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Temporal and spatial variability of precipitation in Sweden and its link with the large-scale atmospheric circulation

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ABSTRACT

The main characteristics of spatial and temporal variability of the precipitation regime in Sweden were studied by using the long-term monthly precipitation amount (1890–1990) at 33 stations. The data were filtered by using Empirical Orthogonal Function (EOF) analysis, which provides principal modes of both spatial variability and time coefficient series describing the dominant temporal variability. Canonical correlation analysis (CCA) was used to reveal association between the atmospheric circulation and the characteristics of the climate variability. Statistically significant upward shifts in the mean precipitation have been found during cold months (March, September, November and December) and only a downward shift (less significant) for August. Simultaneous changes in the time series associated to the optimally correlated circulation patterns were found, indicating an important role of the circulation. The circulation patterns are given by the North Atlantic Oscillation (NAO) in March and December and a cyclonic structure centred over southern Scandinavia in September and November. These changes may have induced changes in the mean precipitation seasonality reflected by a shift of the maximum precipitation from August to July (after 1931 for western part and after 1961 for the southeastern coast) and after 1961 to September, October or November for other regions. Combining rotated EOF analysis with cluster analysis, 4 regions with similar climate variability were objectively identified. For these regions the standardised monthly precipitation anomalies were computed. The frequency of the extreme events (very dry/wet and dry/wet months) over 5-year consecutive intervals was analysed. It has been concluded that extreme wet months were more frequent than extreme dry months over the entire country, especially in the northern and southeastern part.

1. Introduction

The study of physical mechanisms controlling the natural climate variability is important both from a scientific and a practical point of view. The problem becomes more complex when the regional climate variability is studied, which includes the interaction between planetary and regional scale features of climate variability (Von Storch, 1999). From practical point of view many users require information about the range of natural climate variability.

Precipitation is one of the most important climate variables for ecosystems, hydrology and agriculture. There are a few studies, which have examined precipitation variability in Sweden. Among others, Taesler (1971), Karlström (1985), Eriksson (1983) and Alexandersson et al. (1991) can be noted. However, the regional patterns of the Swedish precipitation variability, real changes

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in the internal structure of the climatological data and their association with physically connected mechanisms are still not fully analysed. The studies mentioned above used raw data implying that the reliability may sometimes be questionable due to possible inhomogenity in the data. The availability of the recently homogenised long precipitation time series (Frich et al., 1996) from 33 standard meteorological stations in Sweden, allows us to solve some of the critical issues related to the precipitation variability. The data has been homogenised by using the method reported in Alexandersson and Moberg (1997).

The main goal of this study is to objectively characterise the spatial and temporal patterns of Swedish precipitation variability, to determine the physical mechanisms responsible for these patterns and for changes in various characteristics of precipitation variability. The atmospheric circulation is the main forcing for the regional climate variability, which exhibits variability not only on year-to-year time scales but also on decadal time scale. This is why the link between atmospheric circulation and regional climate is usually studied in order to understand the physical mechanisms controlling the regional climate.

The link can be studied in different ways. One way is to find statistical relationships between regional climate variables and some subjectively defined circulation indices or circulation types (Yarnal, 1984; Kozuchowski et al., 1992; Busuioc and Bojariu, 1994; Malmgren et al., 1998; Chen, 2000). An important source of interannual variability in the atmospheric circulation is the NAO. Walker and Bliss (1932) established correlation between a NAO index and precipitation at a number of stations in Europe, while Hurrell (1995) provided a systematic study on the relationship between the NAO and surface temperatures and precipitation for various European regions. Recently, Chen and Hellström (1999) reported the link between regional temperature variability in Sweden and a NAO index. Another way is to study the connection between the objectively defined patterns of the large-scale circulation and regional climatic variables. The canonical correlation (CCA) is a frequently used tool for this purpose (Zorita et al., 1992, Werner and Von Storch, 1993, Cui et al., 1995; Heyen et al., 1996; Busuioc and Von Storch, 1996) and will also be used here.

The paper is organised in the following way. Section 2 presents the main statistical methods used in this study. The results of the study are presented in Section 3 and the conclusions and discussions are summarised in Section 4.

2. Data and methods

The data used in this work are the time series of the monthly precipitation amount at 33 Swedish stations over the interval 1899–1990. All these data have been carefully examined and homogenised through the NACD program (Frich et al., 1996). The stations are spread over almost the entire country and the time series could be considered long enough to identify the climate signal concerning the main features of temporal and spatial variability of precipitation in Sweden up to decadal scale. None of these time series have any missing values. The names and the positions of the stations are presented in Table 1. The monthly sea level pressure (SLP) data with a resolution of $5^\circ \times 5^\circ$ have been provided by the National Centre of Atmospheric Research (NCAR, USA) (Trenberth and Paolino, 1980) and the area between 40°W–40°E and 40°N–70°N was selected. For both parameters the anomalies have been computed by subtracting the long term mean from the original values.

The main characteristics of spatial and temporal variability of the observed data set are identified by EOF analysis based on standardised data (Haan, 1979; Barnett, 1981; Von Storch, 1995). In some cases the EOFs are rotated in order to obtain physically meaningful and statistically stable patterns. A widely used method is the "varimax" (Richman, 1986). Most commonly, the rotated EOFs are used in the regionalization issue to solve the domain dependence problem that is associated with non-rotated EOFs and will also be used here. One of the drawbacks of the rotated EOFs is the loss of information about the dominant individual sources of variation in the data. For this reason, the non-rotated EOFs were used in this work except in the regionalization. The EOF time coefficient series for each month are analysed with regard to trends and shifts in the mean in order to identify the changes in the precipitation regime in Sweden and in the large-scale circulation. Non-parametric tests are used

Table 1. *Stations used in the analyses; ϕ = latitude, λ = longitude, H = elevation*

Station	ϕ (°N)	λ (°E)	H (m)	Station	ϕ (°N)	λ (°E)	H (m)
1. Falsterbo	55.38	12.82	5	18. Svenska Högarna	59.43	19.50	12
2. Halmstad	56.67	12.92	25	19. Malung	60.70	13.68	308
3. Växjö	56.87	14.80	166	20. Falun	60.62	15.62	160
4. Kalmar	56.72	16.28	15	21. Sveg	62.02	14.35	360
5. Hoburg	56.92	18.13	38	22. Sidsjö	62.38	17.28	60
6. Göteborg	57.77	11.88	19	23. Härnösand	62.62	17.93	8
7. Borås	57.77	12.93	20	24. Östersund	63.18	14.48	376
8. Ölands norra udde	57.37	17.10	135	25. Junsele	63.68	16.87	210
9. Visby	57.67	18.33	4	26. Holmögadd	63.58	20.75	6
10. Vänersborg	58.20	12.37	42	27. Lövånger	64.37	21.32	21
11. Ålberga	58.73	16.55	50	28. Stensele	65.07	17.15	325
12. Landsort	58.73	17.87	25	29. Piteå	65.32	21.48	6
13. Gotska Sandön	58.38	19.18	13	30. Haparanda	65.82	24.13	5
14. Karlstad	59.35	13.47	12	31. Kvikkjokk	66.95	17.73	337
15. Lisjö	59.70	16.07	46	32. Jokkmokk	66.62	19.63	260
16. Uppsala	59.85	17.62	60	33. Karesuando	68.43	22.48	327
17. Stockholm	59.33	18.05	44				

for this purpose. Testing of the significance of a linear trend against the null hypothesis of "no trend" is made with the non-parametric Mann-Kendall's test (Sneyers, 1975; Kulkarni and Von Storch, 1995). Determination of the different "regimes" in time coefficient series is done by applying the concept of "change points" which are times of abrupt changes in the statistics of a time coefficient series. For this objective a technique called Pettitt-test (Pettitt, 1979; Sneyers, 1975) is used. An alternative to the Pettitt-procedure is presented by Solow (1987) referring to the piecewise linear trends and Hubert (1997) by a segmentation procedure of time coefficient series. But for any of these procedures it is unclear whether a once determined "change point" in the data is due to a change of the dynamical regime or to inhomogeneities in the analysed data set. To overcome this problem Busuioc and Von Storch (1996) proposed to search for simultaneous change points in dynamically related time coefficient series. This procedure is applied in this paper. The changes in the mean precipitation seasonality are then analysed as a consequence of changes in the mean regime of precipitation.

