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Regionalisation of the precipitation pattern in the Baltic Sea drainage basin and its dependence on large-scale atmospheric circulation

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Regionalisation of precipitation in the Baltic Sea drainage basin was realised using the principal component analysis of gridded monthly precipitations during 1900–1996 obtained from the global land precipitation dataset created in the University of East Anglia. Four main precipitation regions were determined for the Baltic Sea drainage basin: northern, eastern, southern and western. The latter contains also the Baltic Sea. Significant relationships were found between atmospheric circulation and precipitation, being the strongest in winter and the weakest in summer. Circulation variables indicating the intensity of westerlies were usually positively correlated with precipitation in windward regions during the cold part of the year. The area with the highest correlation was located in the Scandinavian Mountains. Lower positive correlations were revealed also in Denmark, southwestern Sweden, Lithuania, Latvia, Estonia, Finland and northwestern Russia. A different relationship was typical to the leeward side of westerlies in most of Sweden. Even a negative correlation was found with the circulation variables describing the intensity of westerlies. Precipitation in Sweden was mostly related to the airflow from the Baltic Sea expressed by the circulation form E. The teleconnection patterns (North Atlantic oscillation, East Atlantic, Polar/Eurasia, East Atlantic/West Russia, Scandinavian) had high correlations in specific regions at certain seasons.

Introduction

Precipitation is one of the most important climatic variables for human activity. At the same time, it is characterised by extremely high variability in space and time. To determine general regularities of spatial and temporal variability of precipitation, it is useful to analyse spatially averaged values summed by longer time interval.

Precipitation regime in northern Europe is mostly determined by atmospheric circulation and local geographical conditions. Prevailing westerlies cause the transport of mild and moist maritime air from the North Atlantic to the continent. It is followed by large amounts of precipitation. Intense cyclonic activity is the second factor inducing wet climate in northern Europe.

To investigate regularities of precipitation patterns, regionalisation is often used. It allows isolating regions with similar precipitation regimes. Principal component analysis (PCA) is the most common statistical method used for regionalisation. It enables to determine regions with coherent fluctuations. Consequently, similar dynamics of precipitation, caused by circulation, is put forward as an objective of regionalisation, and local factors such as the sea and relief are of less importance.

One of the most thorough investigations in this field was made for Australia (Drosdowsky 1993). It gave a detailed analysis of the patterns of variability of Australian district rainfall on seasonal time-scales, based on rotated PCA using both the S and T modes. Various criteria were examined to determine the number of principal components to rotate. The S-mode PCA, which groups districts with similar temporal variations, divided the continent into eight coherent and more or less equally-sized regions.

PCA has been applied for the regionalisation and analysis of long-term changes in precipitation in many areas all over the world. The territory of the United States has been exhaustingly studied. In the first studies, only the principal components (empirical orthogonal functions i.e., EOF), using a few stations, were composed and mapped over the entire continent (Kutzbach 1967) in the western United States (Sellers 1968) and in Nevada (Stidd 1967). Later, a much larger amount of data were analysed using PCA (Diaz and Fulbright 1981, Diaz 1981). Spatially coherent precipitation regions in the USA were identified in a synoptic scale by factor analysis with varimax rotation (Walsh *et al.* 1982). PCA was also applied for the analysis of climatic fluctuation (Diaz 1986).

The regionalisation of Indian summer monsoon rainfall has been an important climatologic topic. The first attempt to use PCA was made by Gregory (1989), who identified 10 macro-regions. Kulkarni *et al.* (1992), Gadgil *et al.* (1993) and Iyengar and Basak (1994) also analysed spatio-temporal variations and composed classifications for precipitation in India. Similar studies have been made for Africa: for South Africa (Dyer 1975), the Sahel region (Klaus 1978), in East Africa (Ogallo 1989) and for the continent as a whole (Nicholson 1986, Janowiak 1988). PCA was also used for the study of precipitation patterns over small areas such as Hawaiian Islands (Lyons 1982), northeastern Australia (Lyons and Bonell 1994), Kenya (Bärring 1987, 1988) and Mallorca Island (Sumner *et al.* 1993).

