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no. 07/2005
Climate

Relations between long-term variations in seasonal runoff and large scale atmospheric circulation patterns

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Title Relations between long-term variations in seasonal runoff and large scale atmospheric circulation patterns	**Date** 22.02.2005
Section Climate	**Report no.** 07/2005
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Client(s) EBL-Kompetanse A/S Norwegian Meteorological Institute Norwegian Water Resources and Energy Directorate	**Client's reference**

Abstract

The relation between large scale atmospheric circulation and seasonal runoff is investigated. The atmospheric circulation is described by principal component analysis of gridded mean sea level pressure for two different geographic extents, and two different periods. The analysis shows that extending the domain to include Siberia do not change the leading principal components significantly,

The temporal principal components are related to regional runoff by a correlation analysis. Despite the coarse seasonal resolution significant correlations between runoff and atmospheric circulation modes are found. These relations are used to establish regression models using the principal components of atmospheric circulation as predictors for regional runoff.

The results indicate that atmospheric circulation patterns might be used to predict variations of runoff in order to address the impact of a future climate on runoff.

Keywords

Atmospheric circulation, runoff, teleconnections, PCA, climate impacts

Disiplinary signature	**Responsible signature**
	Eirik J. Førland

Contents

Introduction

A possible climate change caused by human activity have been intensively discussed in recent decades. IPCC (Houghton et al., 2001) stated that anthropogenic effects could at least partly explain the global warming observed in the last decades. Water and water resources are in most areas of the world an important and valuable resource, as well as a key environmental variable. Too little or too much water are critical in most societies. In countries like Norway variations in runoff might have major consequences for the society. Floods are the most dramatic events causing economic loss, and governmental regulations are applied to establish design values preventing such loss. In a changed climate however, the frequency of floods will be changes, and in the worst case also the total runoff regime in certain regions. Periods of water deficits have also economical consequences. In the recent years the low level of the water reservoirs for hydropower production has led to increased electricity prices. Drought periods also lead to shortage of water for industrial and household purposes. As the water resources also are treated as an economic good, and cost-efficiency principles are introduced also for managing the water resources, there is an interest to investigate possible changes in runoff due to a changed climate.

Runoff in Norway show large inter-annual and inter-regional variations. These variations can to a large extent be related to regional climate anomalies caused by variations in the pressure fields in the North-Atlantic region. Hanssen-Bauer & Førland (2000) showed that long-term variations in temperature and precipitation on decadal scale can be related to mean sea level pressure. The spatial distribution of both precipitation occurrence and amounts in Norway can also be explained by atmospheric circulation (Tveito, 2002). Tveito and Hisdal (1995) found significant relations between empirical orthogonal function of monthly pressure and precipitation observation series in Norway. Kiem at al. (2002) showed a clear link between ENSO (El Nino Southern Oscillation) modes and flood risk in New South Wales (Australia). Phillips et al. 2003 found significant coherence between runoff in two British catchments and several atmospheric circulation indices.

Large-scale climate modes are often described by atmospheric circulation indexes. The most known, SOI (Southern Oscillation Index) and NAOI (North Atlantic Oscillation Index) are simple pressure oscillations. The one most important for Northern Europe, the NAOI is described as the pressure difference between Iceland (Stykkisholmur) and the Azores (Ponta Delgada). Several authors have revealed significant links between NAOI and climate variables in the Scandinavian region (Chen and Hellström 1999, Bleckner and Chen, 2003, Uvo 2003). These simple pressure indices do not, however, take the tracks of the cyclones into consideration. Different directions of the airflow towards Northern Europe can e.g. result in similar NAOI-values. There is therefore a need to address other circulation indices that also take other characteristics of the atmospheric circulation into consideration. Yarnal (1993, 2001) and Tveito and Ustrnul (2003) discussed different approaches to characterize the atmospheric circulation. Traditional weather type classifications like the Grosswetterlagen of Hess and Brezowsky (1977) and the Lamb catalogue (Lamb, 1972) are not ideal for establishing relation with response variables like runoff since they only provides discrete weather types, and not continuous numeric circulation indices. One approach that has been frequently applied to identify patterns of spatio-temporal fields also within climatology, is the method of empirical orthogonal functions (EOF) also known as principal component analysis. This approach provides both circulation patterns as well as circulation indices.

The objective of this study has been to identify possible links between large-scale atmospheric circulation and runoff anomalies in Norway. The motivation is to address future runoff-anomalies based on future changes in atmospheric circulation, and assess climate change impacts on flood- and drought conditions in Norway.

Data & methods.

Runoff data

The runoff of Norway shows regional variations due to different physiographical and climatological characteristics. Studies of long-term runoff series have shown that Norway can be divided into thirteen homogenous runoff regions (Roald, 2005). In this study regional index series for twelve (region 1 through 12) of these regions are applied. For region 13 there are no sufficient homogenous runoff records to establish a high-quality index series. The regions are shown in Figure 1. The series cover different time periods due to the available runoff record. In this study the period 1901-2000 is analysed. In the three northernmost regions the runoff observation network was established in the beginning of the 20th century, so for the regions 10, 11 and 12 the index series starts in 1908, 1909 and 1912 respectively.

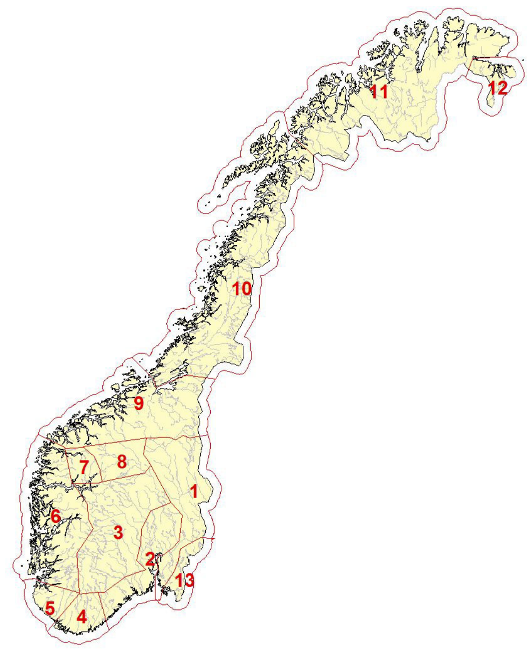

Figure 1. The Norwegian homogenous runoff regions.

Pressure data and circulation patterns.

Two pressure data sets are used in this study. The main data set is the well known Grid-Point Pressure Data for the Northern Hemisphere (Jones, 1987) provided by the CRU at East Anglia University (http://www.cru.uea.ac.uk). This gridded dataset of monthly mean sea level pressure (MSLP) has a spatial resolution of 5° in latitude by 10° in longitude. It covers the period 1873 to 2000, but in this analysis only the period 1901-2000 is applied. The other dataset is the NAO-data (Hurrel, 1995), also provided by the CRU-website.

The circulation patterns are derived by principal component analysis. Principal components are established for two different domains (Figure 2). Domain 1 covers the North Atlantic region from 60°W to 40°E and 30-80°N. Domain 2 is extended to the 100 °E. The data coverage in the former Soviet territory have large gaps during both during the Russian revolution and following civil war (1917-1921) and World War II. The analysis for this larger domain is therefore restricted to the shorter time period 1946-2000.

A principal component analysis (PCA) results in mathematically derived functions describing the variance of the data set in an efficient way. In a PCA of geographically distributed time series, the two functions can be regarded as spatial and temporal components respectively. Both the spatial and temporal components are mutually uncorrelated (orthogonal), meaning that different components do not explain the same portion of the variance. The components are derived so that most variance is explained by the first component, second most by the second component and so on. Adding all components for a given time will return the observed field. In most cases a few of the principal components will explain most of the total variance (see Table 2). The first components will explain the main variations common to the whole domain, and in the case of pressure the most prominent large scale circulation type. Lower ranked components will consist of perturbations around these large scale patterns, and the scale of these perturbations will be smaller and smaller. The lowest ranked components will in principle contain only noise signals.

The spatial components of a PCA on air pressure will describe circulation patterns, while the connected temporal components will represent the intensity of the patterns, and can therefore be regarded as circulation indices. An example is given in Figure 3. It shows the first component for autumn, and is a quite typical pattern for domain 1. In this area the most prominent circulation pattern is connected to the NAOI, and therefore reflects the westerly airflow over the North-Atlantic. In this case the low-pressure centre is located in the Norwegian Sea, instead of near Iceland. The temporal component describes how the magnitude of this circulation pattern varies in time.

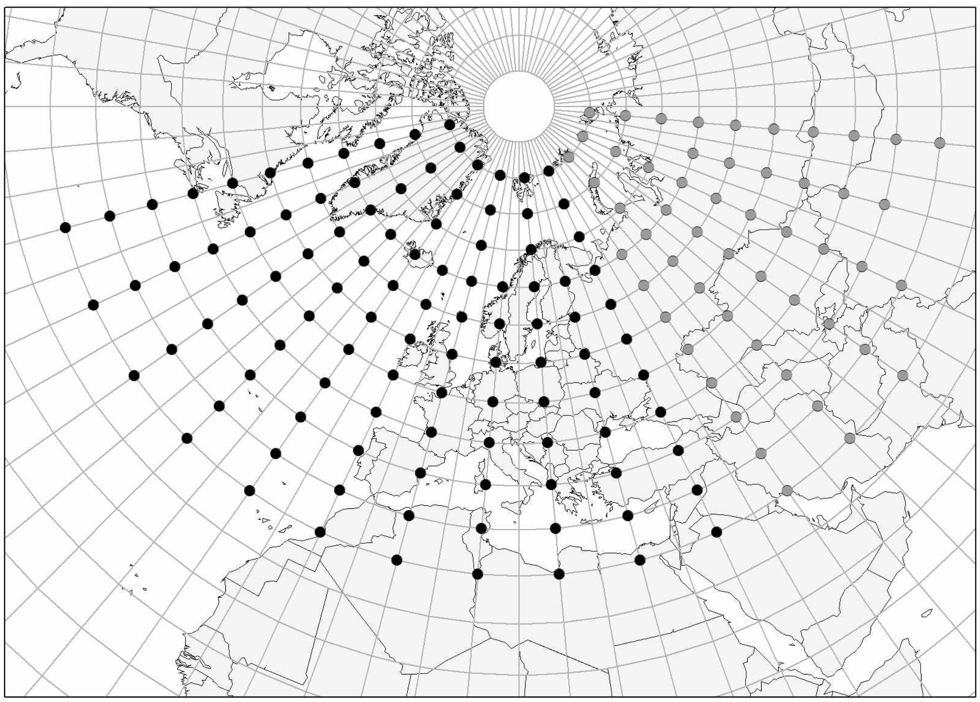

Figure 2. Pressure dataset grid-points used. Black points describes domain 1, while all the points (grey and black) describes domain 2.

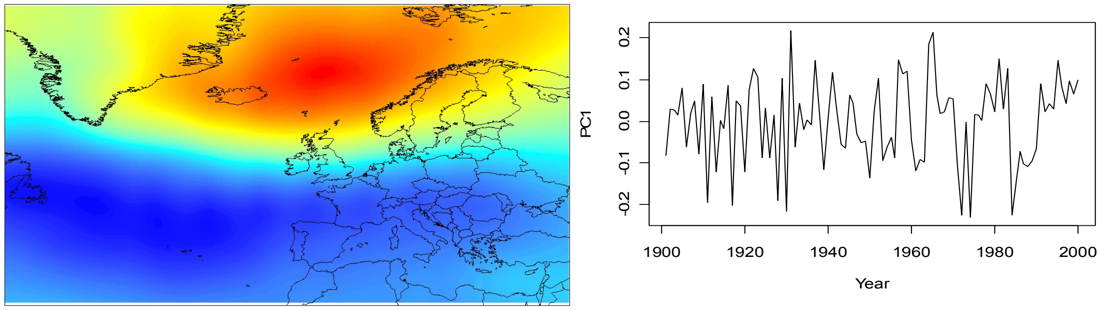

Figure 3. Circulation pattern (PC1) and the connected circulation indices for autumn (SON) 1901-2000 (domain 1).

Anlysis of large scale atmospheric circulation

Circulation patterns domain 1, 1901-2000

Tables showing the variance covered by the principal components (Table 1 and 2) reveal seasonal variations. In the winter season the first component is very strong, explaining almost half the variance, and almost three times as much as the second component. This indicates that the pattern of the first component represents stable and dominant patterns from year to year. This is not indicating that there are no variations in the intensity of this pattern only that it is dominating over other patterns. To the contrary autumn shows little difference in explanation between the first three components, implying that all these patterns are almost equally significant and thereby varies to be the dominant.

The North Atlantic Oscillation Index (NAOI) is regarded as a good descriptor for climate variations in Europe, and the patterns of PC1 for all seasons reflects similar features as the NAOI (Table 3). It is worth noticing the location of the northern anomaly in PC1, which is located north of Iceland for all seasons except autumn where it is located in the Norwegian Sea.

Figure 4a shows the circulation patterns described by the first four PCs for spring 1901-2000. The first pattern shows the ideal westerly flow, which in principle reflects the NAOI. This temporal component of this pattern has a correlation with NAOI like 0.67 (Table 3). The second component shows a pressure anomaly over Fennoscandia, with an opposite anomaly in the North-Atlantic. This pattern is often referred to as the Scandinavian pattern. It reflects the often persistent high pressure centre that occurs regularly over Eastern Fennoscandia, a typical blocking situation.

The third component contains pressure anomalies east of Newfoundland and over the British Isles and the North-Sea. The pressure anomaly near the British Isles is also called the east Atlantic pattern. The fourth component shows features opposite of the second component, with a long-stretched pressure anomaly in north-easterly direction.

Table 1: Proportion of variance of the principal components of domain 1 1901-2000:

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.386	0.172	0.118	0.097	0.056	0.032	0.026	0.021	0.019	0.010
Summer	0.366	0.166	0.113	0.081	0.053	0.037	0.028	0.027	0.017	0.015
Autumn	0.278	0.217	0.168	0.082	0.056	0.036	0.030	0.024	0.019	0.011
Winter	0.477	0.165	0.135	0.076	0.033	0.021	0.017	0.014	0.012	0.009

Table 2: Cumulative variance of the principal components of domain 1 1901-2000:

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.386	0.558	0.676	0.773	0.829	0.862	0.888	0.909	0.927	0.937
Summer	0.366	0.531	0.645	0.726	0.779	0.816	0.844	0.871	0.888	0.904
Autumn	0.278	0.495	0.663	0.745	0.800	0.836	0.866	0.891	0.910	0.921
Winter	0.477	0.642	0.777	0.853	0.886	0.907	0.924	0.938	0.950	0.959

Table 3: Correlation between domain 1 principal components and NAOI 1901-2000.

	Spring	Summer	Autumn	Winter
PC1	0.6685	0.3195	0.7520	0.8495
PC2	0.0891	0.4930	0.1998	-0.3785
PC3	0.0598	-0.1349	-0.1316	0.0974
PC4	-0.4621	0.0339	0.3714	0.0929
PC5	0.2031	0.1358	0.0658	0.0816
PC6	-0.2631	-0.3071	-0.2261	-0.2261
PC7	0.1113	0.1494	0.0624	-0.0217
PC8	0.0870	-0.2732	-0.0124	-0.0279
PC9	-0.0250	-0.0684	0.1062	0.0279
PC10	-0.1550	0.0191	0.0262	-0.0942

Figure 4b shows the temporal component of the PCs. It shows large year-to-year variations of the components. They also show trend tendencies. For example there is a positive trend in PC1 for the period 1950-1990. PC2 have a decreasing trend throughout the entire century, while PC4 has a positive trend. In PC3 there is a negative trend in the first half of the series and a positive trend afterwards.

In summer (Figure 5a) the first component shows a pattern where the cyclones moves more in a northeasterly directions than for the other seasons. The second component has the highest correlation with NAOI. The northern pressure anomaly is positioned in the Norwegian Sea just north of the Shetland and Faeroe Islands. This pattern will cause a westerly airflow towards central Europe. The PC3 pattern shows pressure opposite anomalies in the north-Atlantic and over the Kola Peninsula. The most significant pattern of the fourth component is the East Atlantic pressure anomaly. All temporal components show trend tendencies, except the third (Figure 5b). The first component has a positive trend, especially in the first part of the series, while the second and fourth show negative trends.

The patterns of the three first components for autumn (Figure 6a) are the ones having most equal significance (Table 1). PC1 reflects the NAO-pattern, PC2 the Scandinavian pattern, PC3 the British Isles anomaly and PC4 pressure anomalies in the north Atlantic and over central Europe. These patterns show some short term trends, like a weak positive trend in PC1 the first decades and in PC2 since 1970. In PC4 there seem to be a shift in the series around 1930 (Figure 6b).

PC1 accounts for nearly half the variance (47.7%) in the winter season. Figure 7a shows that it describes a pattern similar to NAO (correlation 0.85). The intensity of this pattern shows a weak negative trend until around 1970. In the period 1970-mid 1990s it shows a distinct positive trend. The second component reflects the British Isles pressure anomaly and the third an anomaly over southern Scandinavia. The fourth component is a four-pole pattern with negative anomalies over the North-Atlantic and Russia, and complementary positive anomalies over central Europe and north-west of Iceland. There are no clear trends in these last three components (Figure 7b).

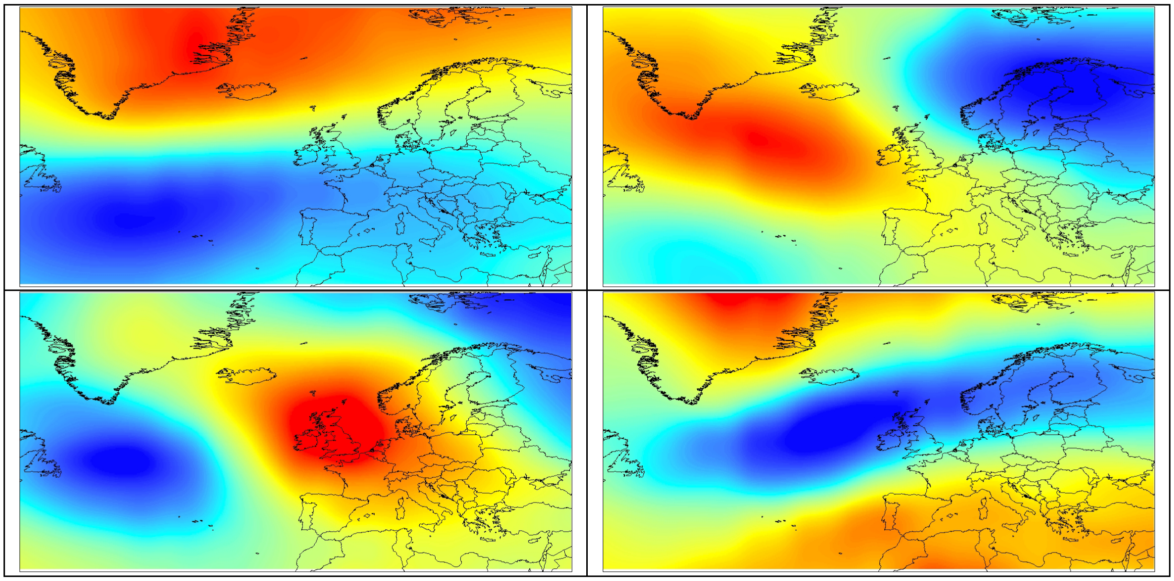

Figure 4a. Principal component patterns of domain 1, 1901-2000, spring.