In order to define homogeneous sub-regions with similar precipitation regimes, cluster analysis is used in conjunction with a rotated EOF analysis. From the EOF analysis the component scores for each station are obtained. These component scores are subjected to cluster analysis (Wolter, 1987; White and Pery, 1989). The similarities among stations are measured by distance in the EOF space of monthly and annual precipitation. A similar procedure is also presented by Domroes et al. (1998).

For every region M the standardised regional precipitation is computed by using the relationship,

$$S_M(j) = \frac{1}{N_M} \sum_{i=1}^{i=N_M} (P_{k,i}(j) - \overline{P_{k,i}})/S_{k,i}, \quad k = 1, \ldots, 12,$$

where j is time, $\overline{P_{k,j}}$ is the long term mean for month k and station i, $S_{k,i}$ is the corresponding standard deviation and N_M is the number of stations in region M. In this way the annual cycle is removed and all months can be considered together. A similar procedure has been used by Busuioc and Bojariu (1993).

In order to study the long-term characteristic of dry and wet months, the monthly regional precipitation have been ranked in each region. A month is classified as "very dry" ("very wet"), "dry" ("wet"), or "slightly dry" ("slightly wet"), if it is among the 4%, 12%, or 25% driest (wettest) months. A similar definition has been used by Hansen-Bauer and Førland (1998a) for seasonal precipitation in Norway. A climatological terminology of extremes and normal conditions has also been defined by Eriksson (1979) using a slightly different percent limit. In this work the monthly-standardised precipitation is used in order to get a picture of the temporal distribution of the extreme events. The frequency of these characteristics is then calculated over a 5-year interval for every region and the "change points" in the respective time coefficient series are then analysed. In this way a possible link between changes in monthly precipitation and temporal variability of the extreme events may be found.

The dominant patterns of the large-scale circulation, which control the regional climate variability, are identified by using the canonical correlation analysis (CCA) (Barnett and Preisendorfer, 1987; Von Storch et al., 1993; Von Storch, 1995). CCA has the main advantage, among other statistical methods, to select pairs of optimally correlated spatial patterns, which may lend to a physical interpretation of the mechanism controlling the regional climate variability. This method has been successfully used by, among others, Zorita et al. (1992), Werner and Von Storch (1993), Cui et al. (1995), Busuioc and Von Storch (1996) and Heyen et al. (1996). The 1st CCA pair gives the maximum correlation between the two parameters, followed by the 2nd CCA pair and so on. Since the coefficients are normalised to unity the canonical correlation patterns represent the typical strength of the signal. Prior to the CCA, the original data are projected onto their EOFs to reduce noise (small-scale features) and overfitting, and only a limited number of them are retained, explaining most of the total variance. The time coefficient series associated with the most important CCA pairs are analysed concerning the trend and change points and the physically meaningful changes in the regional climate regime can be found. Busuioc and Von Storch (1996) present more details concerning this aspect.

3. Results

3.1. *Spatial and temporal variability of Swedish precipitation*

3.1.1. Trends and shifts. Monthly precipitation anomalies for the 33 stations were computed and Mann-Kendall and Pettitt's tests were applied to find possible trends and change points. Only for some months significant trends and change points were identified. Almost all are increasing ones (September, November and December). A slight decrease in August is noted. In March, one increase and one decrease were identified and therefore no significant trend was noted.

For every month the EOF patterns and corresponding time coefficient series were computed. The 1st 3 EOFs are most important, displaying the main features of the spatial variability. As an example, Fig. 1 shows the patterns of the 1st 3 EOFs for January and August. The variances explained by the 1st 3 EOF patterns for all months are presented in Table 2. The 1st EOF explains the highest fraction of the total observed variance (above 50%) for the cold months between September and March. The lowest explained variance is recorded for summer months. For all months the 1st EOF pattern shows the same sign of variability over the entire country, meaning that a common large-scale process might be responsible for a large part of the Swedish precipitation variability. This process could be different from one month to another and it will be studied by canonical correlation analysis (CCA) in Subsection 3.3.

Generally, two centres of high variability were identified for all months. The 1st one is located in the southern part (Borås station) and the 2nd (that appears in all months except for January, February, September and October) in the eastern part (Sidsjö–Härnösand area). The lowest variability is identified, generally, in the northern part of Sweden at the Karesuando station. For June, minimum variability is recorded in the eastern islands (not shown) and for September along the southeastern coast. To investigate possible impact of spatial density of stations for northern and southern parts on the results, the EOF analysis was repeated by using fewer stations for the southern part (30 stations instead of 33 stations) and almost identical result was obtained, which confirms the objectivity of the result. Concerning the magnitude of the variability, the highest was identified in October and the lowest in March.

The 2nd EOF patterns show, generally, 2 regions with opposite signs of variability (except for January and November) with north-south gradient. In February and October, they are disposed in west-east direction. For the north-south gradient the separation line between the two regions generally is positioned near the Falun station but it moves more or less from one month to another,