PCA is applied for precipitation in some European regions: northern Europe (Uvo 2003), Sweden (Busuioc *et al.* 2001), the Mediterranean (Goossens 1985, Maheras 1985, 1988), Great Britain (Wigley *et al.* 1984, Gregory *et al.* 1991), Italy (Molteni *et al.* 1983), Austria (Ehrendorfer 1987), Croatia (Pandzic 1988) and Ireland (Logue 1984). A detailed EOF analysis of precipitation regime in Sweden distinguished four main regions: north, middle, south and southwest (Busuioc *et al.* 2001). The influence of the North Atlantic Oscillation (NAO) on the precipitation pattern in Sweden was estimated using canonical correlation analysis. Uvo (2003) created a regionalisation scheme for winter precipitation in northern Europe based on its relationship with the NAO. Three main precipitation regions — western/northwestern, northern/northeastern and southern/southwestern — were clearly detected for Austria (Ehrendorfer 1987).

Relationships between circulation and precipitation are an important topic in climatology. Correlation between the frequencies of the main circulation forms W, E and C according to the Vangengeim-Girs classification and European precipitation during the warm and cold half-years was analysed by Kożuchowski and Marciniak (1988). They found that the form W (westerlies) is positively correlated with precipitation in northern Europe and negatively in southern Europe, especially in winter. The form C (northerly airflow) has a negative correlation with precipitation in the Baltic Sea region and the form E in northern Russia, especially in summer. In case of the form E, more precipitation is observed in southern Europe.

A thorough research on relationships between circulation and precipitation in Europe was made by Wibig (1999). Based on the 500-hPa geopotential height data, the main circulation indices were detected by using PCA. They were related to the precipitation data for the period from December to March. The NAO index has a significant positive correlation in northern Europe and a negative one in the Mediterranean. The Scandinavia index is positively correlated with precipitation in Iceland, Ireland and the Mediterranean, and negatively correlated in northern Russia and central Norway. The following precipitation regions were defined in Europe:

the British Isles, the Scandinavian Peninsula, western, central and eastern Europe, the Iberian Peninsula, and the Mediterranean (Wibig 1999).

Hurrell and van Loon (1997) demonstrated that in case of the NAO positive phase, wet conditions can be found in western Scandinavia, Denmark, Ireland and Scotland, and dry conditions on the Iberian Peninsula and western Balkan. Dependence of precipitation on the NAO index and on the frequency of the Lamb weather types was studied in northern England (Fowler and Kilsby 2002). A positive correlation between the NAO index and precipitation was found in the western part and a negative correlation in the eastern side. Higher correlations were revealed in winter.

Higher precipitation over Sweden was related to stronger westerlies (higher NAO index) in Sweden (Busuioc *et al*. 2001). The influence of NAO on winter precipitation (DJFM) in northern Europe (125 station data during 1967–1996 in Norway, Sweden, Finland, Denmark, northwestern Russia, the Baltic states) was analysed in detail by Uvo (2003). The highest correlation was detected on windward sides — Norwegian coast, northern Sweden, southern Finland. Precipitation on the leeward side of the Scandinavian mountains in Sweden is mainly related to south-easterly winds (Uvo 2003).

Relationships between circulation and precipitation were studied in Estonia (Jaagus 2006). Trends in air temperature and precipitation were related to changes in atmospheric circulation. It was shown that an increase in winter precipitation is related to an increasing trend in the intensity of westerlies (NAO and AO indices). An increase in precipitation in October is connected with negative trends in the East Atlantic/West Russia teleconnection index and in the frequency of the circulation form C (Jaagus 2006). Precipitation patterns in the Baltic Sea drainage basin and their relationships with atmospheric circulation still need a more detailed research.

The main objectives of this research are to create a regionalisation scheme for precipitation over the Baltic Sea drainage basin using principal component analysis and to analyse the influence of atmospheric circulation on precipitation in these regions. Due to the fact that the influence of NAO on precipitation in the Baltic Sea region has already been widely analysed, this study mostly concentrates on relationships with other characteristics of large-scale atmospheric circulation rarely used for such analyses. Spatial differences in the relationships over the Baltic Sea regions are put forward in this study.