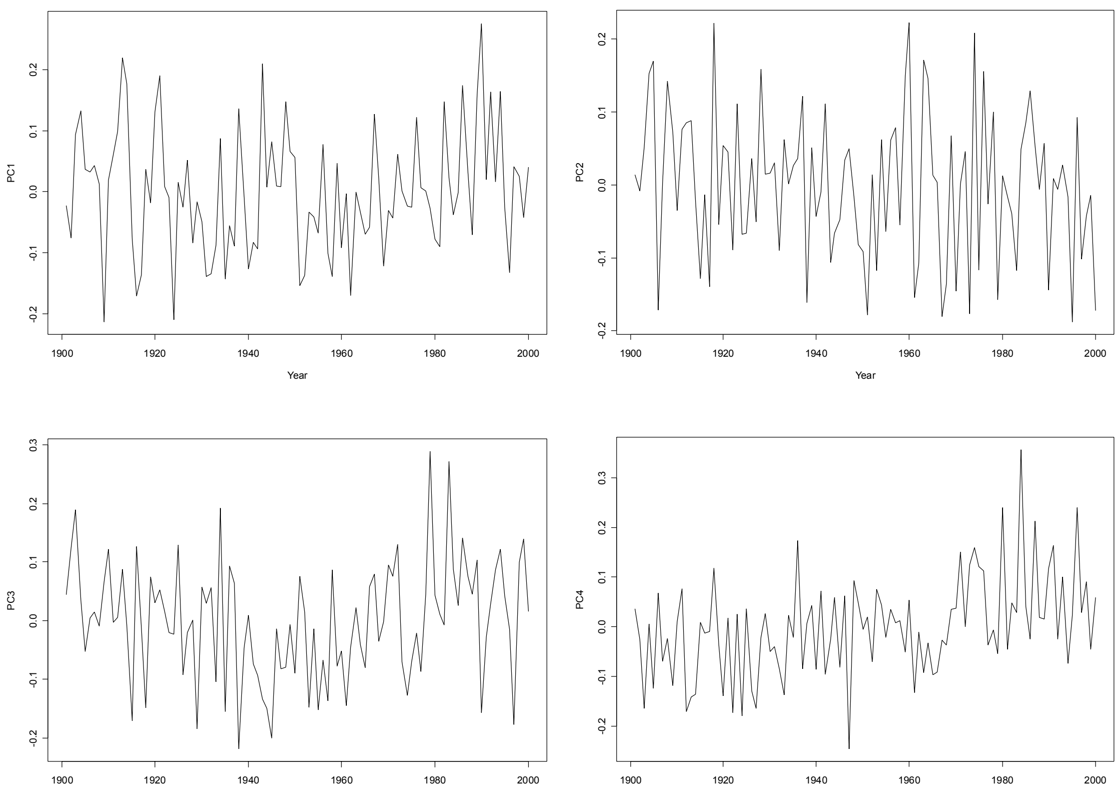

Figure 4b. Temporal variations of the components, spring, domain 1 1901-2000.

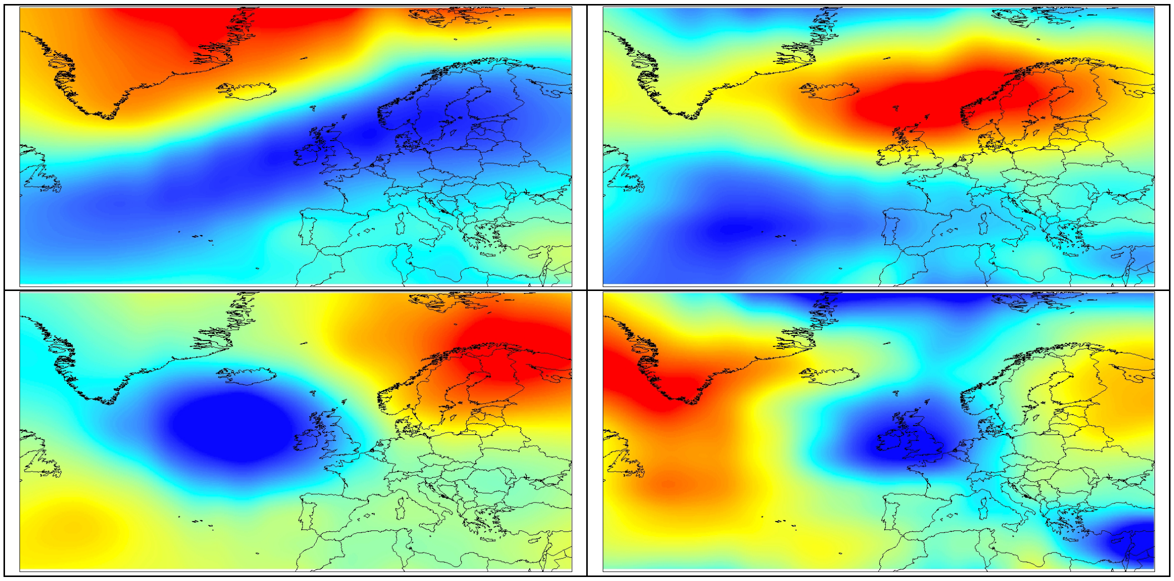

Figure 5a. Principal component patterns of domain 1, 1901-2000, summer.

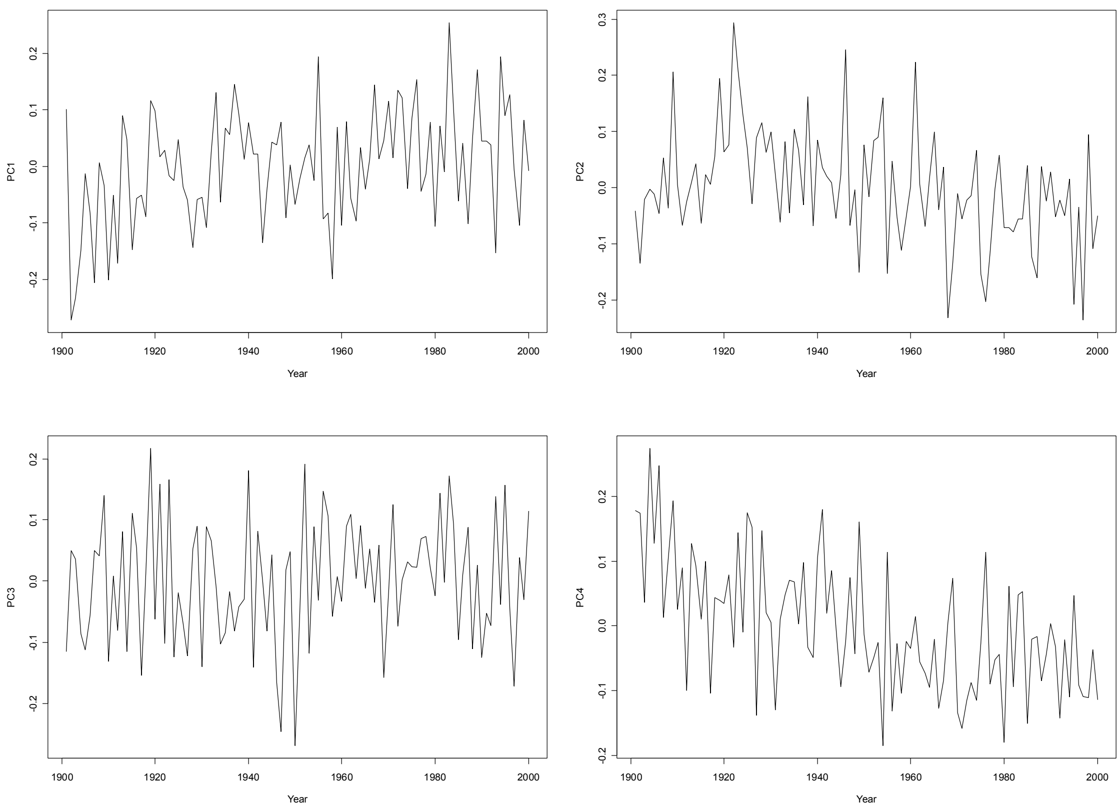

Figure 5b. Temporal variations domain 1 summer.

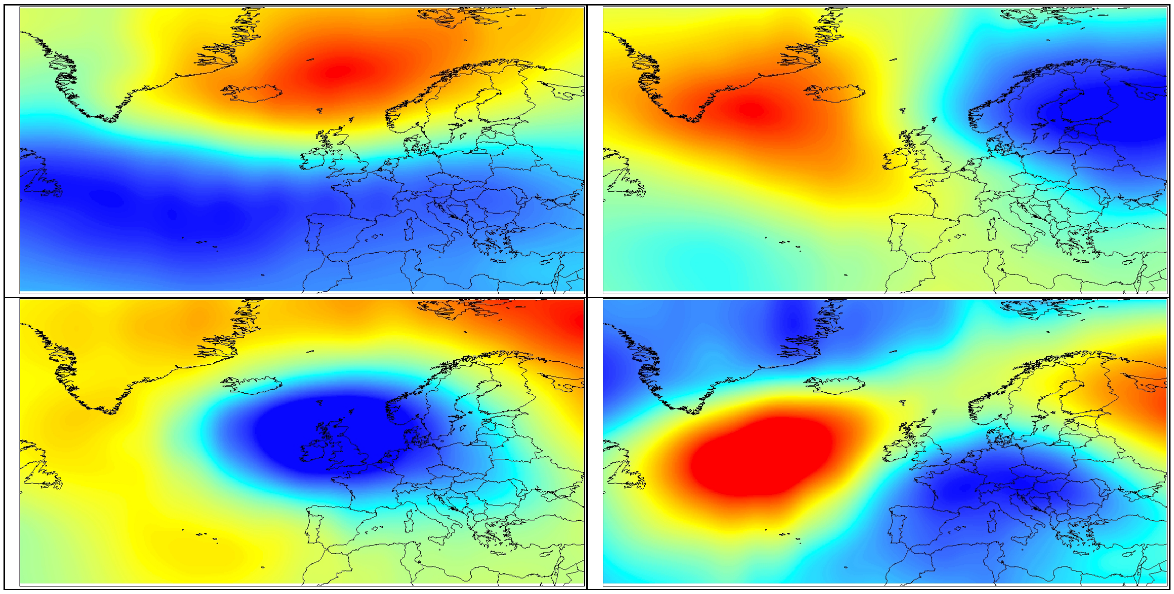

Figure 6a. Principal component patterns of domain 1, 1901-2000, autumn.

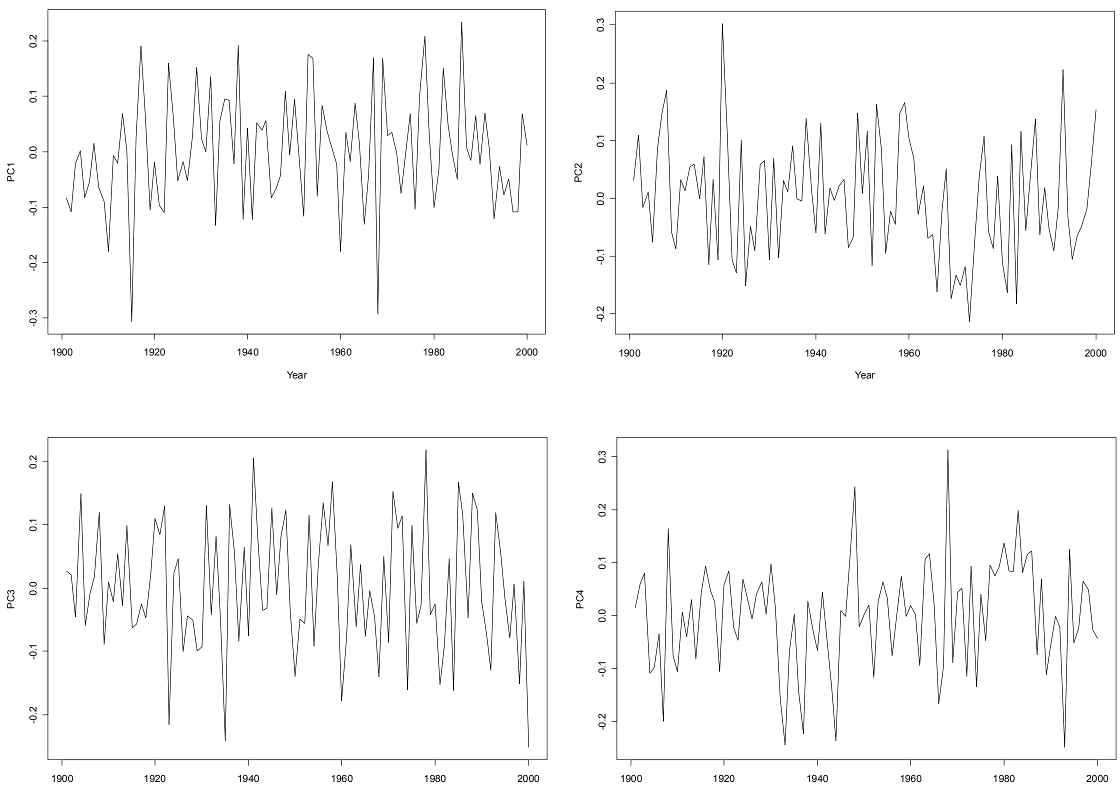

Figure 6b Temporal variations domain 1 autumn, 1901-2000.

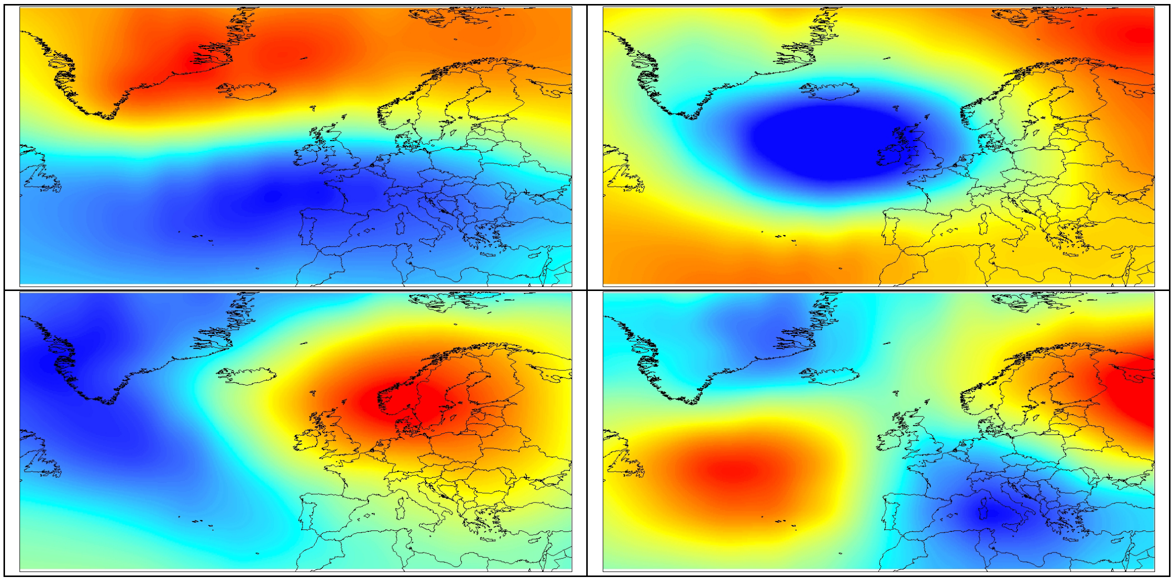

Figure 7a. Principal component patterns of domain 1, 1901-2000, winter.

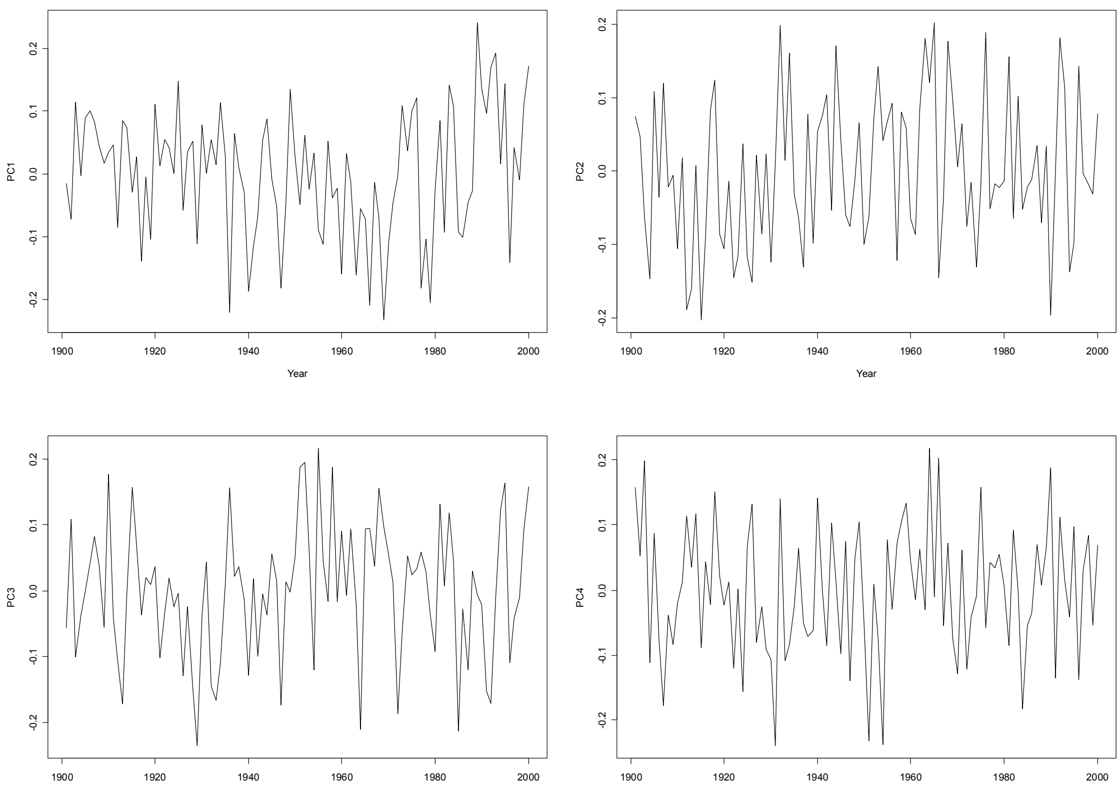

Figure 7b. Temporal variations domain 1 winter, 1901-2000.