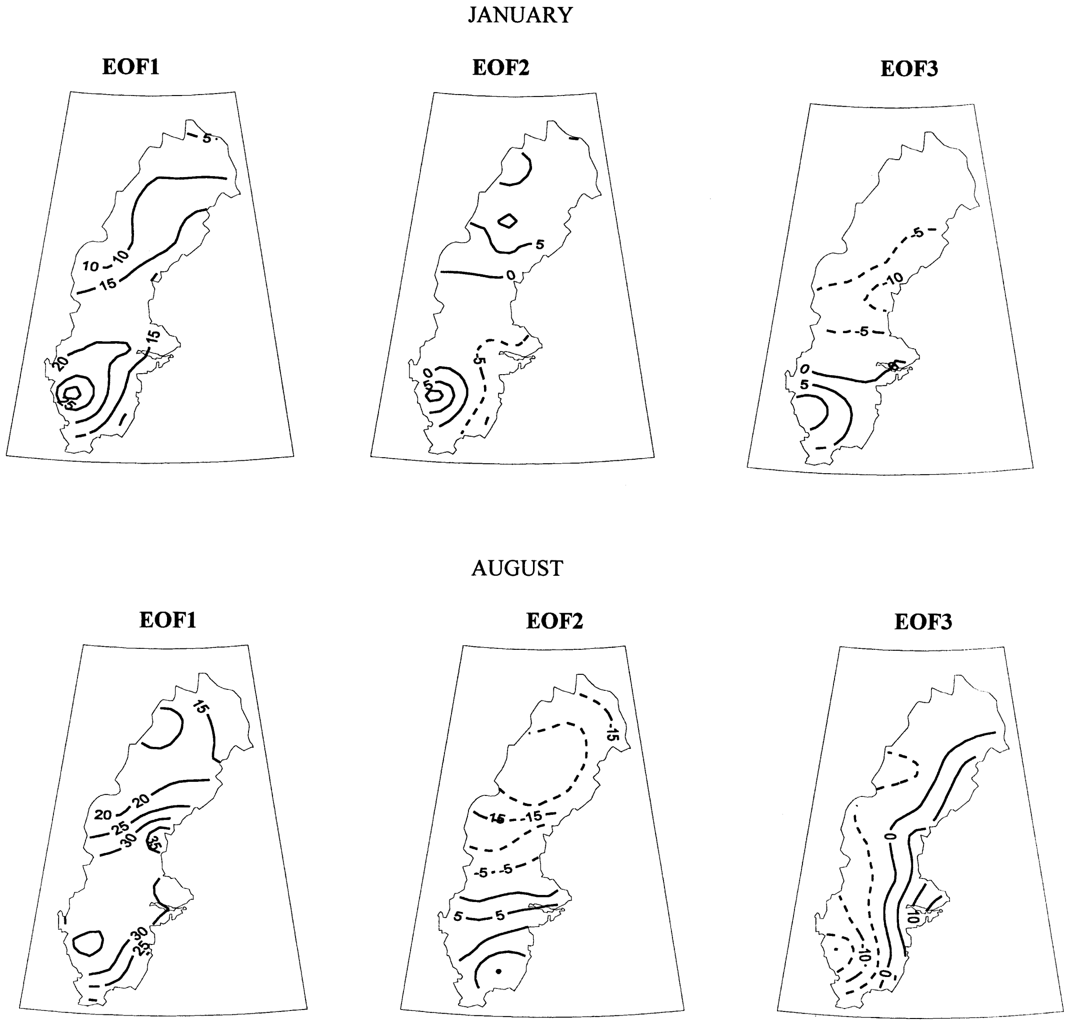

Fig. 1. The patterns of the 1st 3 EOFs of the Swedish precipitation (1899–1990) for January and August. The eastern islands are not shown. The coefficients are normalised to one so that the patterns represent typical dimensional distributions (in mm).

the most southerly position occurs in December. In November, there are 3 regions, the northern, southwestern, and southeastern (including middle of the country) areas. The 1st two regions have the same sign of variability. For January the southwestern part is much more limited around the Borås station.

The patterns of the 3rd EOF are quite similar to the 2nd EOF but the sizes of the areas are different. For annual values, the EOF analysis shows essentially the same characteristics as for the monthly data.

The time coefficient series associated with the 1st two EOF patterns were analysed regarding change points and trend, and the results are summarised in Table 2. Climate signals similar to those of the individual stations appear but the noise (small scale features) is now much more filtered out. For the September time coefficient series an increase around 1918 is identified. For

Table 2. *Explained variance of the 1st 3 EOF patterns of the monthly mean SLP and monthly total amount of Swedish precipitation*

Month	Explained variance (%)						Shifts in EOF time series		
	SLP			precipitation					
	EOF1	EOF2	EOF3	EOF1	EOF2	EOF3	SLP	precipitation	Mechanism
January	41	24	18	52	11	8	EOF1↑ (1934, 0,06)		NAO (E) ↑
February	39	27	17	55	10	8	EOF1↑ (1928, 0.06)		NAO (E) ↑
March	39	23	19	54	10	8	EOF1↓ (1965, 0.15)	EOF1↑ (1965, 0.01)	NAO (W)↑*-
							EOF1↑ (1927, 0.12)	EOF1↓ (1922, 0.08)	
April	31	23	20	47	14	7			
May	32	19	17	46	10	8			
June	33	20	16	41	12	7			
July	32	24	16	35	10	7	EOF1↓ (1919, 0.07)		NAO (E) ↓
August	37	24	14	45	11	7	EOF1↑ (1965, 0.02)	EOF1↓ (1963, 017)	Anticyclonic ↑
September	41	22	15	52	11	7	EOF1↓ (1916, 0.04)	EOF1↑ (1917, 0.04)	Cyclonic ↑*
October	35	24	17	61	12	6			
November	34	26	18	58	10	8	EOF1↓ (1914, 0.14)	EOF1↑ (1936, 0.05)	Bipolar ↓
December	40	22	13	55	13	8	EOF1↓ (1938, 0.05)	EOF1↑ (1943, 0.13)	Bipolar ↓

The change points in the mean of monthly coefficient time series of the 1st EOF pattern of the 2 variables are presented. The year and significance level are shown; arrows show the direction of the shift. Last column presents the explanation of the mechanism leading to changes in the atmospheric circulation; * shows the equivalent mechanism (for example NAO (W)^{n}a* is equivalent with NAO (E)↓) *and* W/E means western/eastern flow.

the November and December time coefficient series, an increase around 1936 and 1943 are noticed, respectively. In March an increase around 1965 and a decrease around 1922 are identified. The downward shift in August around 1963 is also emphasised. As expected, the time coefficient series associated with the 1st EOF pattern derived from the annual anomalies shows an upward shift around 1923. The time coefficient series associated with the 2nd EOF pattern shows a significant decrease for annual values around 1917. Fig. 2 shows, as an example, the temporal evolution of the 1st EOF coefficients corresponding to the March, August, September and November.

3.1.2. Regionalization of precipitation regime. From the analysis of the 1st five rotated EOF patterns of the monthly precipitation a general regionalization of Swedish precipitation concerning climate variability could be made, though there are some differences among some months. Generally, 4 regions could be emphasised: North, Middle, South, and Southwest. The regions were delimited more objectively combining the EOF analysis with cluster analysis. The results depend on the number of EOF used in the cluster analysis and the number of clusters considered as well as month. Finally, in order to synthesise the characteristics of all months the regionalization was made using the 1st 4 rotated EOFs for annual precipitation with 4 clusters. The 4 regions obtained are presented in Fig. 5. It should be noted that the regionalization can not capture small scale variability caused by topography, coasts or the big lakes due to the relatively low density of stations. Because of this, only four regions are considered and they are thought to represent a rough division concerning climate variability.

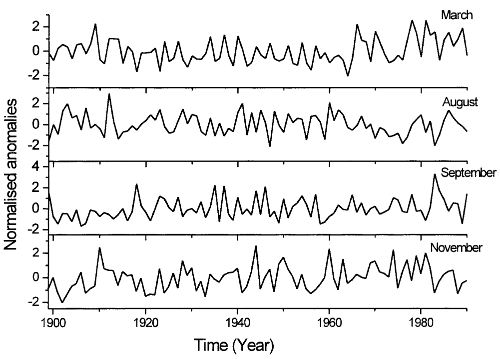

Fig. 2. Time coefficients series of the 1st EOF pattern derived from the total monthly Swedish precipitation for March, August, September and November.

3.1.3. Change in the precipitation extreme events. For the 4 regions presented above the monthly standardised regional time coefficient series has been computed. The frequency of very dry (wet) and dry (wet) months over a 5-year interval were computed and analysed with respect to change points. Figs. 3, 4 show the temporal evolution of these time coefficient series and Table 3 presents the change points with the corresponding statistical significance. It was found that the frequency of very wet months has increased since the 1940–1944 interval in region 1 (southeastern part), and the 1955–1959 interval in region 3 (middle part). The frequency of wet months has increased in the southeastern, middle and northern part of Sweden since the 1940–1944, 1930–1934 and 1915–1919 intervals, respectively.

The dry months were significantly less frequent after the 1920–1924 interval in the middle region and after 1955–1959 in the region 4. Thus the frequency extreme wet months in Sweden has increased over the entire country except in the southwestern part where no significant changes in the frequency of extreme monthly events were recorded. The frequency of extreme dry events has decreased significantly in the northern half of the country.