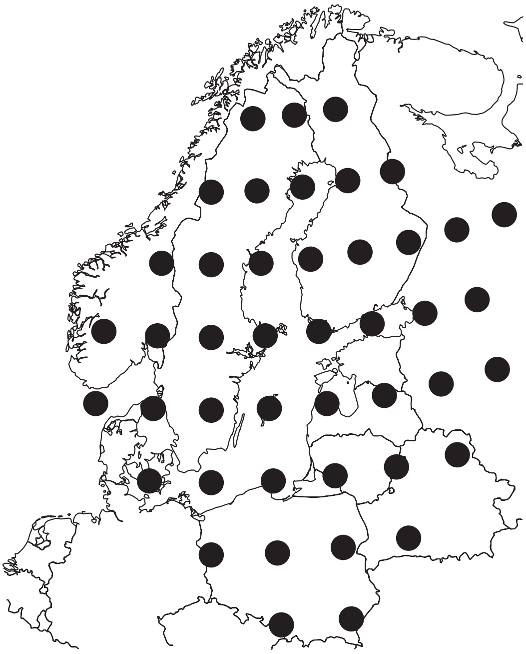

Fig. 1. Study area with the tide gauge stations and modelling locations.

Material and methods

Precipitation data were obtained from the global gridded precipitation dataset for land areas created by the Climate Research Unit, University of East Anglia (Hulme 1992, 1994). Grid resolution was 2.5° × 3.75° latitude/longitude. Forty-four grid cells on the Baltic Sea drainage basin were used in this study (Fig. 1). Monthly and seasonal precipitation data during 1900–1996 were used as initial data. Seasons were defined as spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Sequential monthly and seasonal precipitations, as well as precipitation in single seasons, were analysed.

A large number of characteristics of large-scale atmospheric circulation were used for analysing their relationships with precipitation. Monthly frequencies of the circulation forms W, E and C according to the Vangengeim-Girs classification and frequencies of the zonal (Z), half-meridional (H) and meridional (M) circulation groups according to the Hess-Brezowsky classification (*Grosswetterlagen*) express circulation conditions in the most general way, but these classifications are subjective. The form W indicates westerly circulation, E presents easterly, south-easterly and southerly circulation and C shows airflow from the northern directions. The zonal circulation group Z corresponds to westerly circulation in central Europe, half-meridional group H denotes south-westerly and north-westerly circulation and the meridional group M includes all the other directions between the north, east and south.

The North Atlantic oscillation (Jones *et al.* 1997) and Arctic oscillation indices (Thompson and Wallace 1998) are used as numeric variables describing the intensity of westerlies in the Atlantic/European sector in mid-latitudes. The NAO index is expressed as a difference between the standardised sea-level pressure values measured in Gibraltar and Iceland. In case of a high positive NAO index, pressure gradient is high over the North Atlantic and westerlies are intense carrying hot and moist maritime air from the ocean to the continent. A high negative NAO index denotes a weak pressure gradient leading to the weakening of westerlies.

The Arctic Oscillation (AO) can be observed as an opposing atmospheric pressure pattern in northern middle and high latitudes. The oscillation exhibits a negative phase with relatively high pressure over the polar region and low pressure at mid-latitudes (about 45°N), and a positive phase in which the pattern is reversed. The NAO is an expression of the Arctic Oscillation in the Atlantic/European sector.

In addition, five teleconnection indices defined by Barnston and Livezey (1987) were involved in the analysis. The North Atlantic oscillation (NAOT), East Atlantic (EA) and Polar/Eurasia (POL) patterns reflect zonal circulation in different latitudes while the East Atlantic/West Russia (EAWR) and the Scandinavia (SCA) patterns describe meridional circulation. The values of the teleconnection indices were used for 1950–1996 and were obtained from the web site of the Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml).

The NAOT consists of a north-south dipole of sea-level pressure anomalies with one centre located over Greenland and the other centre of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N. The positive phase of the NAOT reflects the below-normal pressure across the high latitudes of the North Atlantic and the above-normal pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of pressure anomalies over these regions. The NAOT has a small difference from the NAO index in winter and a substantial difference in the other seasons, especially in summer.