Circulation patterns domain 1, 1946-2000.

Domain 1 is also analysed with respect to the shorter period 1946-2000 in order to compare results between to the circulation patterns of both pressure domains. In this section the components of the short period is compared to the components covering the whole century.

Table 4 shows the variance contribution of each of the PCs. The variance contribution of the components is similar for the two periods. The winter season PC1 shows 5% higher explanation for the short period, indicating that this pattern was more pronounced for the latter half of last century as for the century as whole.

Table 5 shows the correlations between the PCs and NAOI. For all seasons except winter the correlations for PC1 are highest for the long period. In the winter season the correlation coefficients are almost similar and very high for both analyses.

Table 4. Variance contribution of the principal components for domain 1 1946-2000.

a) Proportional variance

Season	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.346	0.205	0.125	0.109	0.047	0.034	0.027	0.023	0.016	0.011
Summer	0.368	0.188	0.119	0.067	0.056	0.038	0.031	0.022	0.019	0.015
Autumn	0.306	0.244	0.140	0.084	0.050	0.036	0.025	0.022	0.014	0.012
Winter	0.529	0.144	0.129	0.066	0.032	0.020	0.016	0.012	0.009	0.008

b) Cumulative variance

Season	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.346	0.550	0.675	0.784	0.832	0.866	0.893	0.915	0.931	0.941
Summer	0.368	0.556	0.675	0.741	0.797	0.835	0.866	0.888	0.906	0.921
Autumn	0.306	0.550	0.690	0.774	0.824	0.860	0.885	0.907	0.920	0.932
Winter	0.529	0.674	0.802	0.868	0.900	0.919	0.936	0.948	0.958	0.965

Table 5. Correlations between domain 1 principal components and the NAOI for the period 1946-2000.

	Spring	Summer	Autumn	Winter
PC1	-0.5393	-0.1833	0.5563	0.8645
PC2	0.1877	-0.6394	0.4154	-0.1537
PC3	-0.1429	0.1290	0.3472	0.3253
PC4	-0.5140	0.0318	0.4203	-0.0740
PC5	*0.3743*	*0.0055*	*0.2935*	*0.0333*
PC6	*-0.3036*	*0.4319*	*0.0577*	*-0.1563*
PC7	*0.1105*	*-0.1020*	*-0.0349*	*-0.1473*
PC8	*0.1512*	*0.0864*	*0.0389*	*0.0192*
PC9	*0.1315*	*-0.0809*	*-0.1554*	*-0.1829*
PC10	*-0.1136*	*-0.0986*	*0.1567*	*0.0235*

Figure 8a shows the results for spring. The patterns obtained show the same features as for the longer period. In the time series, only the third component shows a temporal positive trend (Figure 8b). One interesting feature is found in PC4, which shows low intensity for several consecutive years in the 1960s. The same feature is also found in the component for the longer period.

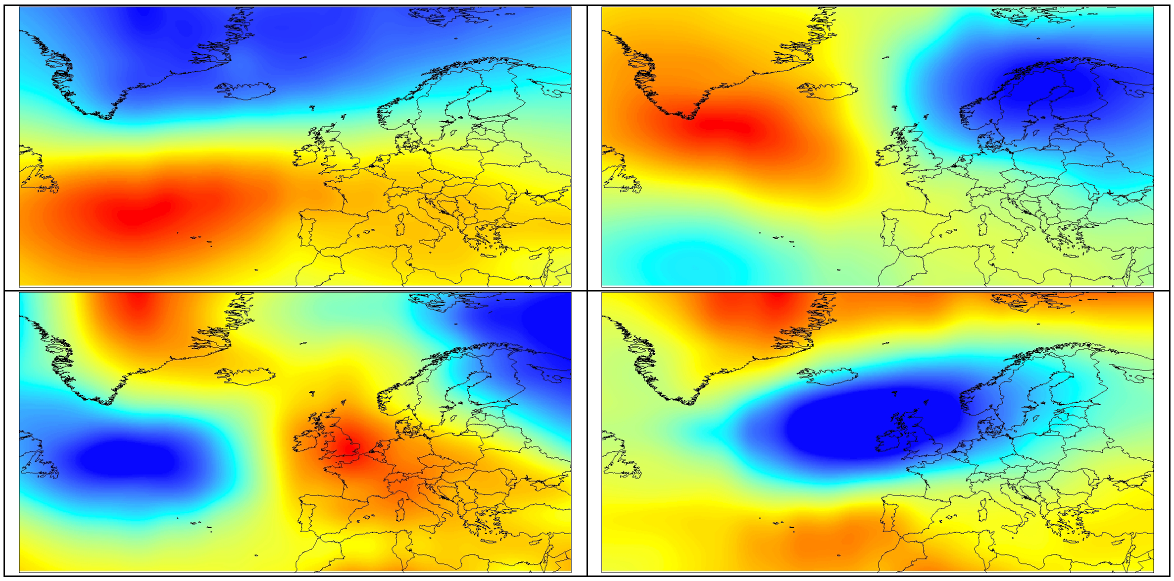

Figure 8a. Principal component patterns of domain 1946-2000, spring.

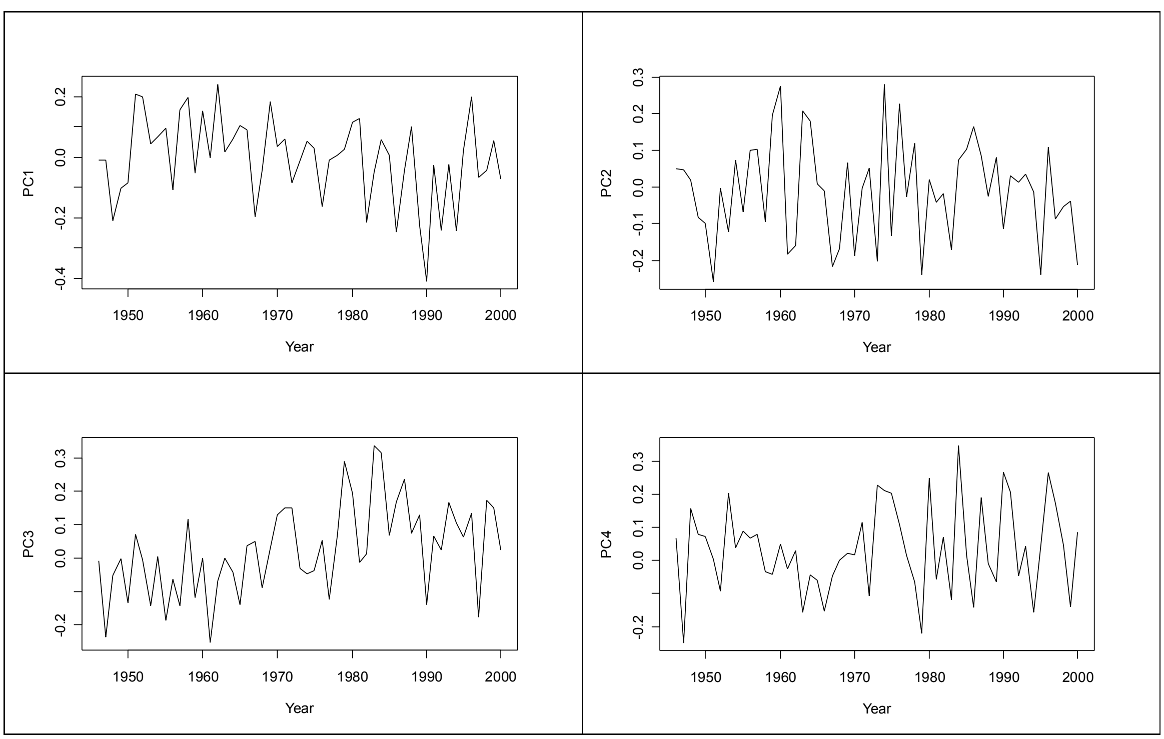

Figure 8b. Temporal components of domain 1 1946-2000, spring.

For the summer season (Figure 9a), the order of patterns related to PC1 and PC2 are shifted between the periods. Otherwise the patterns are similar. PC1 shows a negative trend in the 1960s, as does the fourth (Figure 9b).

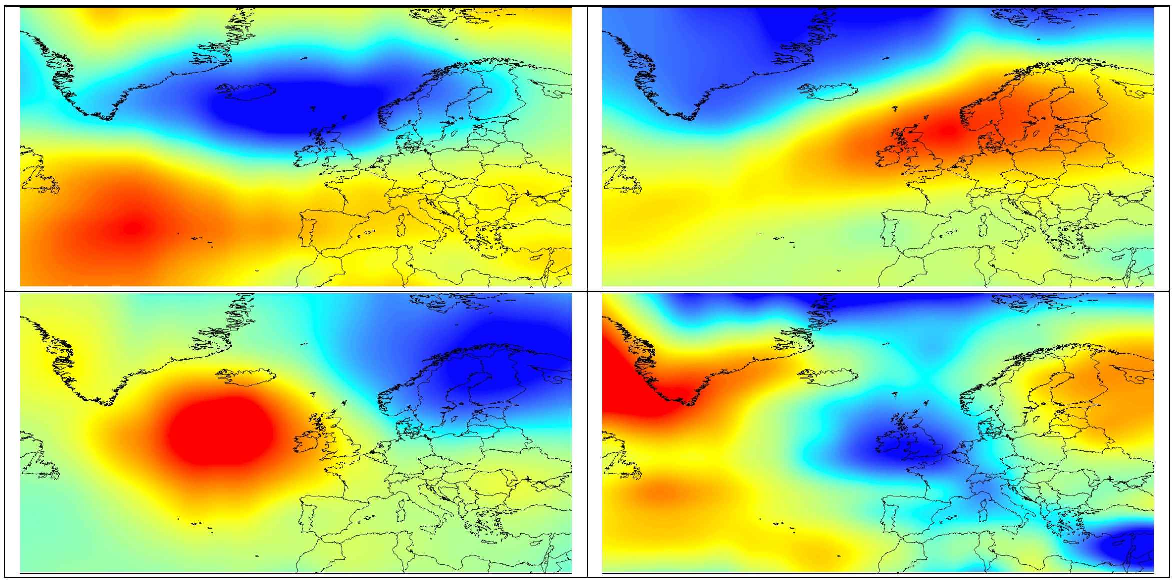

Figure 9a. Principal component patterns of domain 1946-2000, Summer

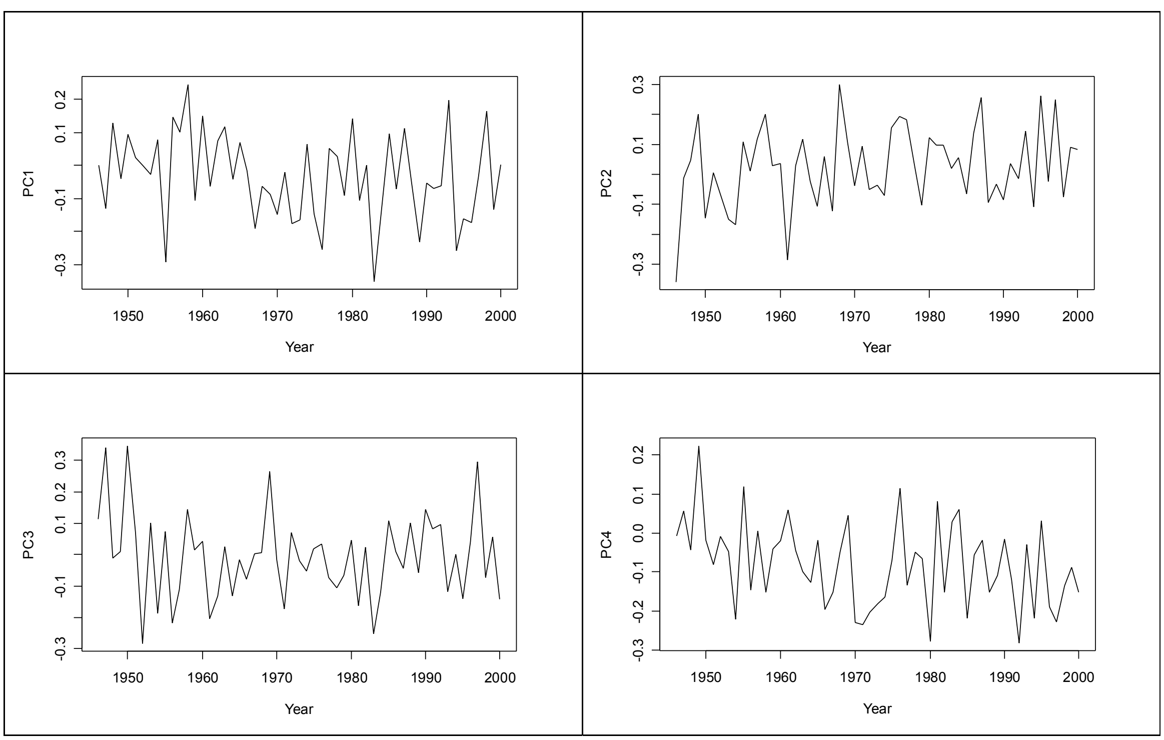

Figure 9b. Temporal components of domain 1 1946-2000, Summer

In autumn the first components were showing almost equal explanation for the long period. The PCs for this shorter period show the same pattern (Figure10a). The two first patterns explain more of the variance (Table 3). There are no clear trends, except for PC2 showing a negative trend in the first half of the series, and positive trend in the last half (Figure 10b).

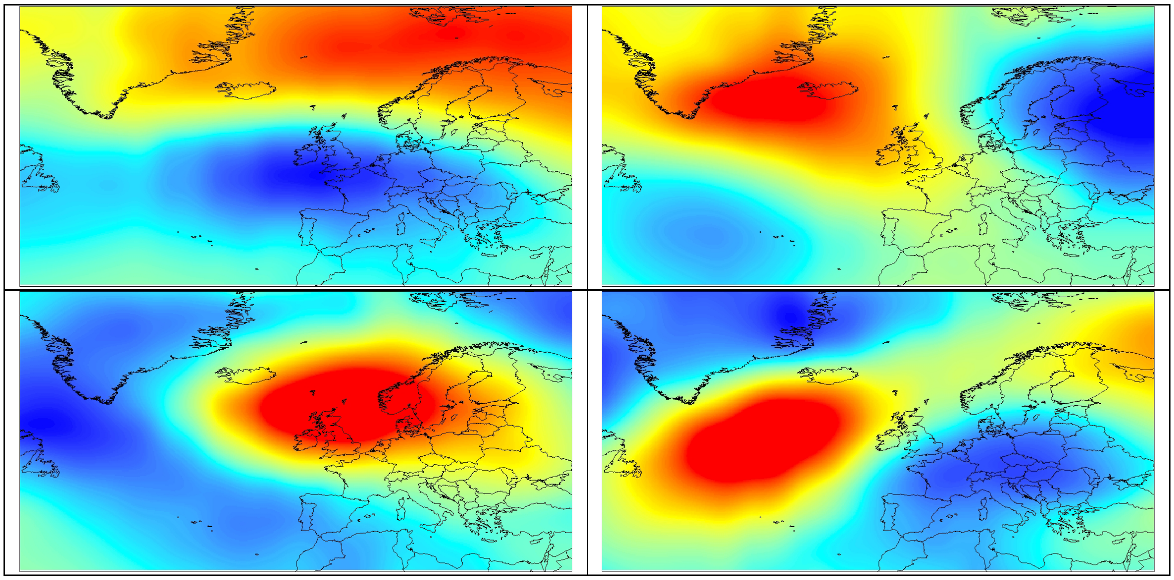

Figure 10a. Principal component patterns of domain 1946-2000, Autumn

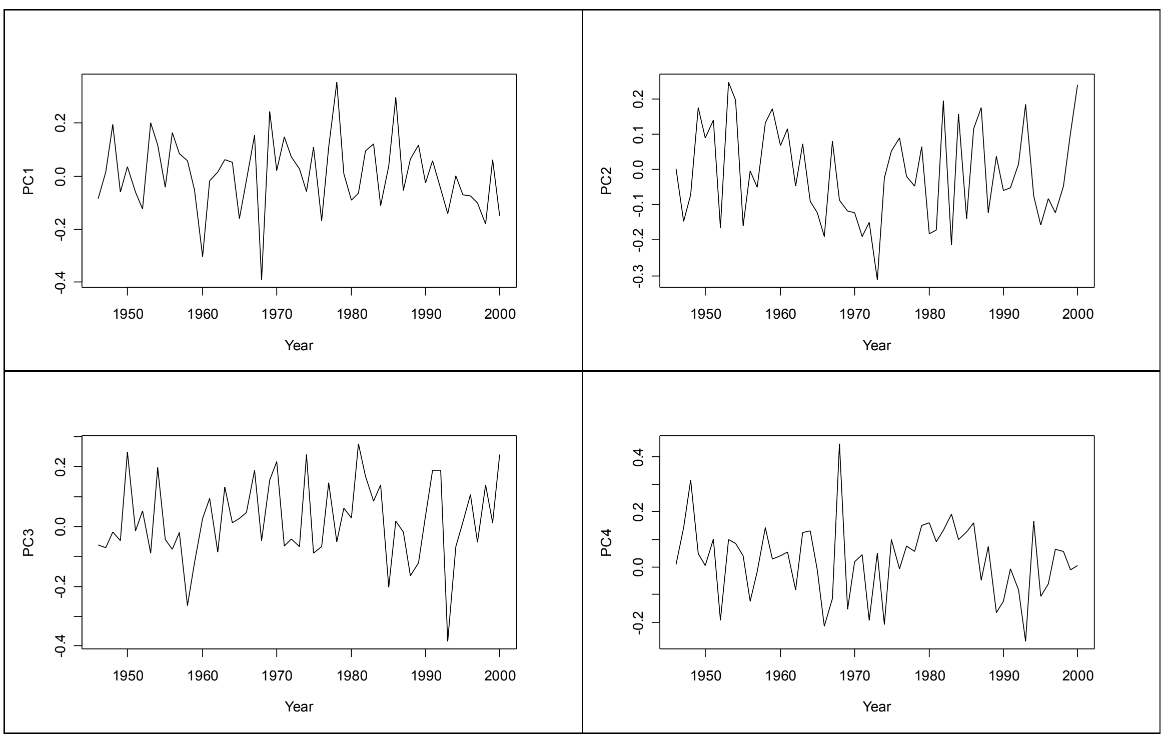

Figure 10b. Temporal components of domain 1 1946-2000, Autumn

The winter patterns (Figure 11a) are also similar to those for the longer period. It seems though that the anomalies in PC2 and PC3 are shifted westwards. PC1 shows a strong positive trend, especially for the last 30 years. The same trend is found in the series of the longer period (Figure 11b).

