winter season (Figure 6a) positive correlations show an evident increase during the twentieth century implying strengthening of the link between regional AT and the NAO. The correlations between PC2 and the NAO are negative and demonstrate strong interdecadal variability with periods of significant correlation centered on the late 1920s to early 1930s, late 1950s and early 1980s.

[22] During spring (Figure 6b) correlations with the NAO index are significantly positive from 1900 to the early 1950s for PC1 and significantly negative in the mid century for

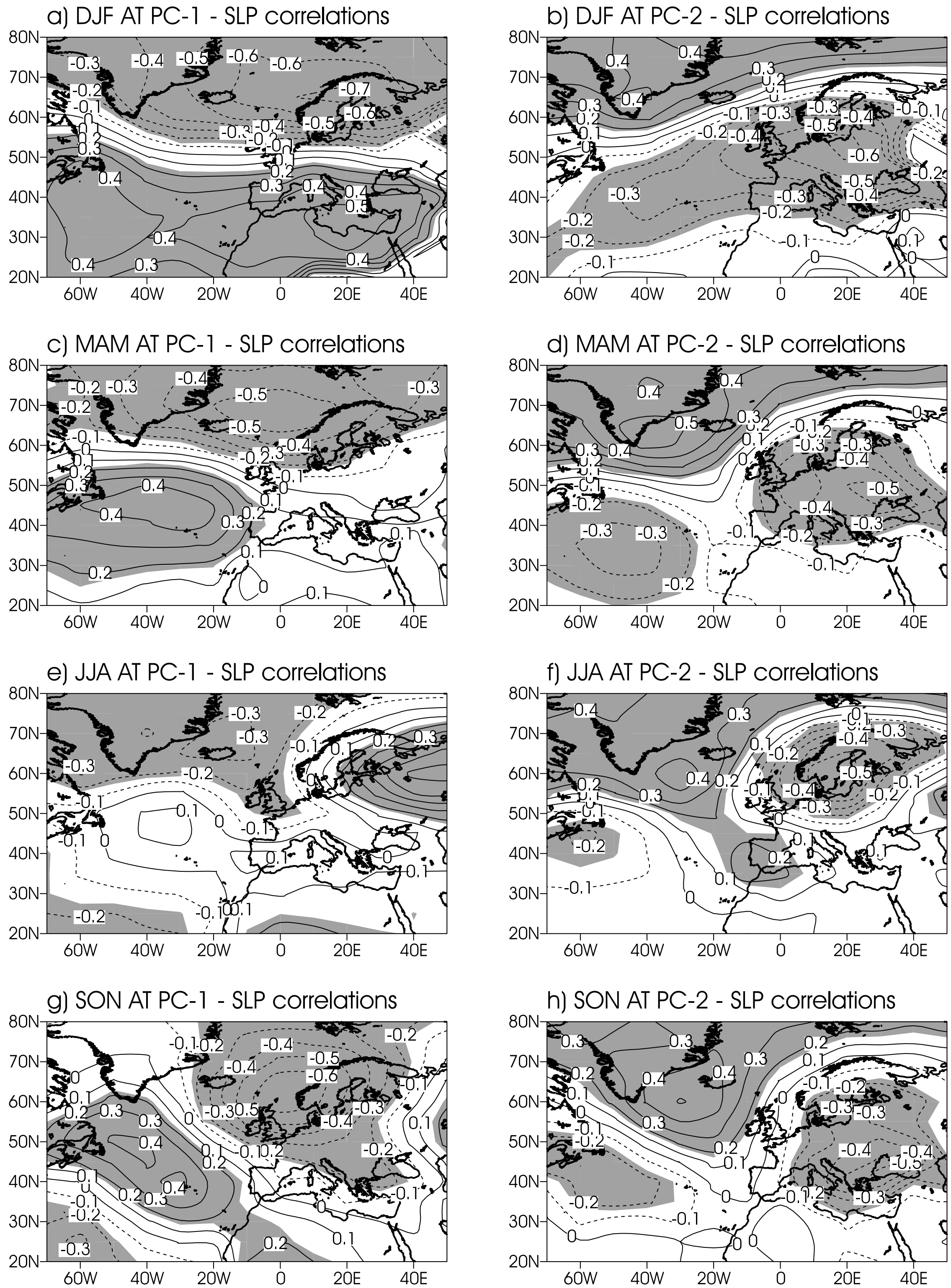

Figure 5. Correlation coefficients between principal components of the first two EOF modes of the (a, b) winter, (c, d) spring, (e, f) summer, and (g, h) fall air temperature (1901–2000) and respective SLP fields. Shaded areas indicate the 95% significance level.

Table 1. Correlation Coefficients Between Principal Components of the First and Second EOF Modes of Seasonal Mean AT and Indices of Teleconnection Patterns[a]

	EOF1-NAO Correlation	EOF2-EAWR Correlation
Winter	0.70	−0.49
Spring	0.49	−0.52
Summer	0.27	−0.35
Fall	0.53	−0.30

[a]Shown coefficients are statistically significant at the 99% significance level.

PC2. After early 1960s the NAO influence on spring AT is very weak (both PC1 and PC2 are not significantly correlated with the NAO). Thus, in contrast to the winter season, during spring the link between European AT and the NAO has been weakening during the twentieth century. These interdecadal changes explain why the springtime correlation with the NAO index estimated for the entire twentieth century is significantly lower than that obtained for the winter season (Table 1). Another reason for this seasonal difference is that in spring the relative role of the NAO in regional SLP variability is smaller.