3.1.4. Change in the precipitation seasonality. Over the interval (1890–1990), the maximum monthly mean precipitation is recorded in August and minimum in February. As presented in the previous section some changes have been identified in the monthly climate regime. The question is whether these changes have modified the main characteristic of precipitation seasonality mentioned above. To answer this question the monthly long term mean over the 3 subintervals (1890–1930, 1931–1960, 1961–1990) have been computed. It can be observed that after 1931 maximum precipitation in Sweden was recorded in July for the western part and after 1961 for the southeastern coast. For other regions (eastern coast of the northern half of the country, the eastern island area and a small area around Borås) the maximum precipitation moved to September,

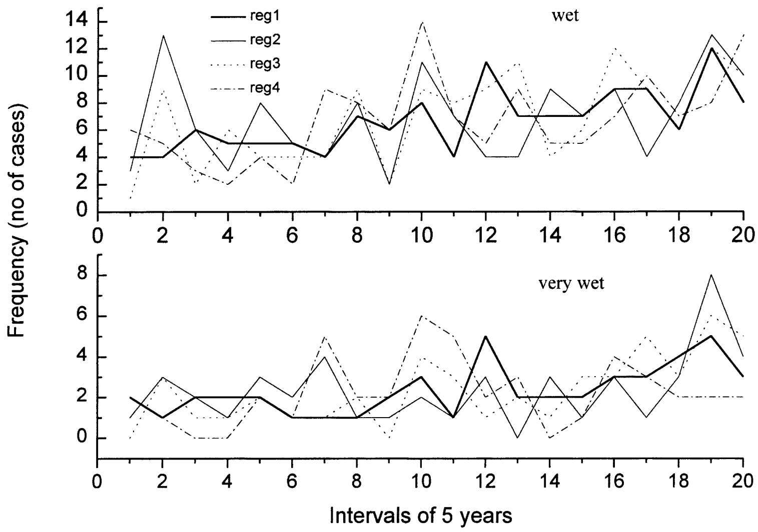

Fig. 3. The temporal evolution of the frequency of very wet and wet months over 5-year intervals.

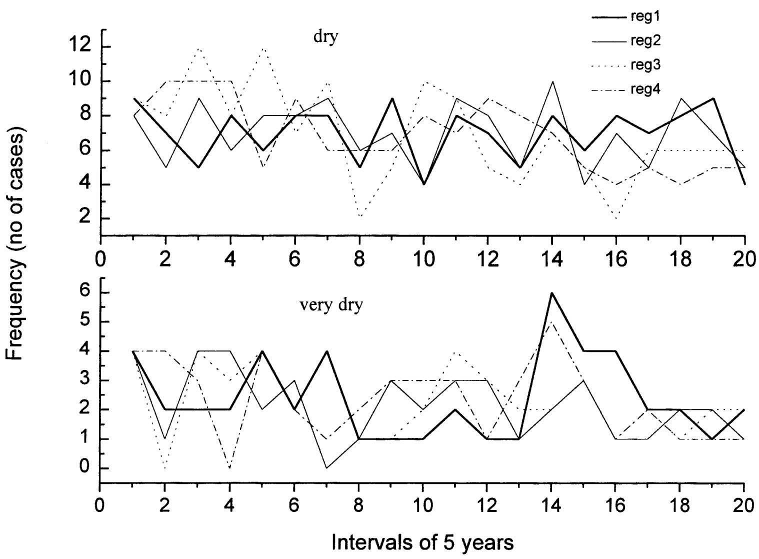

Fig. 4. Same as in Fig. 3 but for very dry and dry months.

October or November after 1961. The results of these changes are summarised in Fig. 5.

The main reasons for these changes are the decrease in precipitation in August and the increase during autumn months (September and November). The physical reasons for these changes could be found by focusing on the link between Swedish precipitation variability and large-scale circulation variability given by the CCA analysis presented below.

3.2. Changes in the large-scale circulation in the North-Atlantic region

The patterns of the 1st 3 SLP EOFs represent the main modes of the atmospheric circulation

Table 3. *Changes in frequencies of monthly extreme events for regional precipitation in Sweden over 5 year intervals; the interval of change points and their statistical significance is presented; arrows show the direction of the shift*

Region	Very dry	dry	wet	Very wet
1			1940–1944↑	1940–1944↑
			0.01	0.02
2				
3		1920–1924↓	1930–1934↑	1955–1959↑
		0.02	0.03	0.02
4		1955–1959↓	1915–1919↑	
		0.01	0.02	

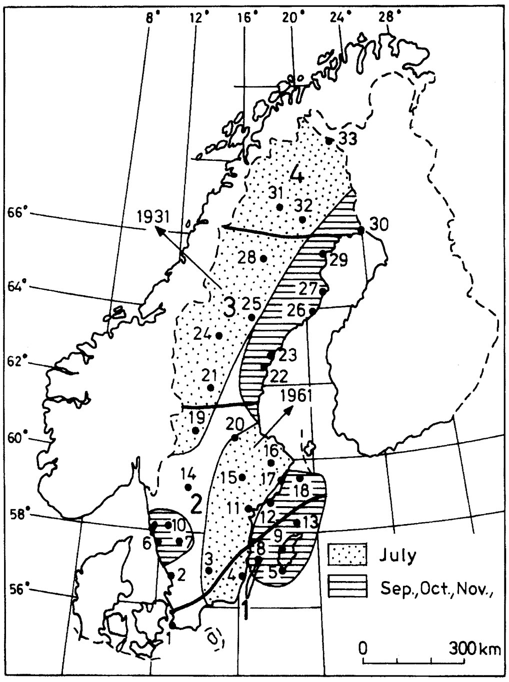

Fig. 5. Locations of the stations as numbered in Table 1 with small number and changes in seasonality of precipitation in Sweden. Thick lines divides the four regions (indicated by big numbers) with similar precipitation variability.

variability over the North Atlantic–European region. These modes explain more than 80% of the total variance from January to March, about 70% in May–June and between 72% and 78% in the rest (Table 2). The order of these patterns is changed for some months (especially the 2nd and the 3rd EOF pattern). The principal mode of the SLP variability (given by the 1st EOF pattern) is represented by the NAO from January to July (less clear for June and July) and for October. The 2nd and 3rd EOF patterns for these months are represented by a dipole structure, generally, with opposite sign between Europe and the North Atlantic Ocean and a cyclonic/anticyclonic structure centred over the British Isles (centre is moving from one month to another), respectively. In the rest of the months the NAO is generally represented by the 2nd EOF pattern. From August to September, the principal mode of the SLP variability is given by a cyclonic/anticyclonic structure over Scandinavia. In November and December the bipolar structure mentioned above represents the principal mode of the SLP variability. Fig. 6a–c shows, as an example, the 1st 3 EOF patterns for January, August and November, which represent the 3 groups of months presented above.

The time coefficient series associated with the 1st EOF patterns has been analysed concerning the change points to detect changes in the atmospheric circulation regime over the Atlantic–European region. Some changes have been found especially for cold months (Table 2). Fig. 7 shows as an example the time coefficient of the 1st EOF pattern of SLP for March. August, September, November and December. Considering the EOF patterns for the respective months, changes in the circulation regime was identified and they are noted in the last column of Table 2. The changes in cold months are, generally, linked with enhancement of NAO. These results are in agreement with those presented by Hurrell (1995), Hurrell and Van Loon (1997).

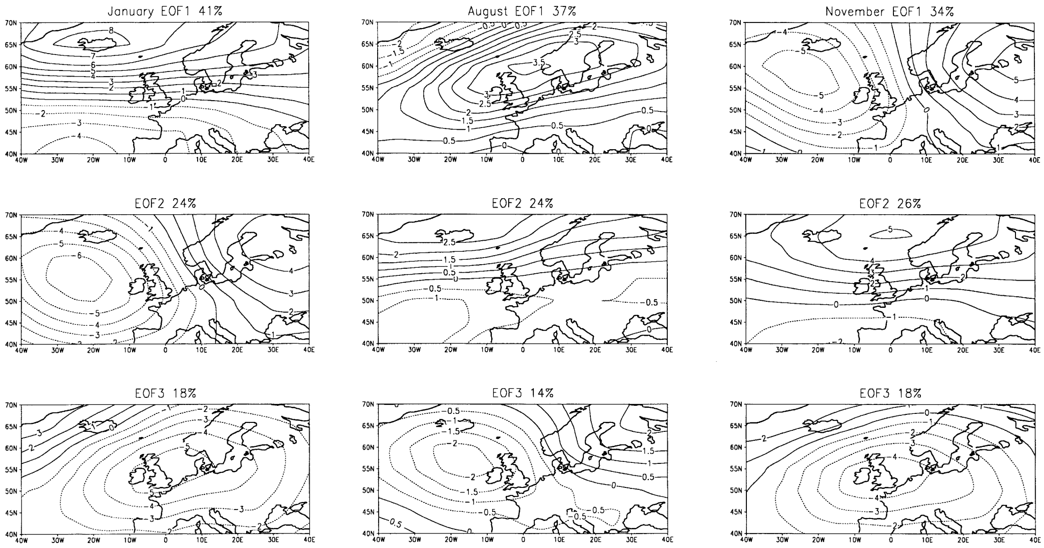

Fig. 6. The patterns of the 1st 3 SLP EOFs for January (a), August (b) and November (c). Explained variance for every pattern is marked. The coefficients are normalised to one so that the patterns represent typical dimensional distributions (hPa).