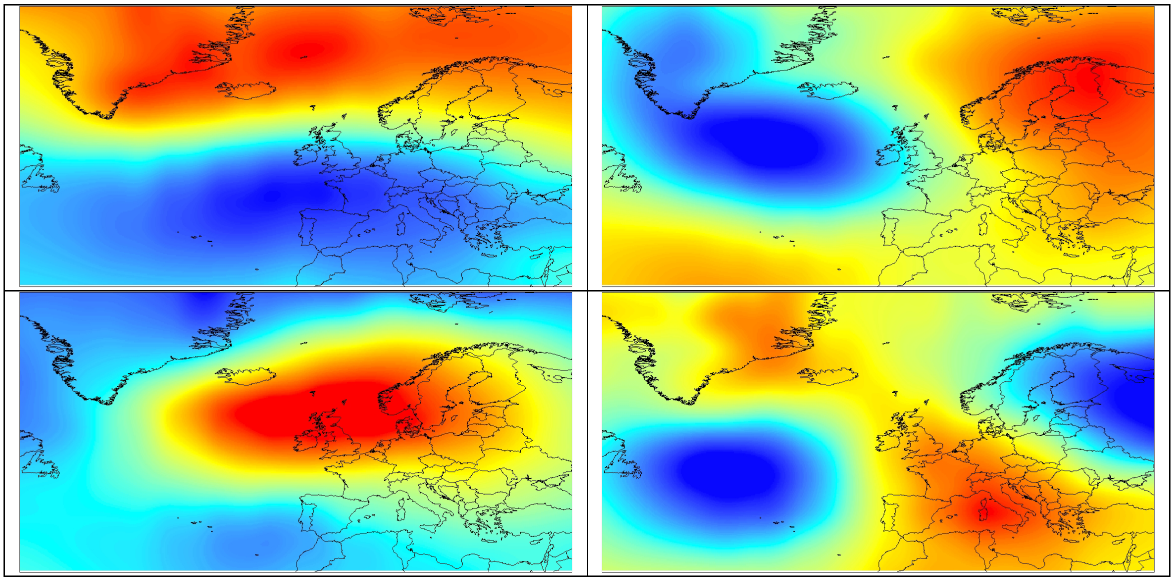

Figure11a. Principal component patterns of domain 1946-2000, Winter

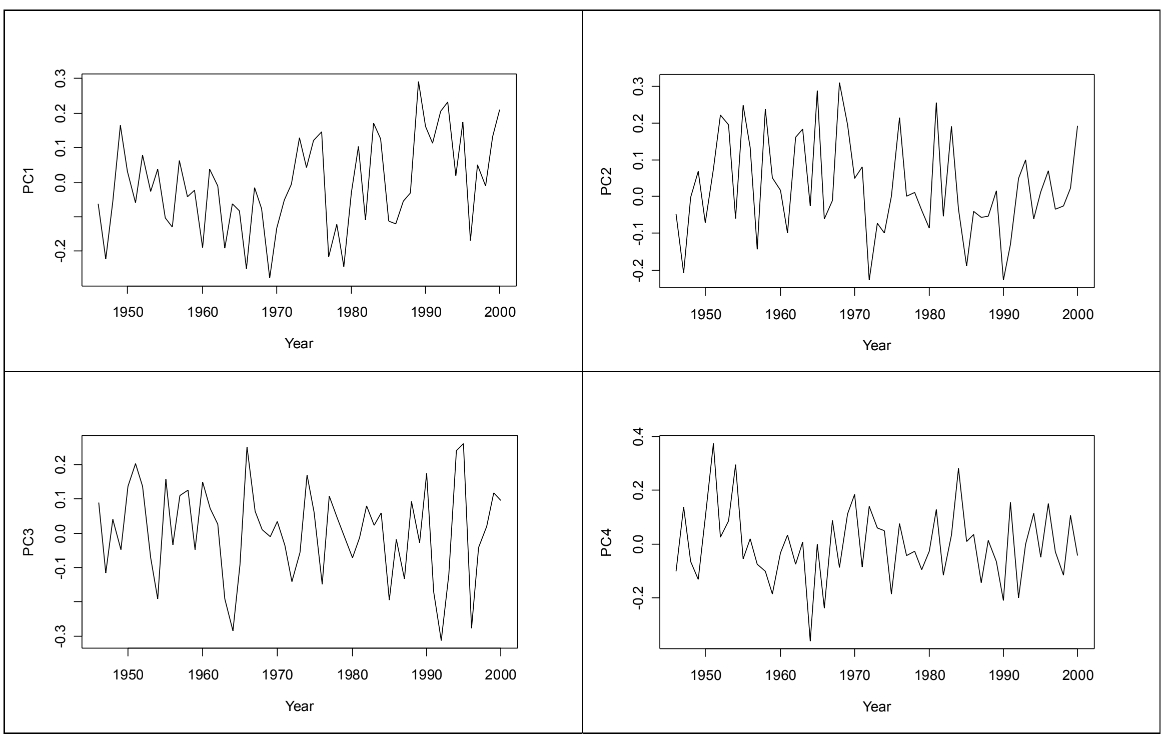

Figure 11b. Temporal components of domain 1 1946-2000, Winter.

Circulation patterns domain 2, 1946-2000.

The circulation patterns for the second domain cover a larger area, including large parts of Russia and central Asia. The variance contribution of the components is shown in Table 6. For all seasons except winter, the first component accounts for slightly less that 1/3 of the total variance. This is less than for the smaller domain in the same period (Table 7). This is expected since a larger area will contain more variability, and consequently less variance will be covered by each component. (The total number of components will also increase) In the winter season the first component covers 46% of the variance, indicating that the circulation in the winter season is mainly influenced by the same pattern from year to year.

Table 6 Variance contribution of the principal components for domain 2 1946-2000.

a) Proportional variance

Season	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.299	0.191	0.127	0.081	0.064	0.042	0.037	0.023	0.019	0.016
Summer	0.290	0.145	0.096	0.082	0.066	0.050	0.041	0.034	0.024	0.020
Autumn	0.287	0.185	0.136	0.078	0.060	0.050	0.037	0.025	0.023	0.019
Winter	0.463	0.134	0.116	0.074	0.052	0.043	0.025	0.016	0.014	0.009

b) Cumulative variance

Season	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
Spring	0.299	0.490	0.618	0.699	0.762	0.804	0.841	0.864	0.883	0.899
Summer	0.290	0.435	0.530	0.612	0.678	0.728	0.769	0.803	0.827	0.847
Autumn	0.287	0.473	0.609	0.687	0.747	0.797	0.834	0.859	0.881	0.899
Winter	0.463	0.597	0.713	0.787	0.840	0.883	0.907	0.923	0.937	0.946

Table 7 Correlation between domain 2 principal components and the NAOI for the period 1946-2000.

	Spring	Summer	Autumn	Winter
PC1	-0.4125	-0.1543	0.2477	0.7937
PC2	-0.3360	-0.6765	-0.6351	-0.4729
PC3	0.0742	0.0211	0.2308	0.0892
PC4	-0.5499	-0.0965	0.2070	-0.0976
PC5	0.3123	-0.0249	-0.4977	-0.0283
PC6	-0.2109	0.0857	0.0647	0.0893
PC7	0.1445	0.0004	-0.0283	0.0785
PC8	0.0887	0.3194	-0.1029	-0.0198
PC9	-0.2827	-0.0541	0.2466	0.2571
PC10	-0.0757	-0.1255	-0.0276	0.0575

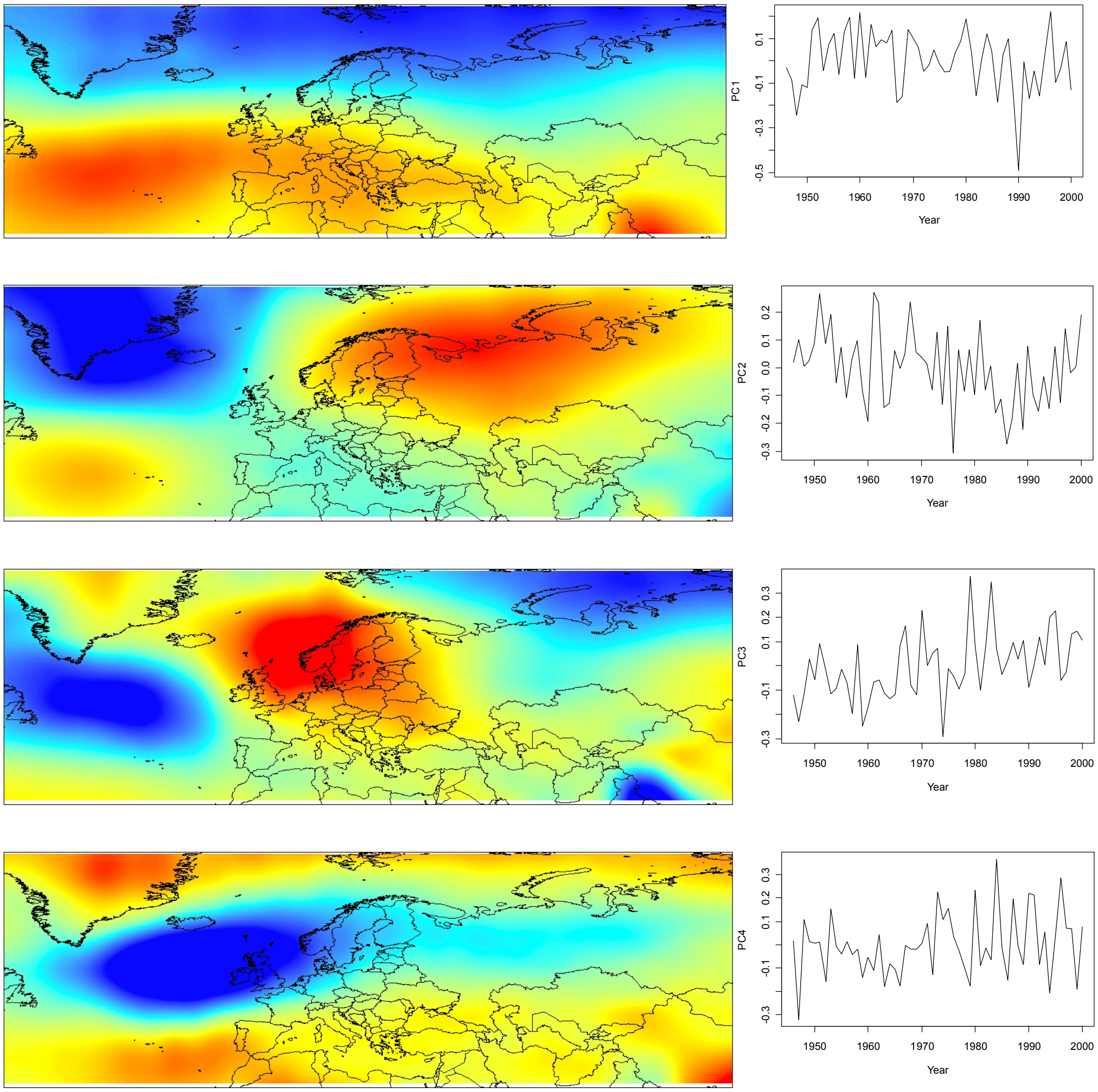

Figure 12. Principal component patterns and temporal variations domain 2 1946-2000, spring.

In the spring season the first component shows a typical NAO pattern (Figure 12). The correlation is however only -0.41, indicating that there are other patterns that also reflect the westerly airflow. Both component 2 and 4 have correlations with NAOI above 0.3. The second component shows a positive anomaly over Iceland, a negative anomaly over northern Russia and a weak negative anomaly west of the Azores. The patterns are similar to the PC patterns of domain 1, but the anomaly over Greenland/Iceland is more shifted to northwest for domain 2. The third component is characterized by anomalies west of the British Isles and in the North-Atlantic between the Azores and Iceland. There is also an anomaly east of Novaya Zemlya. Regarding trends there is a weak negative trend in the first component, except for the last decade. In the second component there is a decrease until the mid-80s and a strong positive trend after that. The third component is increasing throughout the period. PC4 shows a weak positive trend.

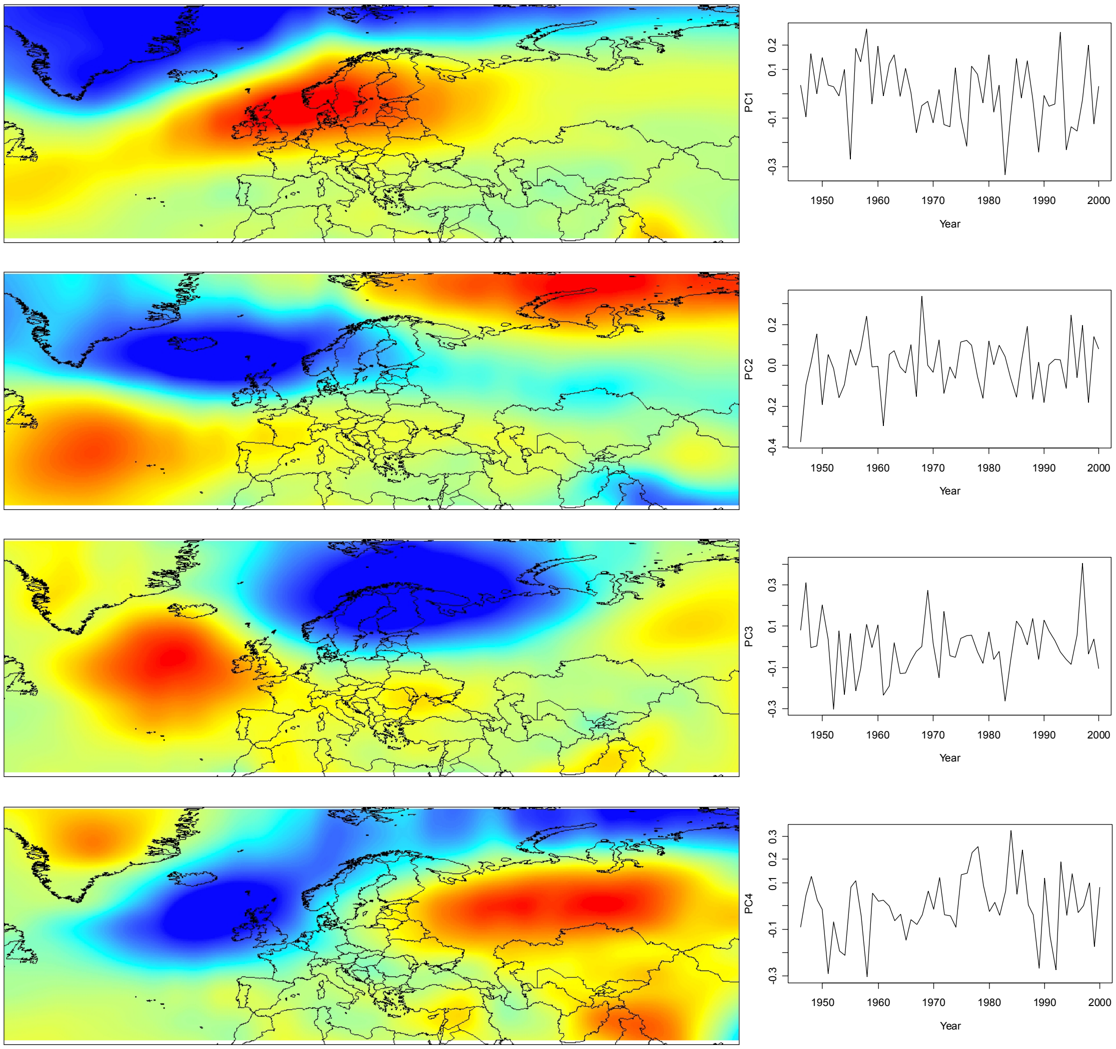

Figure 13. Principal component patterns and temporal variations domain 2 1946-2000, summer.

The PC1 patterns for summer (Figure 13) are similar to the patterns of PC2 of domain 1, showing anomalies over the North Sea and Greenland. The second component is highly correlated to NAOI, and shows the NAO-pattern. It also shows a pressure anomaly in northern Siberia. The third component shows similar characteristics as for the small domain, with anomalies on the North Atlantic and over the Kola-peninsula. Also PC4 reveals similar patterns as the small domain. As for spring the variance explained by the components is lower for this domain than for the smaller, due to the higher variance in the larger field. PC1 shows a negative trend until around 1970, and is stable since then. In the other PCs no trends are detected, except for the first few years of PC3.

For autumn (Figure 14) the northern anomaly in PC1 is shifted eastwards compared with the smaller domain. The second and third components are similar, while the fourth is shifted westwards, and seems weaker. In the latter a strong anomaly however occurs over central Russia. For the autumn components only the last 30 years of PC1 shows a distinct trend.