[23] During summer (Figure 6c) the NAO index shows significant negative correlation with PC2 only for the last two decades of the century. Correlations between PC1 of fall AT and the NAO index are statistically significant from the beginning of the century until the mid 1940s, and from the mid 1960s until the mid 1980s (Figure 6d) with the largest correlations of 0.7 during the 1920s and 1930s. Thus the strength of the link between fall AT and the NAO varied significantly on interdecadal time scale. PC2 of the SON AT is significantly correlated (−0.6) with the NAO index only in the 1970s (Figure 6d).

[24] We conclude that during all seasons the strength of the links between the leading modes of European AT and the NAO varied significantly, implying nonstationarity of the NAO-AT relationships. The character of these links is clearly season-dependent with no two seasons characterized by similar long-term variations of the links between regional AT and the NAO. For instance, winter correlations show the upward trend (Figure 6a), whereas the fall correlations undergo quasi-periodic interdecadal variations (Figure 6d). This provides the dynamical context for the analysis of the leading modes of AT that are not associated with the known regional teleconnection patterns.

4.3. Interdecadal Changes in the Links to Atmospheric Circulation

[25] Running correlations allowed us to identify the periods for which we performed SVD analysis of the seasonal AT and SLP anomalies. These computations were performed for each season except for summer. For winter (Figure 7) we have chosen the periods 1910–1929 (relatively weak links to the NAO) and 1971–1990 (strong links to the NAO, Figure 6a). In 1971–1990 the first SVD mode explains 94.3% of the total covariance of AT and SLP, whereas it explains only 75.7% of the total covariance in 1910–1929. For both periods the AT patterns (Figures 7c and 7d) are similar and resemble the first EOF of AT for the whole period (Figure 3a). The associated SLP patterns (Figures 7a and 7b) are also similar during the two periods and indeed represent "classic" NAO pattern [e.g., *Hurrell*, 1995]. Thus the major difference between the two periods is reflected in the strength of coupling between regional AT and SLP.