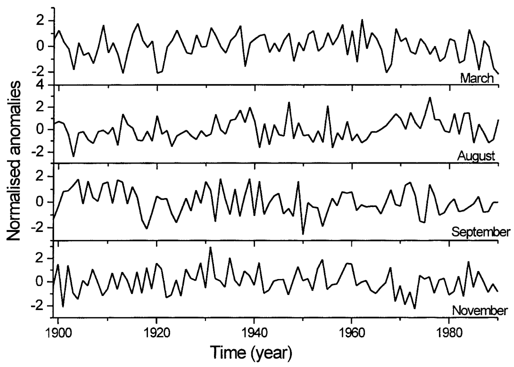

Fig. 7. Time coefficients series of the 1st EOF pattern derived from the monthly SLP anomalies for March, August, September and November.

Almost all of these changes are quasi-synchronous with changes in the monthly Swedish precipitation. Considering the EOF patterns of the two parameters for the respective months these changes seems to be dynamically consistent and indicate a *possible* link between them. For brevity of presentation only one example is discussed. After 1965, the time coefficient of the 1st SLP EOF in August was on average positive so that the anticyclonic structure centred over the southwestern part of Scandinavia was more frequent. Consistently the time coefficient of the 1st EOF for precipitation was on average negative, implying less precipitation in Sweden, with maximum of deficit in southwest. A similar interpretation is suggested by the patterns for March, September and December. More physically plausible explanation can be found in the following CCA analysis where pairs of SLP and precipitation patterns optimally correlated are selected. In the cases mentioned above, the 1st SLP EOF patterns are maximally correlated to the 1st EOF pattern of Swedish precipitation as it will be presented in Subsection 3.3. Details about this procedure can be found in Busuioc and Von Storch (1996). By using this method, it is then possible to determine if the changes in the monthly Swedish precipitation could be due to changes in the large-scale circulation on Atlantic–European scale. The changes detected in the time coefficients of the 1st SLP EOF have no correspondence (there is no significant shift or the shift is detected in different year) in EOF time coefficient series of the precipitation, which could be explained by the fact that these SLP patterns are not maximally correlated to the 1st EOF of precipitation (in the case of July and December) and/or they explain only a portion of the total observed SLP variance (in the case of

January and February). More explanation will follow in the following section.

3.3. Link between Swedish precipitation and large-scale circulation

Canonical correlation analysis (CCA) between monthly SLP anomalies over Atlantic–European region and Swedish precipitation anomalies has been performed for all months. Generally, this link is strong for all months, especially for cold months. Table 4 shows the canonical correlation coefficients as well as the explained variance of the 1st 3 CCA patterns of SLP and Swedish precipitation. The 1st 6 EOFs for SLP and precipitation were retained for the CCA for all months except for December when the 1st 7 EOFs for precipitation were considered. The optimum number of retained EOFs was chosen so that using one more EOF would change the canonical correlation only a little (Werner and Von Storch, 1993, Von Storch, 1995a, Busuioc and Von Storch, 1996).

The connection precipitation-SLP seems to be primarily related to the 1st SLP EOF only for August, September and October. In these months the SLP pattern as well as the precipitation pattern of the 1st CCA pairs is similar to the patterns of the 1st EOF for the respective variables. Also the CCA patterns of both variables explain almost the same variance as the EOF patterns. For the other months the regional variability is mainly explained by one or two mechanisms appearing in the 1st 3 principal modes of the SLP variability. Even if NAO is the principal mode of SLP variability from January to July, it explains only a part of the local variability (higher for the cold months), especially for the southwestern and western part. For other months NAO appears generally among the 2nd or 3rd mode of the SLP variability. This conclusion could be justified by comparing the Figs. 6a–c with Figs. 8–10. The main 3 mechanisms given by the 1st 3 CCA pairs controlling the Swedish precipitation variability could by summarised as following:

(1) NAO pattern representing the western/eastern flow is associated with positive/negative anomalies over entire Sweden with higher anomalies in southwestern part. When the zero-isoline of the SLP anomaly moves to north, a dipole structure of the Swedish precipitation variability with north/south gradient is noted (compare, for example, the patterns of the 1st CCA pair from Fig. 8 with the patterns of the 2nd CCA pair from Fig. 9).

(2) Cyclonic/Anticyclonic structure centred generally over the British Isles is associated with positive/negative precipitation anomalies over almost the entire country with higher anomalies in the south-southeastern part. This structure includes the Baltic Sea influence upon the Swedish precipitation variability. Sometimes, the centre of the SLP pattern moves or it becomes more or less extended, which leads to a regionalization of the Swedish precipitation variability (compare, for example, the patterns of the 2nd CCA pair from Fig. 8 with the patterns of the 1st CCA from Figs. 9, 10).

(3) Dipole structure with a west/east gradient is associated with a dipole structure of the Swedish precipitation anomalies with north/south or west/east gradient depending on the position and extension of the two centres (compare the patterns of the 3rd CCA pair from Figs. 8–10).

The importance of the mechanisms presented above (given by the order of the CCA pairs; 1st CCA pairs is most important and so on) varies with month. For January to March the 1st CCA pair is represented by the 1st mechanism, which associates eastern flow given by the NAO pattern (transporting dry continental air mass) with negative anomalies of the Swedish precipitation over the entire country. The explained variance of the 1st CCA patterns for the two variables is less than the explained variance of the 1st EOF pattern of the respective variables (Tables 2, 4). Therefore it could be said that the NAO explains only a part of Swedish precipitation variability in these months. The 2nd and 3rd CCA pairs explain another important part of the total variance. Since the 1st 3 CCA pairs for the 3 above-mentioned months are very similar we present only January in detail (Fig. 8). For the 1st CCA pair of January the correlation coefficient between the time coefficient series associated with SLP and Swedish precipitation patterns is 0.87. The SLP CCA pattern explains 27% of the total SLP variance and precipitation CCA pattern explains 32% from the total observed variance. The 2nd CCA pair (correlation coefficient is 0.79) is represented by the 2nd mechanism pattern presented above. The cyclonic structure given by the negative SLP pattern

Table 4. *Correlation coefficients of the 1st 3 CCA pairs of monthly mean SLP and total Swedish precipitation amount; explained variance of the CCA patterns and the changes in the mean of the time series associated with the 1st CCA pair (year and statistical significance); arrows show the direction of the shift*

	Correlation			Explain variance (%)						Shifts in the CCA time series	
				SLP			precipitation				
Month	R1	R2	R3	CCA1	CCA2	CCA3	CCA1	CCA2	CCA3	SLP	precipitation
January	0.87	0.79	0.66	27	18	14	32	25	10	CCA2 ↑(1935, 0.01)	CCA2 ↑(1914, 0.05)
February	0.84	0.72	0.43	32	17	18	44	17	7		
March	0.84	0.69	0.57	22	24	18	46	14	8	CCA1 ↑(1964, 0.05) ↓ (1922, 0.07)	CCA1 ↑(1964, 0.01) ↓ (1927, 0.05)
April	0.82	0.49	0.36	18	6	17	43	7	12		
May	0.73	0.44	0.37	15	21	25	41	7	8		
June	0.84	0.59	0.49	17	14	30	35	9	4		
July	0.75	0.59	0.49	21	22	10	33	9	8		
August	0.79	0.44	0.41	31	19	10	42	7	10	CCA1 ↑(1966, 0.07)	CCA1 ↑(1964, 0.06)
September	0.87	0.66	0.46	34	7	13	41	10	10	CCA1 ↓(1916, 0.02)	CCA1 ↓1916 0.10)
October	0.89	0.73	0.55	24	18	19	58	10	5		
November	0.88	0.77	0.60	15	21	27	54	10	8	CCA1 ↓(1937, 0.21)	CCA1 ↓(1958, 0.03)
December	0.87	0.86	0.64		14	20	24	38	22	CCA2 ↓(1947, 0.04)	CCA2 ↓(1947, 0.04)