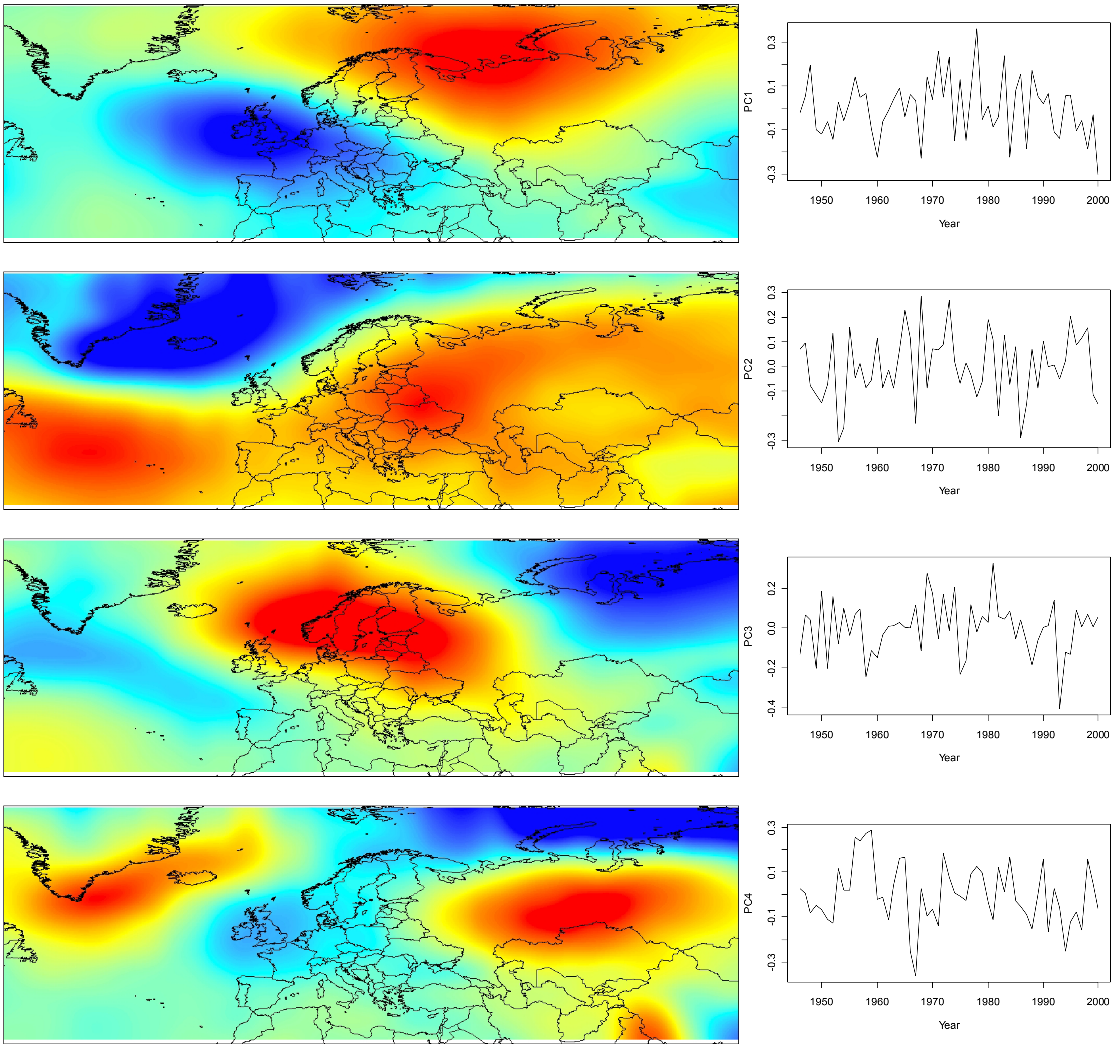

Figure 14. Principal component patterns and temporal variations domain 2 1946-2000, autumn

The first four winter components (Figure 15) for domain 2 are similar as for the same period of domain 1. There is a strong positive trend in PC1 since 1970, and also a decrease in PC3 until 1990. After that this component shows indications of a positive trend.

The analysis of two different pressure domains reveals that the general circulation to a large extent is controlled by the westerlies, which intensity often is expressed by the NAOI. This intensity shows however regional variations due perturbations in the planetary wave pattern. These anomalies are reflected in the PC-patterns.

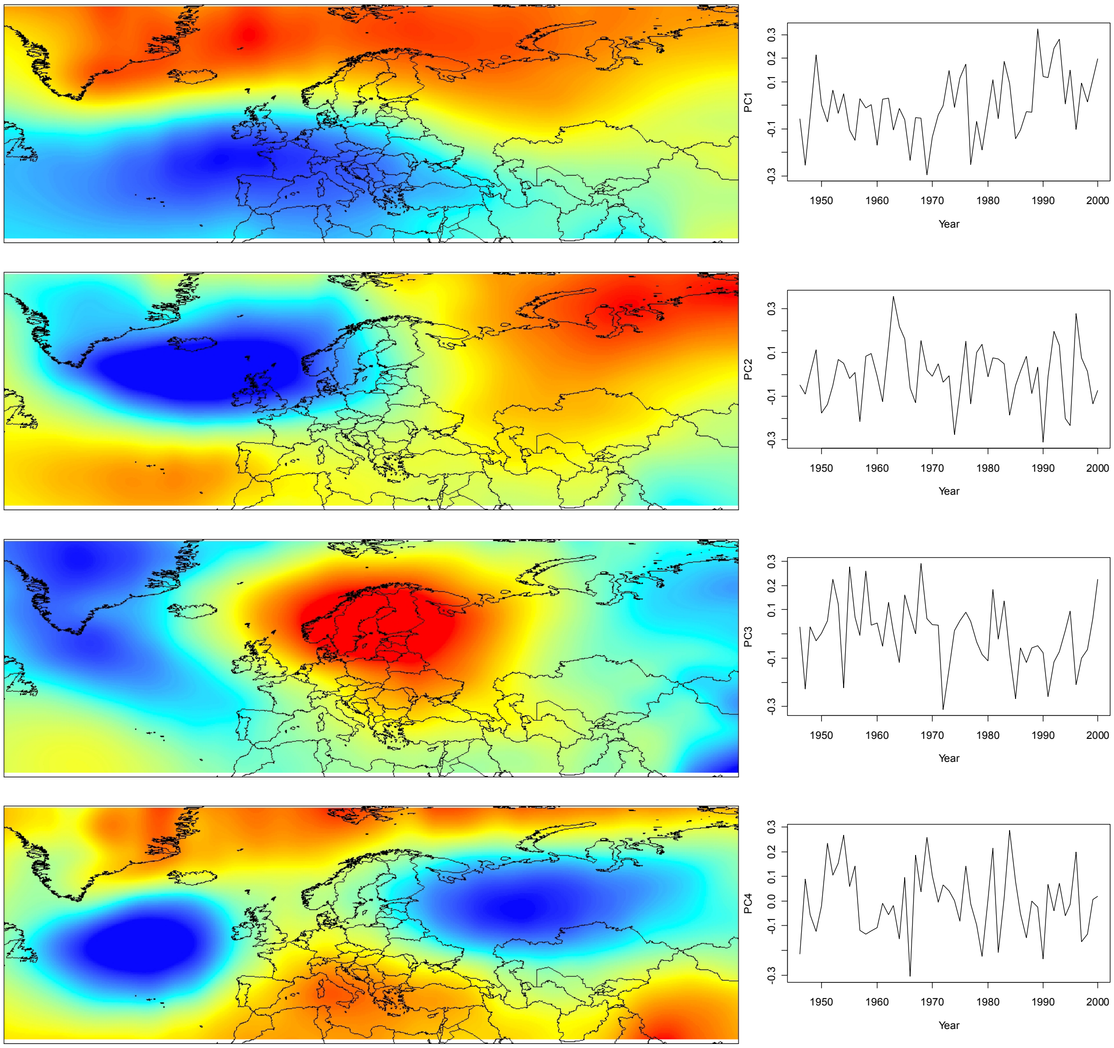

Figure 15. Principal component patterns and temporal variations domain 2 1946-2000, winter.

Relations between seasonal circulation patterns and regional runoff series.

The main objective of this analysis is to find possible links between atmospheric circulation and runoff., and therefore the temporal components of the PCs and the regional runoff series are compared. As a first approach the correlation coefficients between the PCs and the seasonal runoff series are analysed. As the second step, the regional runoff anomalies are estimated by a linear regression model, using the PCs as predictors. The motivation of such predictions is to investigate whether projections of circulation types from climate models can be used to predict future variations in runoff.

Relations between regional runoff and circulation patterns.

The temporal variations in runoff and circulation are related by a correlation analysis. Since the sign of the principal components are arbitrary, the forthcoming presentation of the correlation analysis will be associated with the absolute value of the correlation coefficient. If there are significant correlations with opposite signs, these will of course be discussed.

Domain 1, 1901-2000.

In the spring season the runoff in all regions have correlations with PC1 above 0.4 (Figure 16, Table 8), and in the western and southern regions (along the coast) correlations above 0.5. This is the snow melt season in inland and northern regions, so the runoff will be a result of snow melt intensity in this period related to temperature as well as the precipitation conditions in this season and the previous period with snow accumulation. The first component is highly correlated with the NAOI (0.67), which indicates mild and humid airflow towards Norway. The second component does not show particularly high correlations in any region. The correlations are however highest in the northern regions, associated with the high-pressure centre located in northern Fennoscandia. The third component can be associated with a pressure anomaly over the British Isles, which shows most correlation with the coastal regions, especially region 10 (Nordland). The fourth component shows weak correlations except for the small south-western region (region 5).

In the summer season (Figure 17, Table 9) the correlations between runoff and circulation are low. The opposite sign of the correlations in different parts of the country is typical. PC2 has an impact on region 5, while there is also a correlation of -0.4 between PC3 and the runoff in region 7. Summer is however a difficult season since it in many regions is a low-flow period. Drought events might also complicate the formation of good relations. In addition are the precipitation events usually scattered convective rain showers with high intensity, but with a small local extent.

In the autumn, river runoff generally depends upon larger scale precipitation activity. The first three PCs show high correlations to runoff in different region (Figure 18, Table 10). PC1, the NAO pattern, gives high correlations along the western coast. Also the south-eastern coastal region (region 2) has correlation coefficient higher than 0.5, and the southern region (region 4) is just below 0.5. The reason that also these regions have high correlation is the location of the negative pressure anomaly, which is located in the Norwegian Sea, which will cause south-westerly to southerly winds in this area. Correlations in the northern regions are low. The second component shows lower correlation values. The highest correlation is found for region 10, (r^2 = -0.35), associated with the pressure anomaly over Kola. Component three however is highly correlated with the northern regions (9, 10 and 11). This is the British Isles anomaly, which in positive phase gives westerly winds towards northern Norway. This component is also strongly negatively correlated with the south-eastern regions. This means that when this anomaly is in negative phase, south-eastern Norway gets it share of precipitation. This was the situation in November and December 2000, when this pattern was blocked for almost two months, giving very high amounts of precipitation in south-eastern Norway e.g. regions 3 and 4, and consequently high runoff values. From Figure 6b it can be seen that the lowest value of PC3 is found for just the 2000 season.

For the winter season correlations between PC1 and almost all regions are high (Figure 19, Table 11). Exceptions are regions 1, 3 and 12, which are the ones less affected by intensified westerly airflow. These are also the regions having the most stable runoff regime, usually with very low winter runoff. PC1 can be associated with the NAO, and high intensity of PC will result in mild and humid weather conditions in the winter season. This again will cause high winter runoff, especially in coastal and lowland areas. The second component can be related to runoff variations in the northern regions (regions 9-12), since this cause westerly/north-westerly airflow towards these regions. Component 3 is insignificant for runoff all over Norway in winter, while the fourth only shows weak correlations.

Domain 1, 1946-2000

For the shorter time period 1946-2000 the relations between domain 1 PCs and regional runoff are slightly changed as shown in Figures 20-23 and Tables 12-15. In spring the correlation between the first component and runoff for most regions is increased. The exception is the northern regions. The correlations with PC2 and PC3 are at the same time reduced. Correlations with PC4 in are increased, but the level of the values are still low.

In summer correlations between runoff and PC1 are higher than for the long period for almost all regions. The other PCs show similar features as for the long period.

For autumn the difference of the PC1 patterns for the two periods also gives changes in the correlations. While most of southern Norway shows relatively homogenous positive correlations for the long period, the shorter period gives a more scattered image. It seems also that the shift of the southern anomaly of PC1 “steal” some information from the other PCs compared to the long period.

Table 8. Correlations between regional runoff and principal components (domain 1 1901-2000) Spring

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.489	-0.137	0.025	-0.025	0.136	0.192	0.004	-0.044	-0.026	0.045
2	0.517	-0.167	-0.145	0.143	0.176	0.224	0.004	0.021	-0.012	0.055
3	0.416	-0.210	-0.062	0.088	0.191	0.088	0.005	-0.077	-0.066	0.003
4	0.592	-0.219	0.042	-0.199	0.095	0.001	-0.023	-0.051	0.094	-0.062
5	0.678	-0.364	-0.002	-0.205	0.160	0.035	0.037	0.103	0.107	0.151
6	0.643	-0.226	-0.154	0.012	0.220	0.104	0.128	0.025	0.064	0.108
7	0.610	-0.212	-0.217	0.046	0.230	0.134	0.124	0.057	0.036	0.120
8	0.551	-0.254	-0.232	0.062	0.201	0.119	0.209	0.116	0.146	0.154
9	0.456	-0.198	-0.406	0.100	0.165	0.104	0.152	0.122	0.005	0.136
10	0.441	-0.315	-0.414	0.092	0.238	0.055	0.178	0.172	0.052	0.121
11	0.487	-0.054	-0.299	0.136	0.269	0.132	0.030	0.134	0.026	0.066
12	0.405	0.192	0.095	0.044	0.263	0.015	-0.032	0.056	-0.019	-0.137

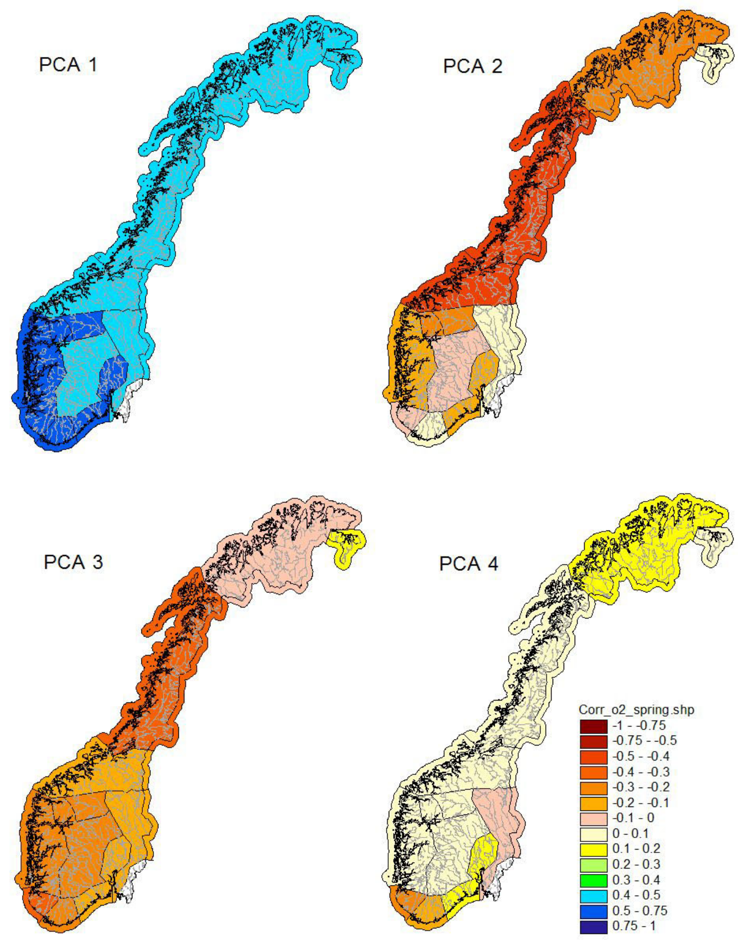

Figure 16. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in spring 1901-2000.

Table 9. Correlations between regional runoff and principal components (domain 1 1901-2000) Summer

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	-0.393	0.273	-0.081	-0.168	0.042	0.152	-0.183	-0.023	0.207	-0.125
2	-0.124	0.182	-0.195	-0.057	0.078	0.135	-0.134	0.019	-0.056	-0.165
3	-0.376	0.239	-0.260	-0.191	-0.107	0.211	-0.215	0.047	0.117	-0.176
4	-0.306	0.329	-0.340	-0.187	-0.026	0.197	-0.161	0.061	0.153	-0.124
5	0.068	0.496	-0.130	-0.157	0.186	0.044	-0.087	0.060	0.135	0.009
6	-0.011	0.168	0.086	0.132	0.345	-0.097	-0.063	0.167	-0.256	-0.105
7	0.281	0.045	-0.403	0.211	0.063	0.164	-0.131	-0.015	-0.114	-0.082
8	-0.113	0.218	0.179	0.286	0.313	-0.045	-0.088	0.072	-0.094	-0.095
9	-0.191	0.227	0.234	0.275	0.243	-0.022	-0.109	0.005	-0.110	-0.161
10	0.257	0.155	0.317	0.350	0.333	-0.002	-0.128	0.106	-0.220	0.014
11	0.237	-0.151	0.215	0.234	0.286	0.062	-0.072	0.066	-0.432	0.060
12	-0.052	-0.122	0.119	-0.057	0.302	0.025	-0.121	-0.009	-0.210	0.069

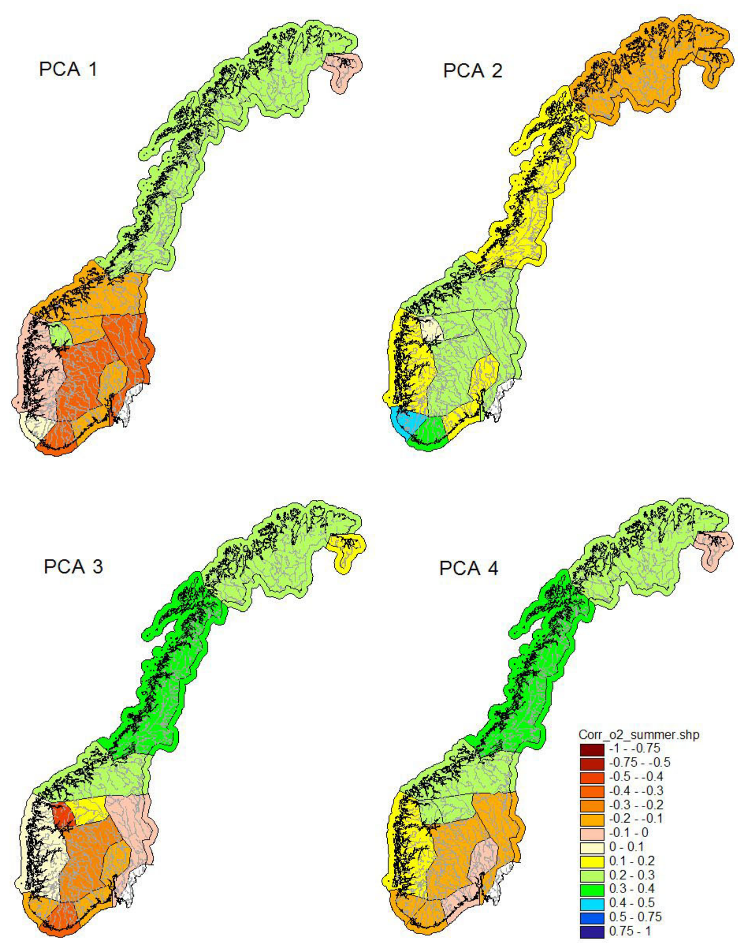

Figure 17. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in summer 1901-2000.