[26] For the spring season (Figure 8) we analyzed the periods 1966–1985 (weak links to the NAO) and 1911–1930 (strong links to the NAO, Figure 6b). Again, the AT patterns for the two periods are rather similar and resemble the first EOF of spring AT (Figure 3c). However, their SLP counterparts reveal noticeable differences. For the period 1911–1930 the SLP pattern (Figure 8a) is a typical NAO pattern revealed also by the correlation analysis (Figure 5c). In 1966–1985 (Figure 8b) the SLP SVD pattern is significantly different compared to the earlier period with the northern center of action centered over Scandinavia and the southern center extending from Newfoundland through the North Atlantic to Mediterranean region and Middle East (Figure 8b). Thus, during 1966–1985 the entire dipole was more zonally oriented, implying weakening of the warm air advection into European region. During 1966–1985 the largest correlation (r = 0.60) for the PC2 of the spring AT was found with the index of the East Atlantic Jet (hereafter EA-Jet) teleconnection pattern [*Barnston and Livezey*, 1987]. The SVD-1 SLP pattern is structurally similar to the EA-Jet pattern presented by *Barnston and Livezey* [1987]. The EA-Jet pattern represents a meridional dipole with one main action center located over the high latitudes of the eastern North Atlantic and Scandinavia, and the other action center located over Northern Africa and the Mediterranean Sea. A positive phase of the EA-Jet pattern reflects an intensification of westerlies over the central latitudes of the eastern North Atlantic and over much of Europe. Although the AT patterns are similar for the two periods, the SVD-1 AT pattern for 1966–1985, showing opposite AT variations over western Europe (Figure 8d), is somewhat different from that for 1911–1930 (Figure 8c). We also note a remarkably large (20%) difference in the explained covariances between the two periods.

[27] For the fall season (Figure 9) the periods 1921–1940 (strong links to the NAO) and 1946–1965 (weak links to the NAO, Figure 6d) were chosen. Compared to winter and spring the differences between the two periods during fall are larger. During 1921–1940 the explained covariance between AT and SLP fields is 30% larger than that in 1946–1965. In 1921–1940 spatial structure of AT (Figure 9c) and SLP (Figure 9a) patterns is very similar to those derived for the whole period from the EOF and correlation analyses (Figures 3g and 5g). Alternatively, in 1946–1965 the spatial patterns of SVD-1 (Figures 9d and 9b) are more

Table 2. Fractions of the Total Covariances Between AT and SLP Fields Explained by the First and Second SVD Modes and Correlations (in Parentheses) Between Time Series of the Respective Expansion Coefficients

	SVD-1 SCF (r)	SVD-2 SCF (r)
Winter AT	79.7% (0.74)	15.7% (0.68)
Spring AT	73.1% (0.61)	12.0% (0.58)
Summer AT	57.1% (0.66)	17.8% (0.70)
Fall AT	71.3% (0.75)	18.7% (0.57)