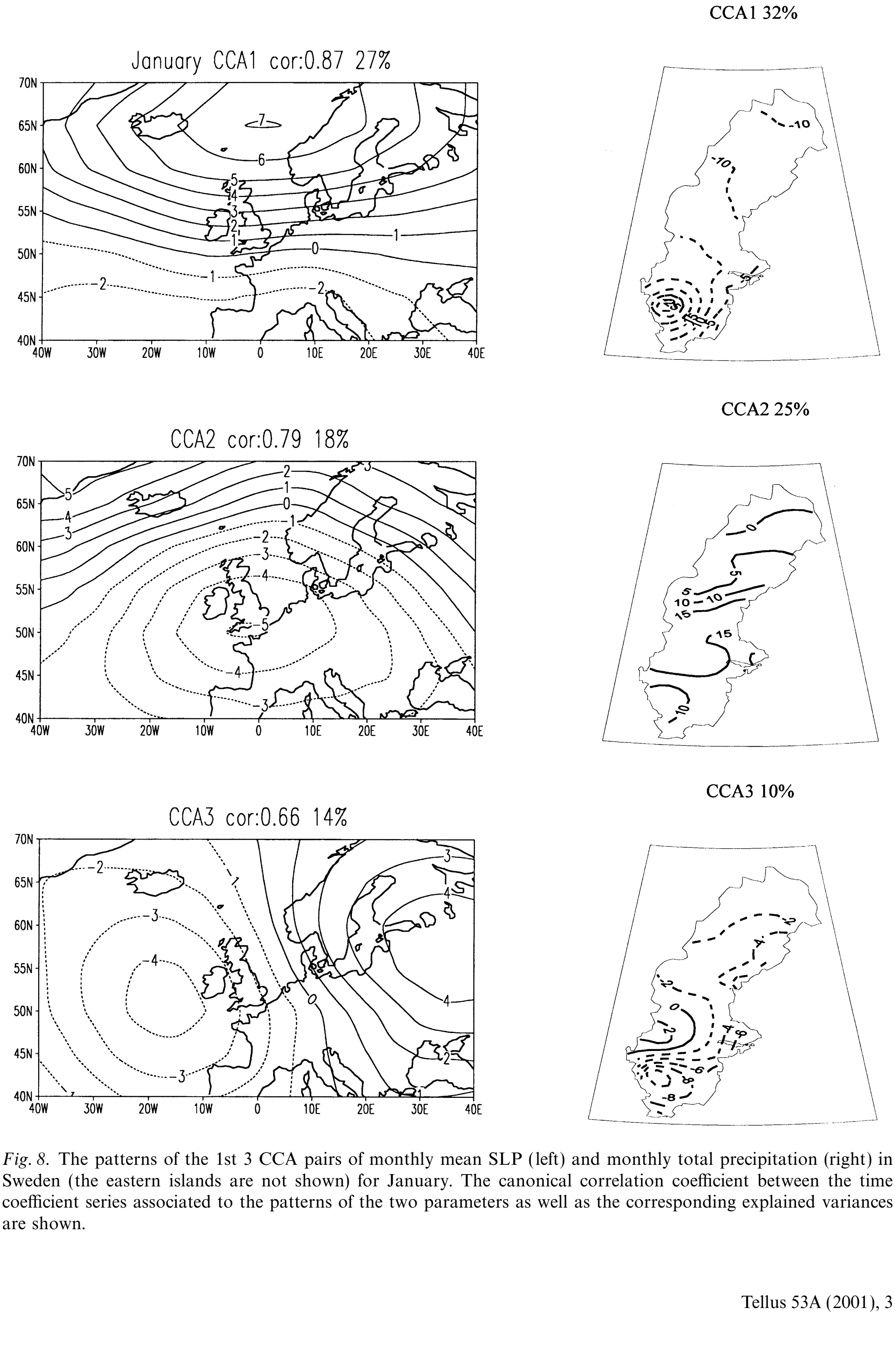

Fig. 8. The patterns of the 1st 3 CCA pairs of monthly mean SLP (left) and monthly total precipitation (right) in Sweden (the eastern islands are not shown) for January. The canonical correlation coefficient between the time coefficient series associated to the patterns of the two parameters as well as the corresponding explained variances are shown.

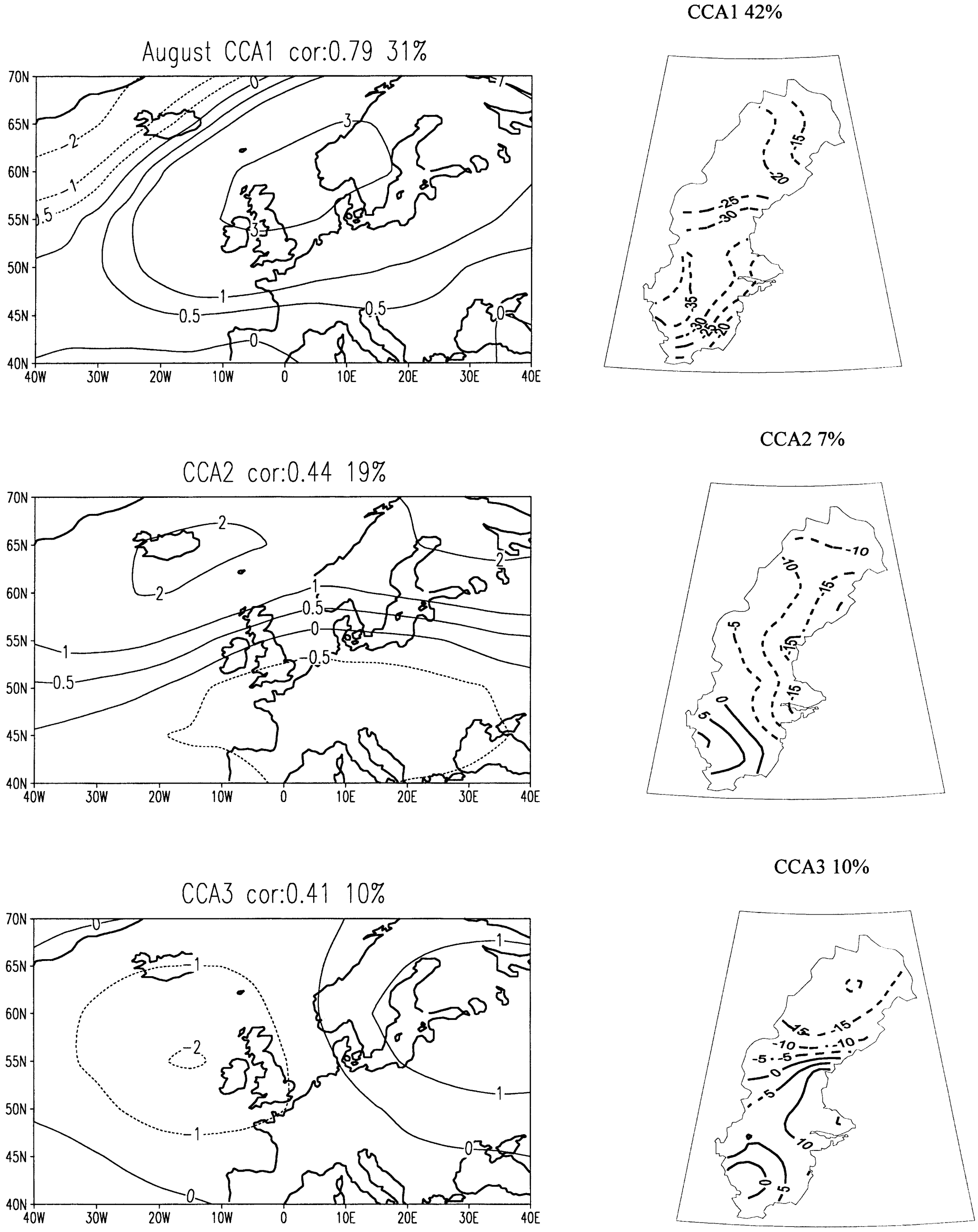

Fig. 9. As in Fig. 8 but for August.