Table 10. Correlations between regional runoff and principal components (domain 1 1901-2000) Autumn

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.374	0.209	-0.423	-0.014	-0.085	-0.095	-0.052	-0.032	-0.106	0.021
2	0.541	0.078	-0.144	0.247	-0.199	-0.137	0.020	-0.073	-0.104	0.074
3	0.338	0.283	-0.541	0.013	-0.141	-0.165	-0.066	0.013	-0.127	-0.062
4	0.499	0.196	-0.512	0.078	-0.110	-0.043	-0.096	0.060	-0.033	0.001
5	0.716	-0.192	-0.204	0.266	-0.120	-0.102	-0.036	-0.044	0.061	0.101
6	0.666	-0.197	0.105	0.297	-0.105	-0.044	0.037	-0.114	0.007	0.109
7	0.506	-0.121	0.283	0.320	-0.124	-0.060	0.145	-0.137	-0.026	0.093
8	0.398	-0.311	0.432	0.211	0.104	0.013	0.135	-0.054	-0.040	0.056
9	0.251	-0.313	0.526	0.185	0.045	0.054	0.119	-0.053	-0.117	0.059
10	0.287	-0.351	0.514	0.194	-0.094	0.024	0.096	-0.023	-0.140	0.104
11	0.195	-0.069	0.577	0.156	-0.298	0.120	0.117	-0.025	-0.140	0.050
12	0.289	-0.054	-0.050	0.076	-0.072	-0.013	0.156	0.066	-0.121	0.147

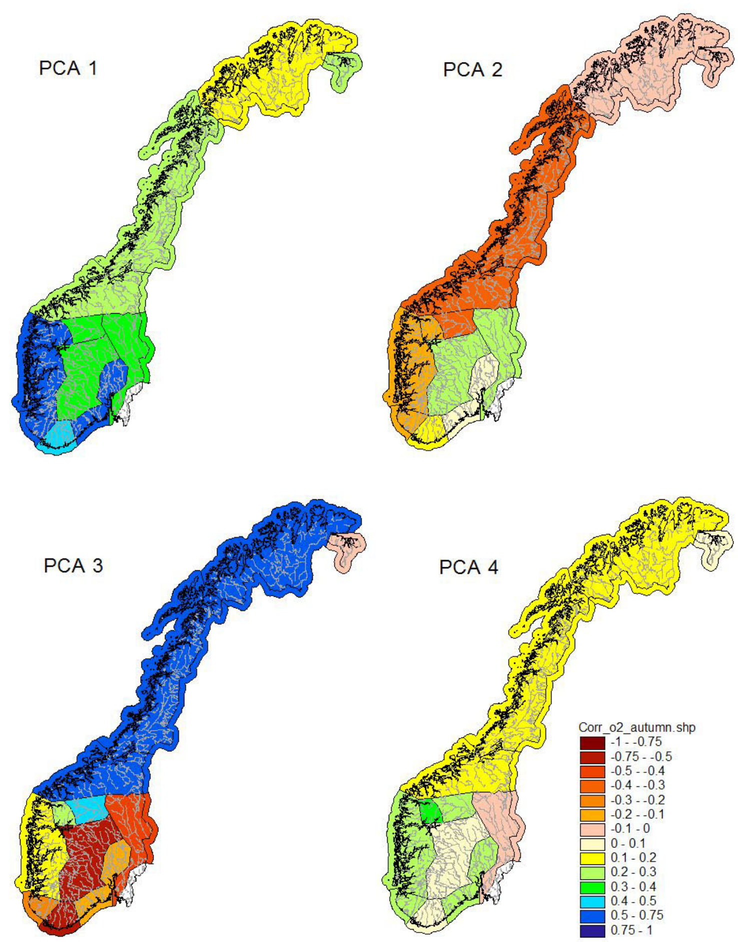

Figure 18. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in autumn 1901-2000.

Table 11. Correlations between regional runoff and principal components (domain 1 1901-2000) Winter

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.246	-0.116	0.123	0.012	-0.172	0.006	0.059	0.112	0.110	0.160
2	0.533	0.075	0.026	0.076	-0.205	-0.064	0.095	0.101	0.070	-0.009
3	0.269	-0.111	0.137	0.019	-0.214	0.088	-0.067	0.060	0.140	0.058
4	0.613	-0.252	0.065	0.184	-0.217	0.029	-0.071	-0.012	0.096	0.087
5	0.795	0.017	0.103	0.197	-0.078	-0.056	-0.013	-0.035	0.026	0.100
6	0.765	0.148	-0.013	0.260	-0.152	-0.038	-0.058	0.045	-0.012	0.092
7	0.735	0.211	0.030	0.248	-0.171	-0.045	-0.021	-0.037	-0.025	0.094
8	0.637	0.313	0.034	0.146	-0.043	-0.079	0.019	-0.131	-0.073	-0.037
9	0.495	0.426	-0.119	0.163	-0.089	-0.022	0.073	-0.049	-0.098	0.020
10	0.510	0.453	-0.144	0.306	-0.222	0.008	0.033	-0.052	-0.074	0.070
11	0.528	0.390	-0.236	0.277	-0.268	0.027	0.010	-0.134	0.034	0.124
12	0.312	0.308	0.149	0.220	-0.101	0.188	-0.094	-0.007	0.080	0.203

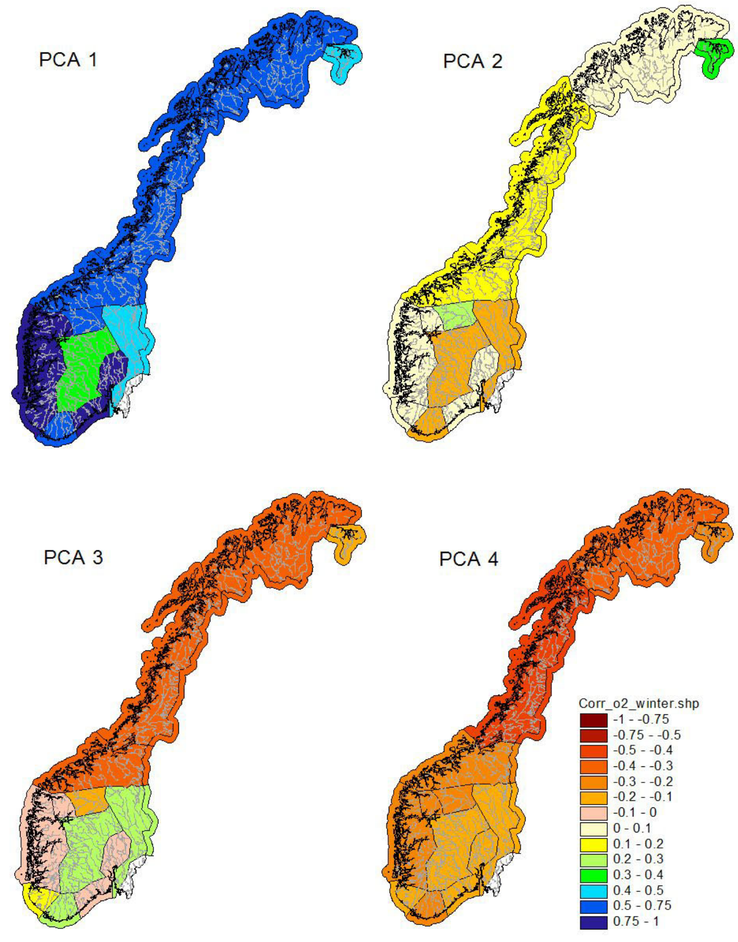

Figure 19. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in winter 1901-2000.

Table 12 Correlations between regional runoff and principal components (domain 1 1946-2000) Spring

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	-0.518	-0.156	-0.105	-0.006	0.145	0.293	-0.048	-0.083	-0.085	0.007
2	-0.522	-0.071	-0.103	0.198	0.120	0.340	-0.008	0.035	-0.051	-0.059
3	-0.444	-0.175	-0.086	0.090	0.121	0.290	-0.019	-0.090	-0.087	-0.108
4	-0.611	-0.311	-0.110	-0.049	0.123	0.151	-0.052	-0.031	-0.149	-0.135
5	-0.697	-0.394	-0.099	-0.241	0.127	0.089	-0.123	0.114	0.003	0.081
6	-0.634	-0.184	-0.164	0.088	0.209	0.287	0.045	0.097	-0.106	0.024
7	-0.563	-0.163	-0.229	0.143	0.254	0.289	0.020	0.136	-0.112	0.060
8	-0.495	-0.236	-0.225	0.229	0.285	0.230	0.060	0.226	-0.021	0.160
9	-0.371	-0.110	-0.325	0.260	0.203	0.190	-0.115	0.303	-0.079	0.023
10	-0.290	-0.260	-0.346	0.288	0.275	0.129	-0.060	0.342	-0.024	0.102
11	-0.384	-0.072	-0.283	0.297	0.291	0.235	-0.220	0.156	-0.046	0.015
12	-0.440	0.245	0.038	-0.037	0.160	0.089	-0.168	0.000	0.018	-0.235

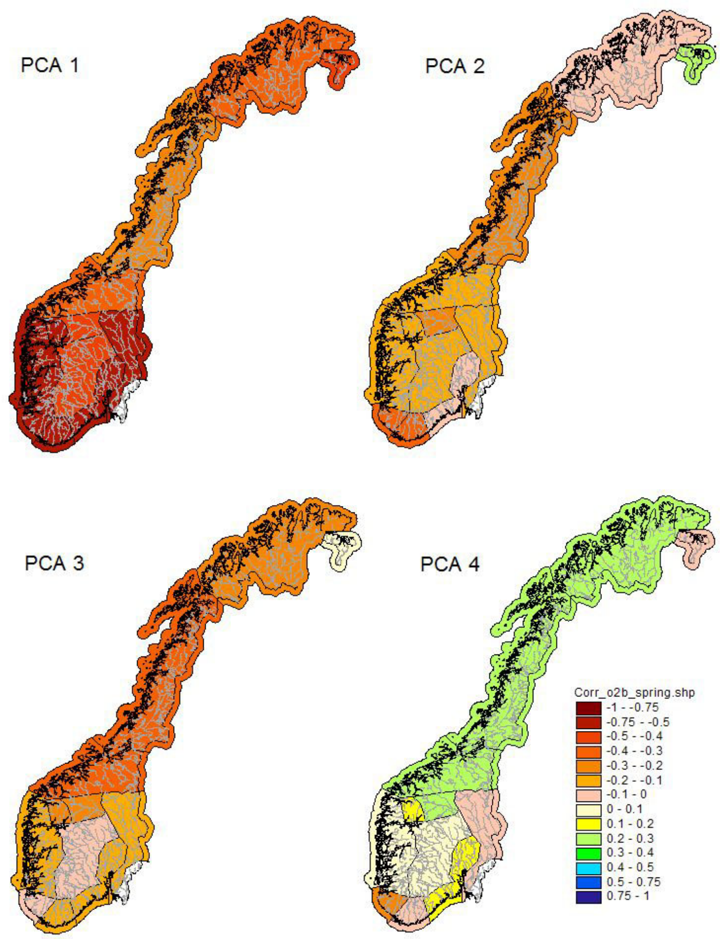

Figure 20. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in spring 1946-2000.

Table 13. Correlations between regional runoff and principal components (domain 1 1946-2000) Summer

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.429	-0.231	-0.067	-0.034	-0.034	-0.064	0.047	-0.020	0.020	0.460
2	-0.012	-0.087	-0.039	-0.003	-0.173	0.187	-0.040	-0.107	0.277	0.130
3	0.446	-0.232	0.067	-0.158	0.032	-0.120	0.068	-0.135	0.206	0.351
4	0.364	-0.411	0.168	-0.138	0.059	-0.156	0.032	-0.207	0.088	0.390
5	0.000	-0.626	-0.155	-0.004	-0.092	-0.005	0.035	-0.226	0.019	0.378
6	-0.303	-0.136	-0.196	0.023	-0.331	0.231	-0.095	-0.133	0.219	-0.003
7	-0.488	-0.177	0.206	0.026	-0.225	0.134	-0.066	-0.045	0.037	-0.055
8	-0.169	-0.170	-0.353	0.169	-0.335	0.253	-0.171	-0.075	0.082	0.071
9	0.045	-0.010	-0.249	0.118	-0.146	0.281	-0.118	-0.078	0.276	0.055
10	-0.412	-0.073	-0.280	0.286	-0.325	0.159	0.045	-0.254	0.144	-0.024
11	-0.498	0.207	-0.153	0.116	-0.344	0.095	0.160	-0.005	0.043	-0.179
12	-0.032	0.102	-0.170	0.060	-0.420	0.237	0.108	0.073	0.048	0.046

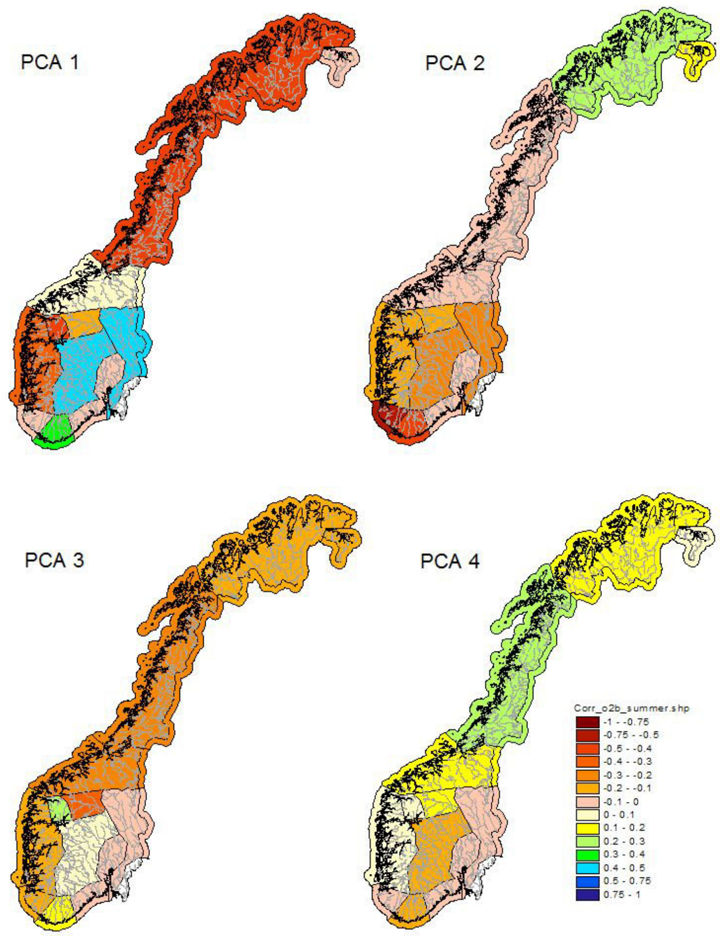

Figure 21. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in summer 1946-2000.

Table 14. Correlations between regional runoff and principal components (domain 1 1946-2000) Autumn

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	-0.039	0.456	0.241	0.006	-0.055	-0.078	0.134	0.076	0.179	0.110
2	0.387	0.336	0.129	0.402	-0.112	-0.084	0.183	0.065	0.132	0.036
3	-0.170	0.600	0.318	0.133	-0.061	0.011	0.137	0.082	0.129	0.025
4	-0.053	0.589	0.457	0.207	-0.098	0.010	0.023	0.086	-0.013	0.117
5	0.493	0.055	0.457	0.251	-0.007	-0.039	0.110	0.098	0.038	0.208
6	0.670	-0.046	0.138	0.274	-0.050	-0.068	0.066	0.024	0.048	0.102
7	0.659	-0.080	-0.062	0.325	-0.058	-0.018	0.007	-0.049	0.040	0.101
8	0.720	-0.240	-0.268	0.216	0.062	0.007	-0.056	0.009	0.027	0.130
9	0.573	-0.409	-0.366	0.151	-0.077	0.007	-0.007	0.019	0.124	-0.009
10	0.572	-0.344	-0.284	0.229	-0.091	-0.001	0.016	0.027	0.212	-0.102
11	0.473	-0.162	-0.395	0.249	-0.238	0.005	-0.090	-0.020	0.237	-0.115
12	0.179	0.023	0.094	0.238	-0.104	0.055	-0.121	0.158	0.002	0.009

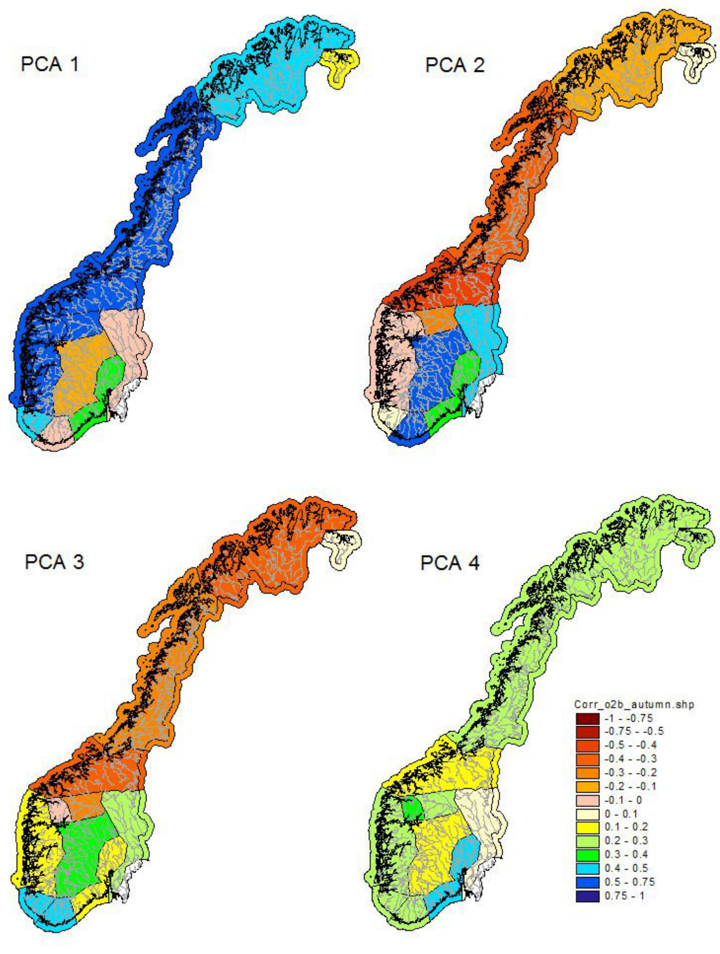

Figure 22. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in autumn 1946-2000.