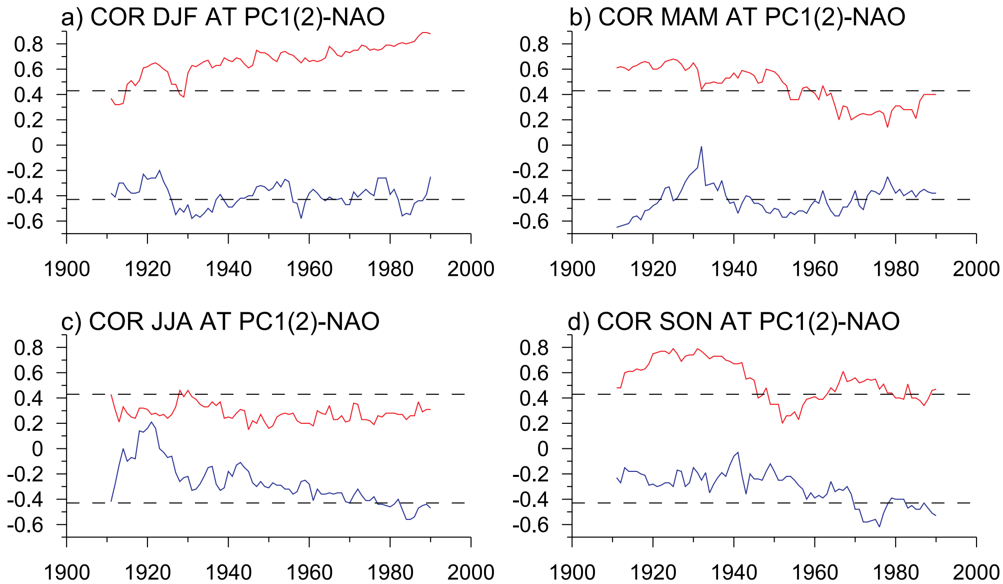

Figure 6. Running correlation coefficients between principal components of the first two EOF modes of the (a) winter, (b) spring, (c) summer, and (d) fall air temperature and the NAO indices calculated over 21-a windows. The first values are plotted in year 11 of the first 21-a period. Red (blue) color indicates correlations for PC1 (PC2). Dashed lines depict 95% significance level.

similar to the EOF-2 pattern in Figure 3h and correlation pattern in Figure 5h. Thus, during the period characterized by the weak links to the NAO, the second EOF mode of the fall AT (Figure 3h) became the leading mode of covariability of AT and SLP fields. This mode suggests that a cyclonic circulation anomaly over Europe (Figure 9b) is associated with advection of the warm air from the tropics into southeastern part of the region, and advection of the cold northern air into northwestern part, resulting in the AT anomalies of the opposite signs in the respective regions (Figure 9d). The correlation between the PC2 of the fall AT and the EAWR index during 1946–1965 is 0.45, implying a leading role of the EAWR mode in the fall AT variability over Europe when the NAO role is weak. Overall, our

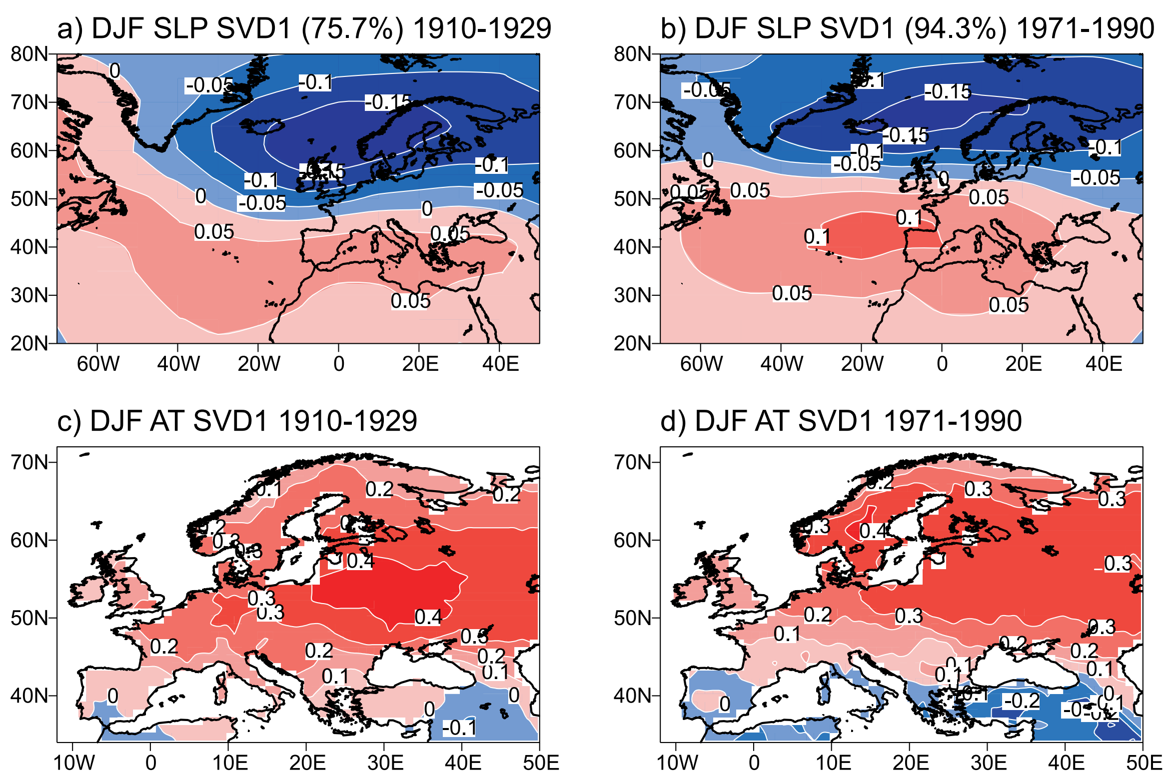

Figure 7. The first SVD mode spatial patterns obtained for pairs of (a, b) winter SLP and (c, d) AT.