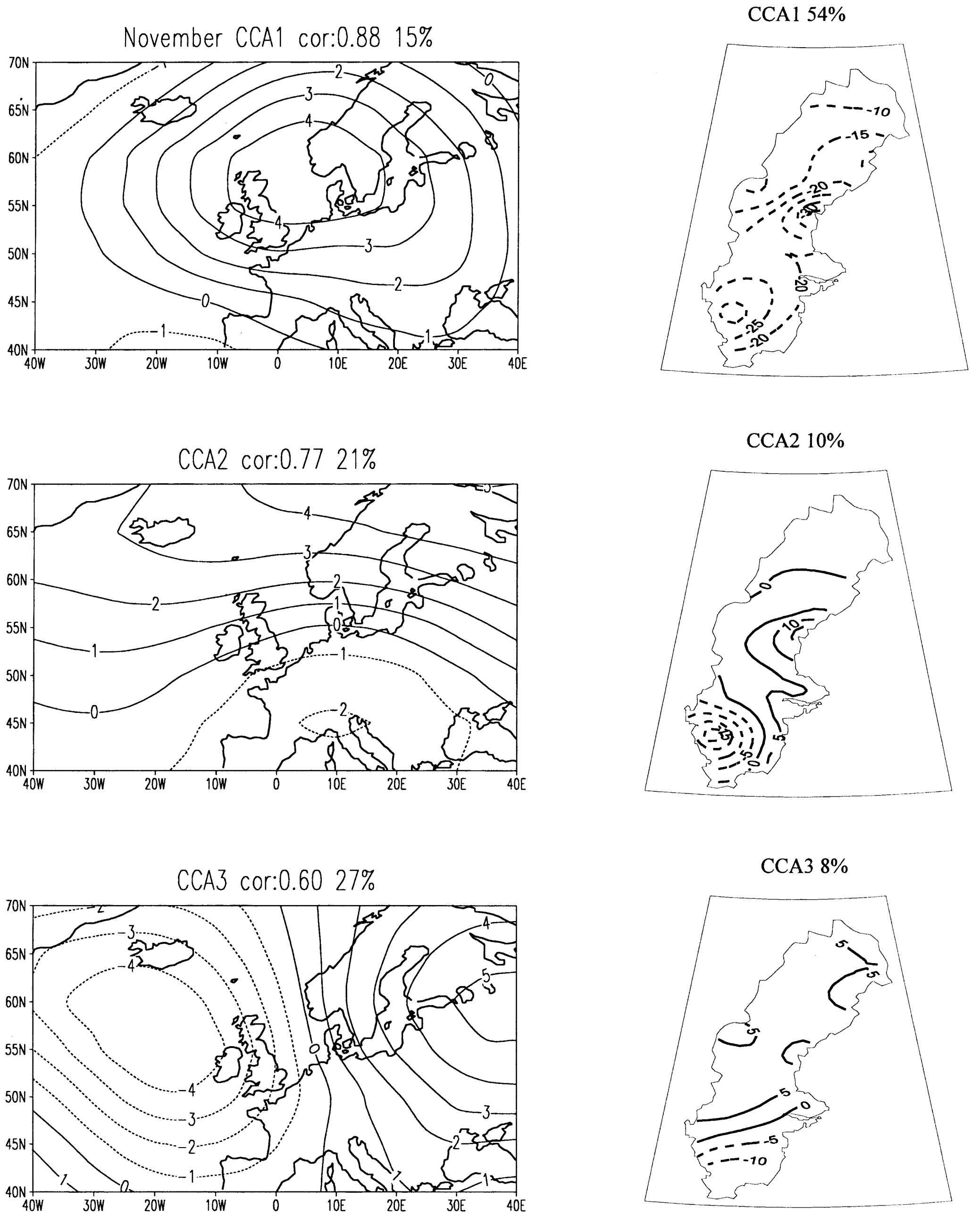

Fig. 10. As in Fig. 8 but for November.

(placed over the British Isles) leads to southerly flow over Southern Europe and southeasterly flow over Scandinavia, transporting maritime air mass from the Mediterranean basin refreshed over the Baltic Sea, brings more precipitation especially in the southern part of Sweden. The negative precipitation anomalies in the northernmost part are probably due to the positive SLP anomalies from the northern area. The SLP pattern accounts for 18% of the total SLP variance and precipitation pattern accounts for 25% of the total precipitation variance. The 3rd CCA pair is represented by the 3rd mechanism: the SLP pattern suggests a southeasterly circulation over Sweden that brings dry continental air mass and below normal precipitation is recorded. The position of the two centres gives some regionalization in the Swedish precipitation variability. So, for example, in March the negative SLP anomaly pattern is more extended, the zero line passing through southwestern Sweden that leads to positive precipitation anomalies in the southern part and negative precipitation anomalies in the northern part.

From April to October the 1st CCA pair is represented by the 2nd mechanism presented above. However, from April to July the SLP CCA patterns are different from the 1st SLP EOF pattern. The spatial structure as well as the explained variance of the CCA pattern of the Swedish precipitation for all these months is similar to the 1st EOF ones. Therefore, we can assert that, in these months, the Swedish precipitation variability is mainly controlled by this mechanism but it does not represent the principal mode of the large-scale SLP variability. The canonical correlation coefficient for the 1st CCA pair is also high but the 2nd and 3rd CCA pair present much lower correlation coefficient than for January to March one (Table.4). From August to October the patterns of the 1st CCA pair are similar to the 1st EOF patterns for both variables, which means that for these months the main mechanism controlling the Swedish precipitation variability is given by the principal mode of the SLP variability. As an example, Fig. 9 presents the patterns of the 1st 3 CCA pairs for August. The 2nd CCA pair is represented by the 1st mechanism presented above but the zero line of the SLP pattern is moved to northward compared to January for example; consequently, the associated pattern of the Swedish precipitation shows a dipole structure with northeast–southwest gradient. The 3rd CCA pair represents the 3rd mechanism with the note that the west–east SLP dipole structure is associated with dipole structure of the Swedish precipitation of north–south gradient.

For November and December, the 1st CCA pair represents the 3rd mechanism. For December it is noted that the canonical correlation coefficients of the 1st two CCA pairs are very close, which indicates that the 2 mechanisms have almost the same importance in terms of the coupling between the precipitation variability and the circulation. The 2nd SLP CCA pair is represented by the NAO pattern. Thus, December could be included in the 1st group of months (January-March). Fig. 10 shows the patterns of the 1st 3 CCA pairs for November.

For March, August, September and November the time coefficient series associated to both SLP and Swedish precipitation patterns of the 1st CCA pair present quasi-simultaneous change points (upward shifts except for August) which are also similar to those found in the 1st EOF time coefficient series for the two variables. For December, the time coefficient series associated with the 2nd CCA pair displays the same upward shift. Figs. 11, 12 show the temporal evolution of the time coefficient series associated with the 1st CCA pair for March, August, September and November. Considering the pattern of the 2 variables, these changes could be explained by changes in the mechanisms summarised as follows.