Table 15. Correlations between regional runoff and principal components (domain 1 1946-2000) Winter

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.436	-0.107	0.210	-0.139	-0.069	0.019	-0.152	-0.049	0.073	-0.194
2	0.751	0.053	-0.016	-0.129	-0.088	0.040	-0.183	-0.065	0.079	-0.009
3	0.377	-0.104	0.217	-0.182	-0.282	0.049	-0.208	-0.049	0.161	-0.095
4	0.705	-0.159	0.216	-0.221	-0.201	-0.025	-0.117	-0.064	0.234	-0.150
5	0.859	0.079	0.111	-0.166	-0.052	-0.094	-0.072	-0.003	0.136	-0.148
6	0.816	0.022	-0.063	-0.233	-0.115	-0.032	-0.142	-0.026	0.133	-0.149
7	0.787	0.090	-0.079	-0.262	-0.138	-0.109	-0.051	-0.001	0.149	-0.126
8	0.703	0.253	-0.127	-0.210	-0.040	-0.201	0.001	-0.045	0.101	-0.035
9	0.578	0.157	-0.305	-0.282	-0.014	-0.157	-0.028	-0.087	0.064	-0.168
10	0.625	0.133	-0.313	-0.410	-0.083	-0.126	0.053	-0.091	0.138	-0.181
11	0.601	0.020	-0.368	-0.353	-0.191	-0.153	0.114	-0.029	0.204	-0.226
12	0.410	0.315	-0.188	-0.297	0.036	0.184	0.080	0.000	0.231	-0.124

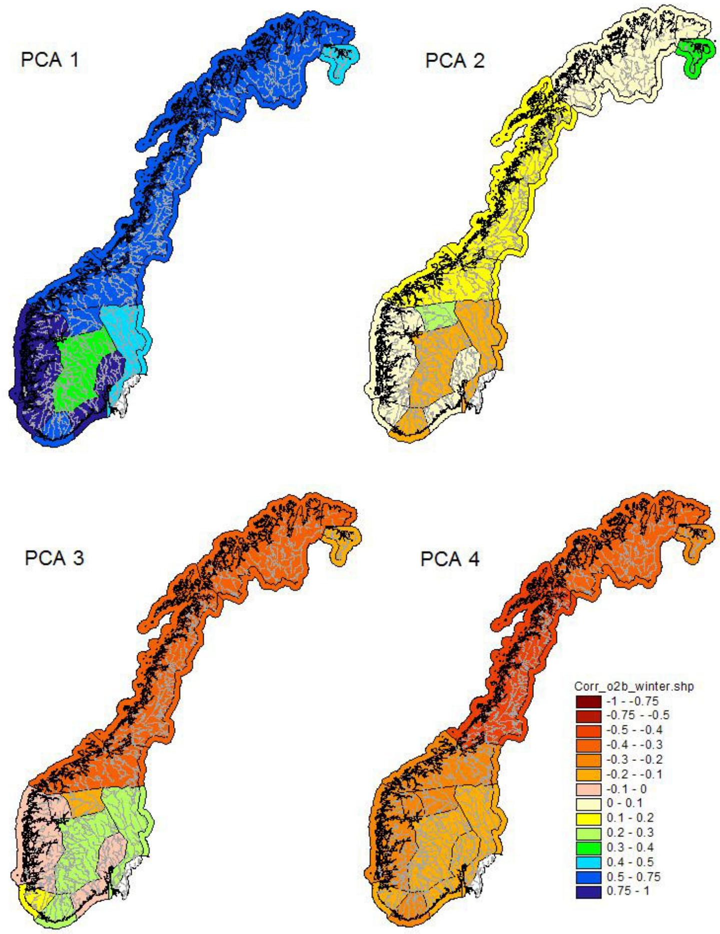

Figure 23. Correlations between regional runoff and the four most prominent domain 1 circulation patterns (PCs) in winter 1946-2000.

Domain 2 1946-2000.

Domain 2 is more extended than domain 1, allowing weather systems in eastern areas (Russia, Siberia and Central Asia) to explain runoff variations in Norway. As explained in a previous chapter the circulation patterns show the same main features for the two domains, and only minor shifts are recognized. This is also reflected in the correlation between regional runoff and the circulation patterns as shown in Figures 24-27 and Tables 16-19.

For spring the first component has a higher correlation with most regions compared to domain 1 components. The only exception is region 12, which has a slightly lower correlation. The second component however shows weak correlations, as do PC3 and PC4.

In summer the correlation patterns are similar as for the PC's of domain 1. The exception is that PC2-4 explains a larger portion of the variations in region 12.

In autumn the differences between the domains are just minor. PC4 is not correlated with runoff in any region.

The winter season is dominated by the first component, which reflects the zonal airflow. The correlations between PC1 and runoff are high in most regions. Compared to domain 1 correlations with PC2 are higher, while PC3 and 4 have less significance. This is probably an effect of the shift of the pressure anomalies in especially PC2 and PC3.

These results indicate that the extension of the pressure area does not explain more of runoff in Norway, except for region 12 in summer.

Table 16. Correlations between regional runoff and principal components (domain 2 1946-2000) Spring

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	-0.620	0.103	0.016	-0.017	-0.170	-0.075	0.227	0.098	0.145	0.020
2	-0.621	0.047	-0.077	0.170	-0.170	-0.128	0.143	0.162	0.146	-0.073
3	-0.554	0.143	-0.006	0.084	-0.194	-0.063	0.147	0.084	0.076	-0.003
4	-0.706	0.175	0.145	-0.035	-0.075	-0.044	0.133	0.079	-0.017	-0.011
5	-0.736	0.147	0.301	-0.210	0.051	0.043	0.092	0.170	0.002	-0.025
6	-0.728	0.099	0.025	0.064	-0.064	-0.204	0.186	0.144	0.143	-0.094
7	-0.677	0.137	-0.053	0.093	-0.037	-0.233	0.194	0.193	0.165	-0.051
8	-0.605	0.186	-0.002	0.185	0.044	-0.278	0.199	0.236	0.162	-0.021
9	-0.501	0.194	-0.200	0.188	0.045	-0.244	0.044	0.363	-0.010	-0.062
10	-0.432	0.328	-0.117	0.216	0.122	-0.299	0.038	0.377	-0.024	0.038
11	-0.517	0.148	-0.217	0.225	-0.050	-0.178	0.186	0.380	-0.002	0.178
12	-0.379	-0.328	-0.062	-0.044	-0.083	-0.011	0.134	0.237	-0.136	0.032

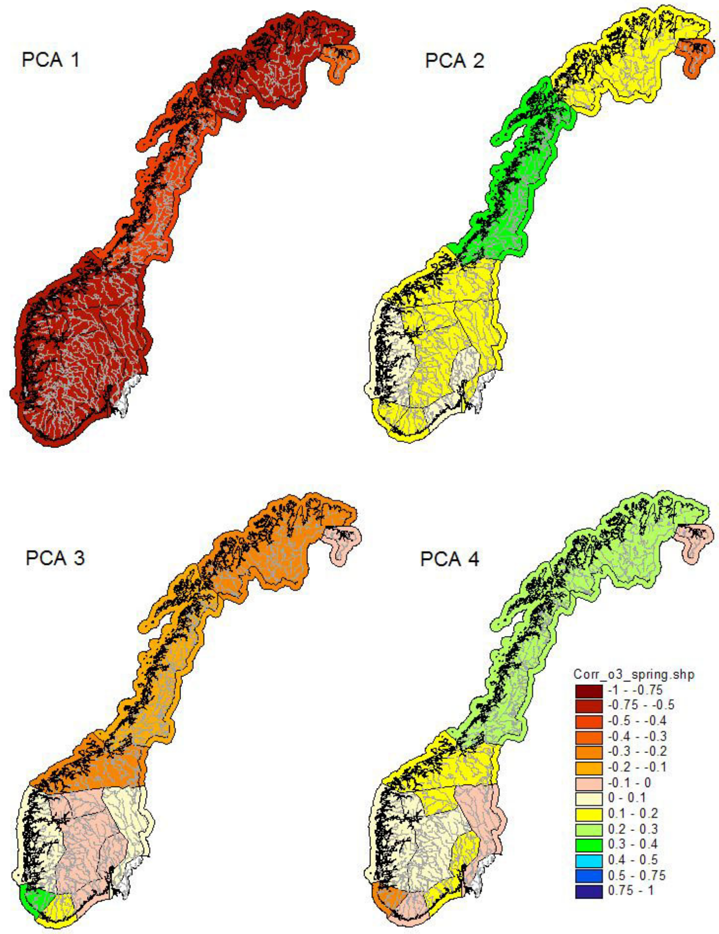

Figure 24. Correlations between regional runoff and the four most prominent domain 2 circulation patterns (PCs) in spring 1946-2000.

Table 17 Correlations between regional runoff and principal components (domain 2 1946-2000) summer.

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.404	-0.170	-0.126	-0.319	-0.206	0.031	0.058	-0.169	0.068	0.061
2	-0.039	-0.029	-0.123	-0.233	-0.200	0.144	-0.182	0.133	0.033	0.099
3	0.430	-0.199	0.008	-0.238	-0.069	-0.032	-0.036	-0.178	-0.035	0.117
4	0.360	-0.392	0.078	-0.245	-0.004	0.016	0.023	-0.160	0.085	0.225
5	0.003	-0.543	-0.290	-0.294	-0.055	0.107	0.136	-0.115	0.001	0.236
6	-0.325	-0.018	-0.309	-0.223	-0.104	0.149	-0.193	0.260	0.090	0.125
7	-0.508	-0.120	0.104	-0.219	0.044	0.129	-0.089	0.218	0.159	0.045
8	-0.191	-0.045	-0.457	-0.169	-0.104	0.180	-0.120	0.234	0.091	-0.089
9	0.021	0.050	-0.290	-0.076	-0.208	0.117	-0.195	0.158	-0.024	-0.079
10	-0.423	0.059	-0.394	-0.100	0.007	0.213	0.045	0.222	0.007	0.027
11	-0.522	0.341	-0.198	-0.104	0.078	-0.009	0.027	0.226	-0.119	-0.168
12	-0.056	0.223	-0.217	-0.274	-0.130	-0.004	0.068	0.265	-0.155	-0.183

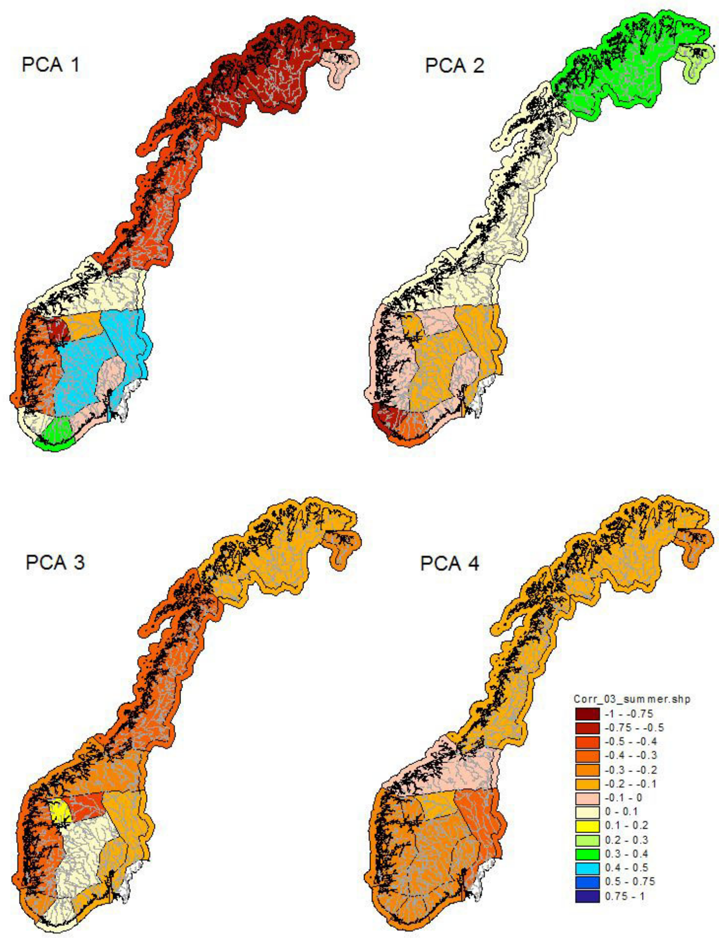

Figure 25. Correlations between regional runoff and the four most prominent domain 2 circulation patterns (PCs) in summer 1946-2000.

Table 18. Correlations between regional runoff and principal components (domain 2 1946-2000) Autumn

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	-0.320	-0.388	0.056	-0.004	-0.088	0.106	0.062	-0.028	-0.074	-0.055
2	0.178	-0.495	-0.048	-0.054	-0.351	0.124	0.292	-0.084	-0.024	0.102
3	-0.466	-0.433	-0.022	-0.032	-0.278	0.172	-0.015	-0.007	-0.053	-0.081
4	-0.392	-0.503	0.097	-0.095	-0.383	0.212	0.018	0.057	0.031	-0.071
5	0.287	-0.376	0.370	-0.172	-0.345	0.187	0.068	-0.133	0.011	0.061
6	0.572	-0.332	0.164	-0.049	-0.218	0.135	0.196	-0.080	-0.010	0.141
7	0.651	-0.260	-0.007	0.016	-0.205	0.065	0.212	0.002	0.067	0.181
8	0.791	-0.166	-0.034	0.042	-0.046	-0.135	0.099	-0.084	-0.017	0.086
9	0.786	0.062	-0.116	-0.027	0.024	-0.140	0.100	0.008	-0.032	0.120
10	0.750	0.019	-0.109	0.010	-0.061	-0.033	0.161	-0.013	-0.079	0.221
11	0.608	-0.048	-0.267	0.096	-0.025	-0.035	0.250	0.179	-0.137	0.250
12	0.146	-0.091	0.054	0.072	-0.206	0.093	0.189	0.194	0.040	0.224

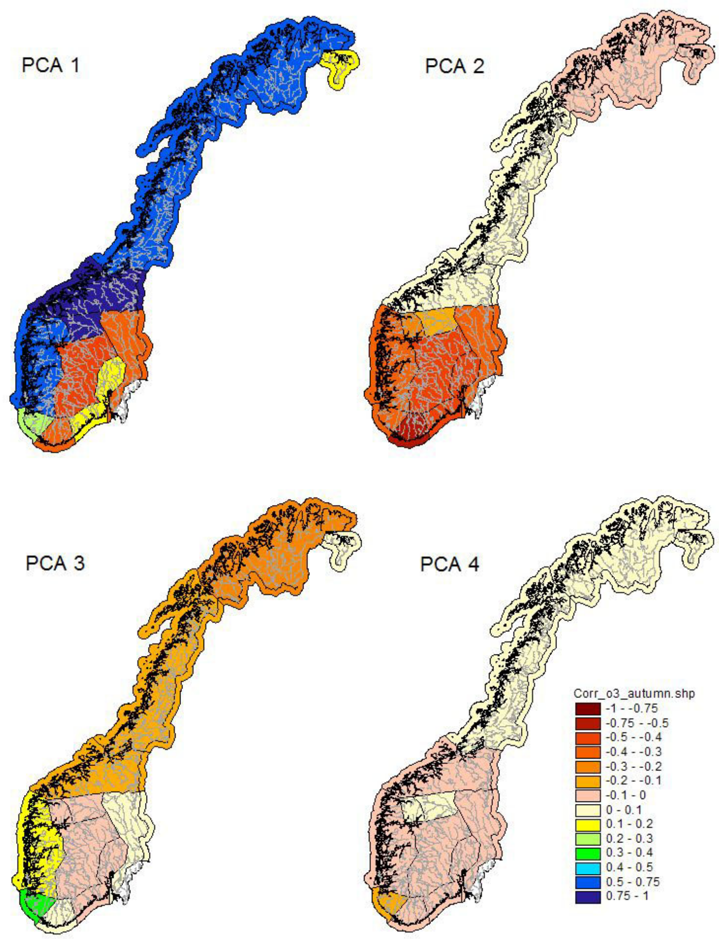

Figure 26. Correlations between regional runoff and the four most prominent domain 2 circulation patterns (PCs) in autumn 1946-2000.

Table 19. Correlations between regional runoff and principal components (domain 2 1946-2000) Winter

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10
1	0.374	-0.343	0.041	-0.079	0.120	-0.001	-0.268	0.009	0.080	-0.135
2	0.747	-0.094	0.025	-0.015	0.149	-0.051	-0.222	-0.007	0.140	-0.051
3	0.336	-0.291	0.017	-0.127	0.014	-0.073	-0.419	-0.037	0.127	-0.106
4	0.656	-0.371	-0.001	-0.188	0.060	-0.006	-0.308	-0.138	0.049	-0.081
5	0.826	-0.218	0.150	-0.027	0.086	0.096	-0.160	-0.096	0.066	-0.071
6	0.819	-0.069	-0.002	-0.086	0.115	0.079	-0.224	-0.077	0.110	-0.002
7	0.803	-0.005	0.050	-0.099	0.075	0.112	-0.210	-0.158	0.043	-0.025
8	0.719	0.080	0.177	0.018	0.143	0.175	-0.148	-0.210	0.021	-0.128
9	0.632	0.245	-0.008	-0.080	0.145	0.167	-0.108	-0.184	0.056	0.032
10	0.691	0.261	-0.015	-0.178	0.072	0.247	-0.177	-0.167	-0.026	0.010
11	0.667	0.247	-0.170	-0.150	0.036	0.198	-0.219	-0.226	-0.048	-0.047
12	0.449	0.219	0.202	-0.074	0.229	0.092	-0.241	0.025	-0.275	0.025

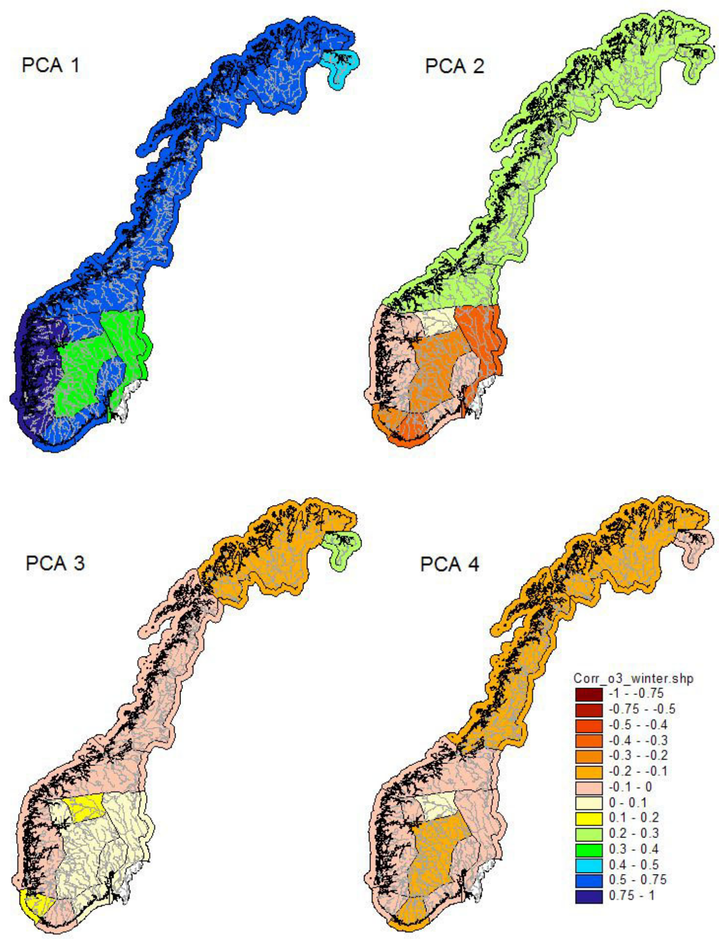

Figure 27. Correlations between regional runoff and the four most prominent domain 2 circulation patterns (PCs) in winter 1946-2000.