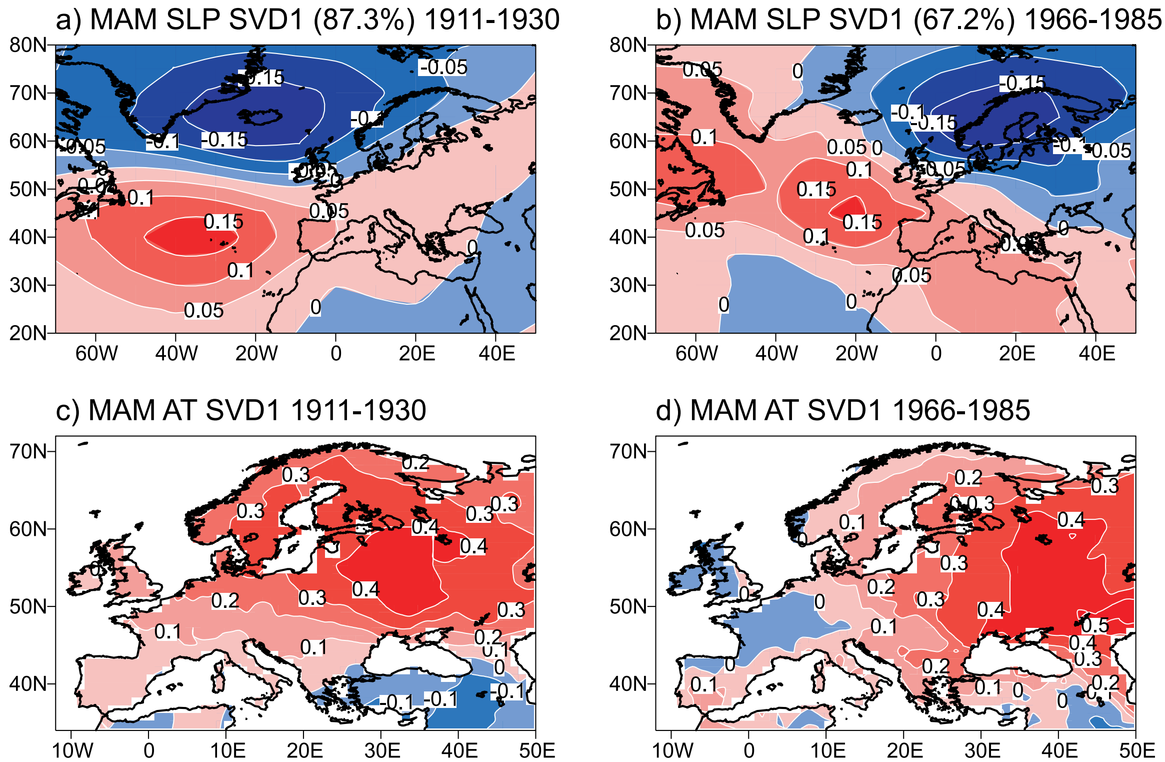

Figure 8. Same as Figure 7 but for spring season.