(i) An intensification of the western flow that is associated with NAO after 1964 (March) and 1947 (December) is linked to above normal precipitation in Sweden in these months. Between 1920 and 1964 the eastern flow was more frequent in March and consequently more frequent negative precipitation anomalies (especially in the southern part) were recorded.

(ii) Increased precipitation after 1917 (September) and 1936 (November) can be associated with more frequent and/or more intense cyclonic structure centred over southern Scandinavia.

(iii) More frequent anticyclonic structure centred over southwestern Scandinavia after 1965 (August) is linked to less than normal precipitation in Sweden.

Since the precipitation time series are homogenised and the link with the SLP is strong for all months, it is most likely that these shifts are real,

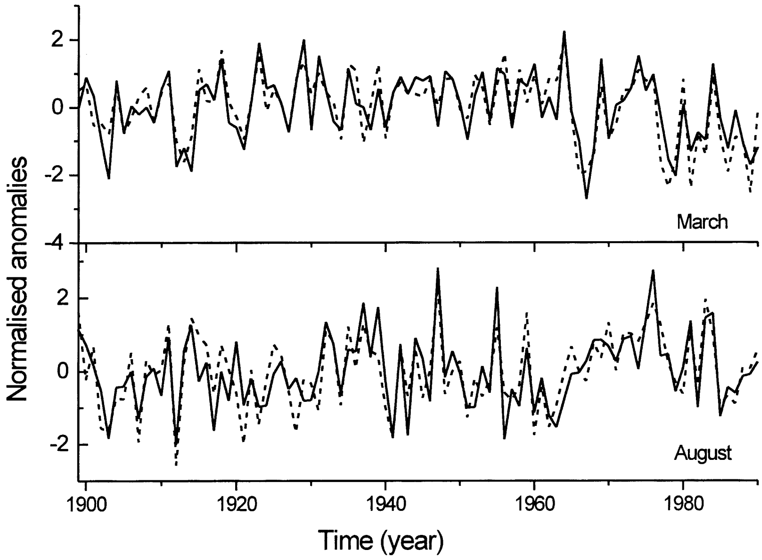

Fig. 11. Normalised time coefficients of the 1st CCA pair of the monthly SLP anomalies (continuous line) and Swedish precipitation anomalies (dashed line) for March and August.

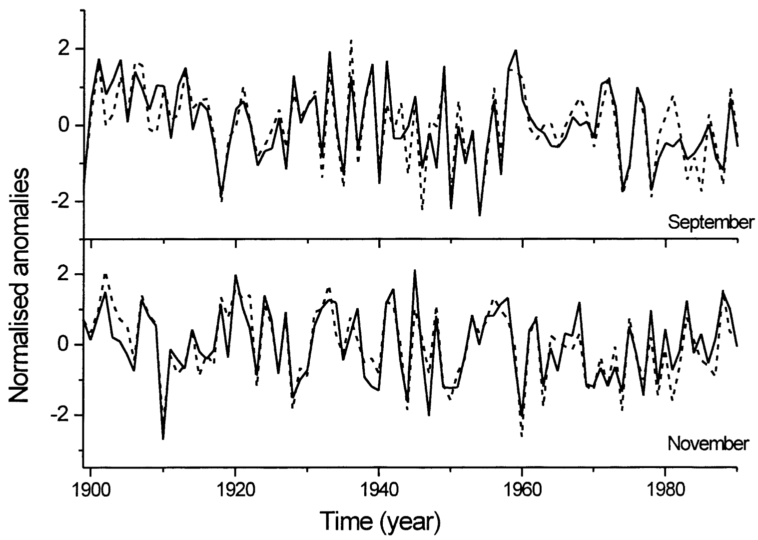

Fig. 12. As in Fig. 11 but for September and November.

i.e., not statistical artifices. Whether the dynamics of the changes in the large-scale circulation mentioned above are due to natural fluctuation of the climate system or are determined by the external forcing remains unknown. It should be noticed that the links between the changes in the large-scale atmospheric circulation and Swedish precipitation are determined statistically and further dynamical studies of the processes involved is needed for better understanding of the physical mechanisms involved. Another question to be answered is whether the global warming around 1920 noted by Jones et al. (1982), Kelly et al. (1982) and Rogers (1985) is coupled to changes in Swedish precipitation through the same mechanism.

4. Summary and conclusions

By using long term monthly precipitation (1890–1990) at 33 Swedish stations, the main characteristics of spatial and temporal variability and atmospheric circulation controlling them were studied. For this purpose various statistical methods were used. The EOF and cluster analyses were used to extract the signal of space-temporal climate variability and to obtain homogeneous sub-regions. The atmospheric circulation controlling the regional climate variability is given by the canonical correlation analysis. The main conclusions, which can be drawn from this analysis, are summarised in the following.

There is a positive trend in the annual precipitation in Sweden over the 1890–1990 interval due to an upward shift around 1924. Different upward shifts in some months have determined this characteristic. In September, an increase around 1917 is identified. For the November and December time coefficient series increases around 1936 and 1943 are noticed, respectively. In March, an increase around 1965 and a decrease around 1922 are identified. Only a less significant downward shift around 1963 is found in August.

These changes in monthly precipitation have induced changes in the mean seasonality of precipitation in Sweden characterised by maximum precipitation in August and minimum in February. This characteristic has been revealed by comparison between the long term mean for the 3 subintervals (1890–1930, 1931–1960, 1961–1990). After 1931 maximum precipitation in Sweden was recorded in July for the western part and after 1961 for the southeastern coast. After 1961 for other regions (eastern coast of the northern half of the country, eastern islands area and a small area around Borås) maximum precipitation shifted to September, October or November.

The 1st EOF pattern shows same sign of variability over the entire country with two centres of high variability (southwest and eastern coast in the Sidsjö–Härnösand area). The lowest variability is generally found in the northern part of Sweden. The 2nd and 3rd EOF patterns show 2–3 regions with the same sign of variability, the size of these regions being different from one month to another. Firstly a delimitation between the northern and southern part is made (the separation line moving more or less from one month to another) and secondly, the west–east splitting is emphasised.

The regionalization procedure identified four regions with similar characteristics of precipitation variability: North, Middle, South and Southeast. These sub-regions were used to analyse whether the changes in the monthly precipitation regime induced changes in the temporal variability of the regional extreme events. Significant changes in the frequency of such extreme events were evident in regions 1, 3 and 4 after the period 1920–24.

The possible causes for these characteristics of spatial and temporal variability associated with the atmospheric circulation were found in the CCA analysis. The regional differences could also be linked to the geographical characteristics such as orography and distance to the sea. The link between monthly Swedish precipitation and large-scale precipitation is strong for all months, especially for cold months. This connection seems to be primarily related to the 1st SLP EOF only for August, September and October. For the other months the regional variability is mainly explained by one or two mechanisms appearing in the 1st 3 principal modes of the SLP variability. Even if NAO is the principal mode of SLP variability from January to July, it explains only a part of the local variability (higher for the cold months), especially for the southwestern and western part. For other months NAO appears generally among the 2nd or 3rd mode of the SLP variability.

Changes in the following circulation patterns may have produced or contributed to the changes in the Swedish precipitation regime.

- An intensification of the western flow after 1964 (March) and 1947 (December) determined above normal precipitation in Sweden in these months. Between 1920s and 1964 the eastern flow was more frequent in March and consequently more frequent negative precipitation anomalies (especially in the southern part) were recorded.
- Increased precipitation after 1917 (September) and 1936 (November) can be associated with more frequent and/or more intense cyclonic structure centred over southern Scandinavia.
- A more frequent anticyclonic structure centred

over southwestern of Scandinavia after 1965 (August) is linked to less precipitation in Sweden.

These results indicate that the observed changes in the Swedish precipitation variability are likely due to changes in the large-scale circulation. However, whether the dynamics of the changes in the large-scale circulation mentioned above is natural fluctuation of the climate system or are determined by the external forcing remains unknown.

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