Prediction of regional runoff series by atmospheric circulation.

The final objective of this study has been to use the relations between atmospheric circulation and regional runoff series to develop a model for describing variation of runoff using the atmospheric circulation indices as predictors. The circulation indices developed in this analysis are based on a principal component analysis, and the predictors will consequently be the temporal components of this analysis. A regression analysis is carried out in order to establish seasonal models for each region. Since the components have different influence on the different regions, a stepwise regression algorithm was chose to establish the linear models.

The results presented in the previous chapter indicated that the use of a wider pressure domain do not improve the relations between circulation and runoff considerably. Therefore only models based on the domain 1 components are established. Figure 28 shows the observed and modelled runoff for three runoff regions (regions 1, 5 and 10) for all the seasons. These regions are selected because they besides covering different areas of the country also represent different climatic regimes.

Table 20 shows the coefficients of determination (R) for the regressions models established. Tables 21-24 show the order of entry of the PCs in the stepwise regression. These tables also show the standard error of the final regression models. For the spring and autumn seasons high values are obtained in several regions. These seasons are characterized by a direct link between weather and runoff, and not by large delays in runoff. In spring the runoff in many regions are heavily influenced by snowmelt, and thereby also a delayed result of winter precipitation. This is not accounted for in the present model. In autumn most of the runoff is a product of precipitation, and the runoff response is usually quite fast. Therefore most of the regions show high coefficients of determination. One exception is region 12. This region is a continental region, and most of the drainage areas are in northern Finland and in Russia. Snow cover is usually established during this season, and the runoff is therefore not so directly influenced by precipitation. Runoff in this region also shows low correlations with the pressure components of domain 1, and is probably more related to circulations over Eastern Europe, Russia and Siberia. The low R-value in summer is also an indication of this.

In summer and winter water storage (soil water, snow storage) in the catchments complicates the direct link to the atmospheric circulation. In addition evapotranspiration is also a major effect in summer, especially the southern parts of the country. In summer the precipitation conditions are different, with a higher frequency of scattered rain showers instead of precipitation due to large frontal systems. This is probably one reason why it is not possible to establish a model for region 2 in summer. Different PCs turns out to be most significant in the different regions, a fact that might confirm the complex weather-runoff relation in summer.

In continental parts of the country snow cover is stable in most winters. The performance of the regression models will therefore be low, since runoff variations in these areas mostly are results of snowmelt associated with occasional “warm spells”. In the coastal regions the climate is mild and winter runoff common. Mild and wet periods are associated with certain circulation types, and the performance of the models is higher in these regions. This can clearly be seen from Figure 28d where the modelled runoff of region 1 shows low variability compared to the observed runoff. This indicates that runoff variations in winter for this region cannot be explained by the large-scale circulation patterns described by the first ten principal components. The only component used in the regression model is PC 1, which covers 48% of the variance of the MSLP in domain 1. This component represents the intensity of the zonal airflow in the domain 1 area. This component represents however only very large-scale variations and the regional variability are not accounted. The circulation anomalies that might explain these variations are either found in the lower ranked components, or the runoff variations are caused by weather events that are not reflected by the *seasonal* pressure fields.

Table 20. Coefficient of determination for the models of regional runoff based on circulation components.

Region	Spring	Summer	Autumn	Winter
1	0.525	0.577	0.602	0.246
2	0.613	-[1]	0.627	0.570
3	0.504	0.651	0.731	0.344
4	0.662	0.646	0.741	0.721
5	0.826	0.529	0.823	0.819
6	0.773	0.429	0.755	0.835
7	0.719	0.534	0.663	0.822
8	0.742	0.509	0.697	0.725
9	0.680	0.526	0.687	0.673
10	0.748	0.623	0.711	0.790
11	0.631	0.642	0.698	0.805
12	0.519	0.365	0.289	0.566

1) No model was established.

Table 21. The order the PCs are entered into the regression equations and the standard error of the final models for the spring season.

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	Standard error
1	1					2					0.271
2	1	4			3	2					0.412
3	1	2			3						0.316
4	1	2		3							0.273
5	1	2		3	4					5	0.191
6	1	2	4		3						0.358
7	1	4	3		2						0.353
8	1	2	3		5		4		7	6	0.264
9	1	3	2		4		5				0.365
10	1	3	2		4		6	5			0.346
11	1		2		3						0.311
12	1		3		2						0.228

Table 22: The order the PCs are entered into the regression equations and the standard error of the final models for the summer season.

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	Standard error
1	1	2		5			4		3		0.286
2											-
3	1	3	2	6		5	4			7	0.347
4	3	2	1	5		4	6				0.407
5		1			2						0.267
6					1				2		0.237
7	2		1	3							0.127
8		3	4	2	1						0.265
9	5	4	3	1	2						0.373
10			3	1	2				4		0.286
11		5	4	3	2				1		0.222
12					1				2		0.308

Table 23. The order the PCs are entered into the regression equations and the standard error of the final models for the autumn season.

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	Standard error
1	2	3	1								0.288
2	1			2	3						0.216
3	2	3	1		5	4					0.327
4	2	3	1								0.256
5	1	4	3	2	5						0.158
6	1	3		2							0.185
7	1		3	2							0.198
8	2	3	1	4							0.199
9	3	2	1	4							0.251
10	3	2	1	4							0.231
11	3		1	4	2						0.227
12	1										0.222

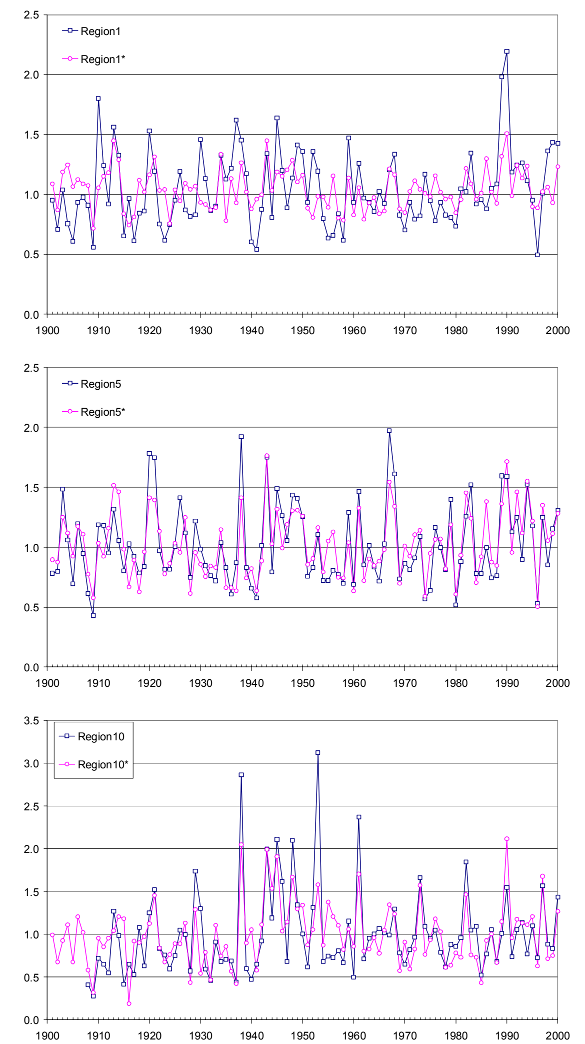

Figure 28a Observed and modelled regional spring runoff for regions 1, 5 and 10.

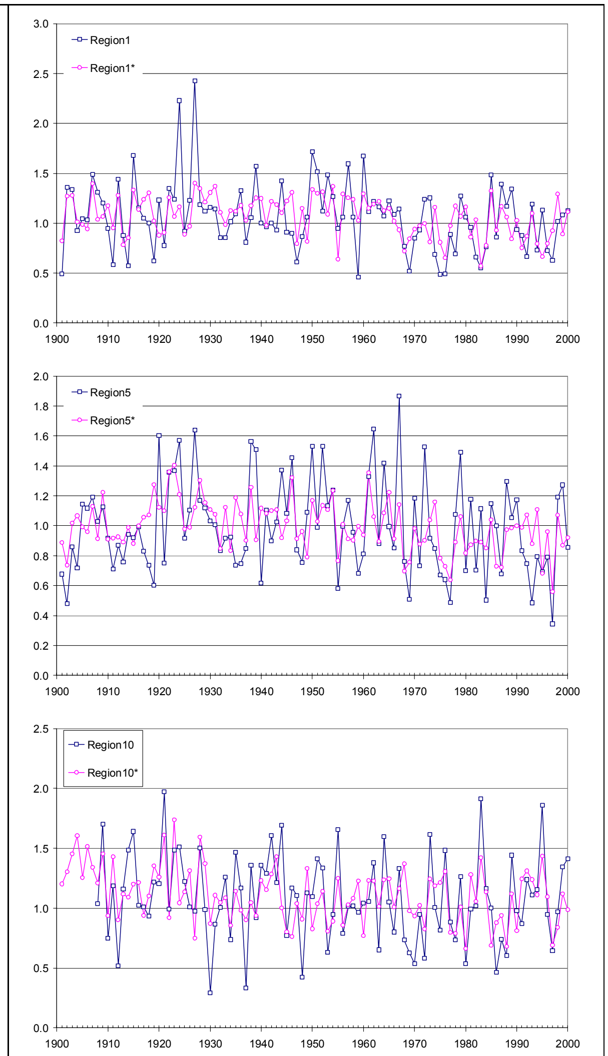

Figure 28b Observed and modelled regional summer runoff for regions 1, 5 and 10.

Table 24. The order the PCs are entered into the regression equations and the standard error of the final models for the winter season.

Region	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	Standard error
1	1										0.288
2	1				2						0.367
3	1				2						0.413
4	1	2		4	3						0.398
5	1			2							0.266
6	1	4		2	3						0.313
7	1	3		2	4						0.308
8	1	2		3							0.345
9	1	2		3							0.463
10	1	2	5	3	4						0.392
11	1	2	4	3	5			6			0.334
12	1	2		3		5				4	0.155

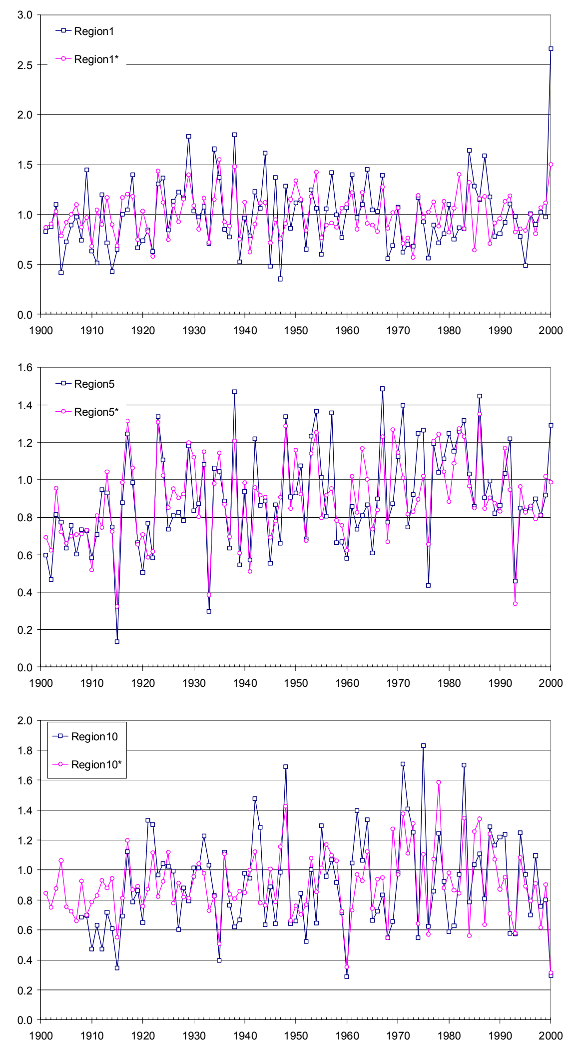

Figure 28c Observed and modelled regional autumn runoff for regions 1, 5 and 10.

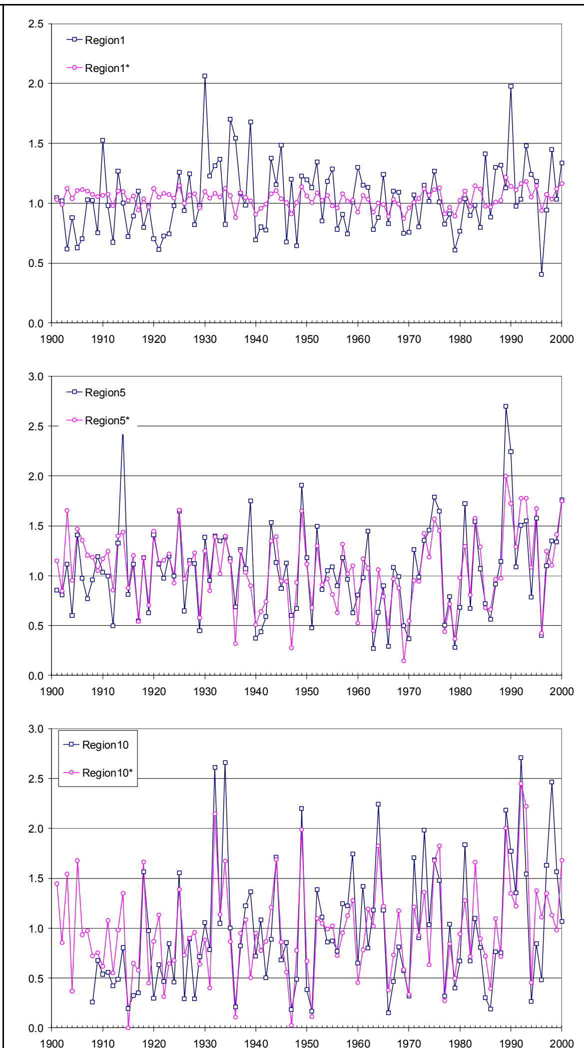

Figure 28d Observed and modelled regional winter runoff for regions 1, 5 and 10.

Floods & droughts.

The atmospheric circulation components describe mean conditions of the circulation. Floods and drought are extreme events that may develop differently from episode to episode, caused by different atmospheric conditions. As floods and droughts are results of time integrated processes in the catchments as well as the occurrence or not of rainfall, the direct link to atmospheric circulation is complicated even more. The most pronounced seasonal runoff anomalies are inspected, and compared to the principal components. For some of the events high values coincide in the runoff series and the PCs. One example is spring 1990 where high values of PC1, combined with low values of both PC2 and PC3 coincide with high runoff values in most south-Norwegian regions (except region 5). In this configuration all these components will contribute to the westerly airflow giving mild and wet conditions. Another striking example is autumn 2000, where a strongly negative PC3 describes the airflow giving floods in south-eastern Norway. But the events where a direct link between a single circulation pattern anomaly and an extreme runoff anomaly can be found are rare. Most intensive rainfall floods are short-term phenomena and are linked to specific weather patterns, which occurs for only a few days. These events will not be well represented in the leading seasonal principal components. Principal components of MSLP will also not describe the moisture of the air. Other meteorological fields, like humidity (Hanssen-Bauer et al, 2003) or geopotential height might therefore be a better descriptors. Droughts in the warm season develop over time, and are more likely to be represented in the seasonal principal components.

Conclusions

In this study relations between atmospheric circulation and regional runoff are investigated on a seasonal scale. Atmospheric circulation patterns are described by principal components of air pressure. The temporal principal components are related to regional runoff series. The analysis shows that atmospheric circulation can describe runoff variations on a seasonal scale. For some regions in some seasons however the relations are weak. One problem dealing with seasonal values is that the atmospheric circulation indices as well the runoff anomalies are smoothed, and thereby hide the direct links between certain atmospheric conditions and weather and runoff response. Especially this will be the case when trying to relate atmospheric circulation to extreme events. These results can though be used to address the effects of future trends and changes in the atmospheric circulation regime on runoff. Addressing effects caused by shifts in the significance of the circulation patterns is of particular interest.

Relating extreme runoff anomalies to atmospheric circulation indices failed since extreme events are a result of unlucky combinations of several temporal and catchment integrated processes. In order to address extremes, analysis at a finer time scale should be carried out, especially when considering floods, which in most cases are caused by relatively short but intensive weather conditions. Also the circulation indices applied should be further developed. Principal components of mean sea level pressure do not represent atmospheric moisture conditions very well. Other atmospheric data should therefore be applied instead, or in combination with the MSLP PCs to establish better relations between runoff and atmospheric circulation. Principal component analysis is also a difficult method to apply, since it describes the atmospheric circulation as linear combinations of the principal components. Physical interpretation of single PC's will therefore only partly be able to describe the circulation and its impacts on e.g. runoff. The advantage of the method is however it ability to cover both temporal and spatial characteristics. Also the fact that the components are orthogonal makes the method suited for establishing linear relations, like the regression models presented here.

The temporal scale of this study is coarse. Seasonal values of both runoff and atmospheric circulation will cause smoothed values. The relations might be weakened by non-simultaneous timing of pressure and runoff within the seasons, and thereby hide direct links. An analysis at monthly scale or even finer could find relations not revealed by this seasonal study.

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