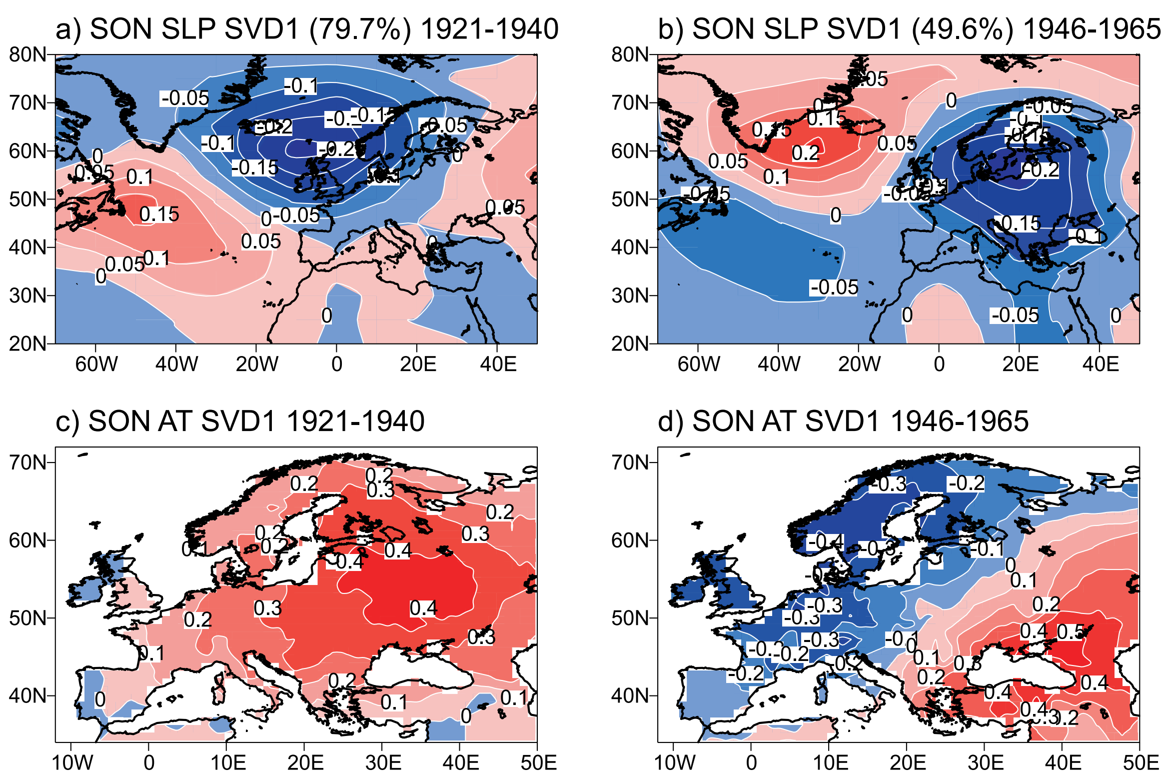

Figure 9. Same as Figure 7 but for fall season.

results suggest significant interdecadal changes in the mechanisms driving regional AT variability during the spring and fall seasons.

5. Discussion and Concluding Remarks

[28] We analyzed seasonality of AT variations over Europe at different time scales using the CRU05 data set for the period 1901–2000. Apparent seasonal differences were detected in linear trends, interannual variability patterns and in the association between leading atmospheric circulation modes and the AT variability in Europe. We demonstrated that the upward change in European air temperatures over the 20th century [e.g., *Trenberth et al.*, 2007] in northeastern Europe is primarily imposed by positive linear trends during the spring season and in southwestern Europe by the trends during the summer and autumn seasons. Remarkably, the winter season trends are not statistically significant over most of Europe except for southern part of European Russia and the Iberian Peninsula. This is a step forward in understanding European AT secular changes during the 20th century described in recent studies [e.g., *Jones and Moberg*, 2003; *Trenberth et al.*, 2007]. We argue that secular trends in European annual mean AT are clearly dominated by signals in specific seasons over different European regions. In other words, assuming the AT trends to be a regional manifestation of the global 20th century warming [*Briffa and Osborn*, 2002], our results provide evidence of seasonally dependent signatures of such a warming, implying, that in different parts of Europe different seasons may contribute to the global warming signal.

[29] We also discovered a seasonally dependent character of shorter period (interannual to decadal) variability of European AT. Furthermore, the leading modes of seasonal AT are clearly associated with quite different regimes of the atmospheric circulation. Considering the first mode of AT, the NAO dominates the European AT variability during winter, spring and fall seasons, playing a minor role in summer, when interannual AT variability is clearly linked to a different mode. It is characterized by the positive SLP anomaly over most of Europe and implies blocking conditions in agreement with the analysis of summertime Mediterranean air temperature by *Xoplaki et al.* [2003]. Analyzing the second leading mode, we argue for the importance of the EAWR pattern in European AT variability, particularly in winter. This link during spring and fall seasons is less evident with the corresponding PCs (Figure 4) being quite different from what we would expect if they were associated with the EAWR. Given the importance of the non-NAO modes of variability of certain climatic parameters in the Atlantic-European sector, it is worth mentioning here the results of *Josey and Marsh* [2005] who demonstrated the dominant role of the East Atlantic pattern in the recent regional precipitation increase with the NAO being just loosely connected to the changes observed.

[30] Our results show that even for seasons when AT is largely dominated by the NAO, the link between the leading modes of European AT and the NAO is highly nonstationary. The strongest differences in the character of AT-SLP association on an interannual time scale between different climate periods were observed in the fall with the smallest ones identified in winter. Therefore, when the NAO impact on European AT variability weakens, the other circulation modes play the dominant role. For instance, during 1946–1965 the EAWR dominated the fall AT variability, and in 1966–1985 the East Atlantic Jet Pattern played the leading role during spring.

[31] Thus different seasons may differently contribute to the regional temperature changes of both secular and non-secular nature. Given the very different mechanisms driving the AT variability in different seasons (proven by SVD analysis in our paper), we can argue that annual time series frequently used for climate assessments [e.g., *Trenberth et al.*, 2007] tell us little, at least over European region, unless seasonal signals are not explicitly quantified.

[32] Our results can be discussed in several prospects. Certainly, the analysis of observational data alone may not be able to disclose the cause and effect relationship between different components of the climate system during different seasons. Nevertheless, our findings provide some novel understanding of the mechanisms driving the AT variability in different seasons. Strong seasonality can be first of all implied by seasonal changes in the air mass transport to Europe. Thus it is of special importance to further analyze seasonality in circulation regimes and associated changes in cyclone activity. Winter patterns in the North Atlantic-European cyclone tracks (primarily driven by the NAO) [*Gulev et al.*, 2001; *Trigo*, 2006] are now much better depicted than those for the other seasons. For instance, there is a considerable debate whether the summer storm tracks indeed deflect to the north providing increasing cyclone activity in the Arctic, or the Arctic regional cyclone counts increase over the last decades due to intensified Arctic cyclogenesis [*Serreze and Barrett*, 2008]. Another important issue to be revisited in this respect is the seasonality in precipitation characteristics over Europe. Our recent analysis [*Zveryaev*, 2006] has essentially shown seasonality in precipitation variability over Europe, and evident non-stationarity in its links to the NAO. However, these results can be influenced by inhomogeneities in data coverage in the CRU data set used by *Zveryaev* [2006]. The recent results of *Zolina et al.* [2005, 2008] based on the collection of best and homogeneously sampled European rain gauges imply seasonality in extreme precipitation for the central European region while changes over the eastern European Russia were qualitatively consistent for winter and summer.

[33] In this regard the analysis of long-term integrations with climate models may shed more light on the links between seasonality in temperature and precipitation changes, especially in the context of extreme precipitation changes. Extreme precipitation is constrained by the atmospheric moisture content while mean precipitation is constrained by the energy budget of the troposphere [*Allen and Ingram*, 2002], and these two factors may have quite different manifestations in different seasons. Of particular interest would be the analysis of simulations of the observed climate variability starting from preindustrial period (late 19th century).

[34] Since the large seasonal differences in AT variability were detected and anomalously high/low ATs may have significant consequences for the regional strategic planning and risk management during all seasons, importance of the further detailed analysis of seasonal aspects of AT variabil-

ity over Europe is evident. Contributing some novel insights to the understanding of the mechanisms of European climate variability during different seasons, we also recommend further development of such an understanding through the analysis of cyclone activity, extreme events and the role of local processes.

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