The East Atlantic (EA) pattern is the second prominent mode of low-frequency variability over the North Atlantic (Barnston and Livezey 1987). The EA pattern is structurally similar to the NAOT, and consists of a north-south dipole of anomaly centres spanning the North Atlantic from the east to the west. The anomaly centres of the EA pattern are located south-eastward to the approximate nodal lines of the NAO pattern. For this reason, the EA pattern is often interpreted as a "southward shifted" NAO pattern.

The positive phase of the Polar/Eurasia (POL) pattern consists of negative pressure anomalies over the polar region and positive anomalies over northern China and Mongolia (Barnston and Livezey 1987). This pattern is associated with fluctuations in the strength of the circumpolar circulation, with the positive phase reflecting an enhanced circumpolar vortex and the negative phase reflecting a weaker than average polar vortex.

The East Atlantic/West Russia (EAWR) pattern is one of three prominent teleconnection patterns that affect Eurasia throughout a year (Barnston and Livezey 1987). The East Atlantic/West Russia pattern consists of four main anomaly centres. The positive phase is associated with the positive pressure anomalies located over Europe and northern China, and the negative pressure anomalies located over the central North Atlantic and north of the Caspian Sea.

Northerly and north-westerly airflows over the East European plain and the Baltic Sea region is typical for positive EAWR values and the opposite circulation for negative ones.

The Scandinavia pattern (SCA) consists of a primary circulation centre over Scandinavia, with weaker centres of opposite sign over western Europe and eastern Russia/western Mongolia. The positive phase of this pattern is associated with positive pressure anomalies, sometimes reflecting major blocking anticyclones over Scandinavia and western Russia, while the negative phase of the pattern is associated with negative pressure anomalies in these regions.

Sequential monthly and seasonal precipitations are used for regionalisation. In this case, differences in the annual precipitation curve form the important criteria for grouping. The S-mode PCA is usually applied for regionalisation. It means that spatial units (stations, grid points) are the variables and temporal units (months, seasons) are the cases in the initial data matrix. To put forward the regions with coherent fluctuations of precipitation, rotation of the main components using varimax normalised technique is applied (Richman 1986). The number of principal components to rotate was determined according to the Kaiser criterion (Kaiser 1958), i.e. the eigenvalue of the last component to rotate should be 1 or above.

The selection of significant components for regionalisation among the rotated components followed the rule that the share of a component in the total variance should be at least 10%. All the rotated components with eigenvalues above 10% are considered significant. Precipitation at each grid cell is related to one component that has the highest correlation between the time series of its scores and of precipitation at this grid cell. Groups of the grid cells related to the same component form one precipitation region. These regions were mapped.

Regionalisation of the single seasonal precipitation was made by the use of all rotated significant components. Seasonal precipitation values are more evenly distributed between many components and the use of the 10% criterion is not suitable. Involving of more components enabled to carry out regionally more detailed analysis of relationships between circulation and precipitation. Correlation analysis was applied to the relationships. Due to the fact that the relationship between a variable of atmospheric circulation and precipitation might be different throughout a year, only seasonal precipitation was used.

Correlation between time series of scores of principal components of seasonal precipitation and of variables of atmospheric circulation was calculated mostly for the 1900–1996 period. The teleconnection indices (NAOT, EA, EAWR, POL, SCA) were the only exception with the 1950–1996 period. Correlation coefficients, whose absolute values exceed 0.3 were taken into the analysis as sufficiently high. Statistical significance of a correlation coefficient depends on the length of time series. Correlation above 0.3 is significant at $p < 0.01$ for the long period (1900–1996) and at $p < 0.05$ for the short period (1950–1996).

Results and discussion

Regionalisation and trend analysis

Cumulative eigenvalues indicate the percentage of the total variance that is described by some of the first principal components (Table 1). In case of sequential monthly and seasonal precipitation, the first component described more than a half of the total variance, but this was much lower for single seasonal precipitation. There were five significant components for sequential seasonal precipitation and six for sequential monthly values. They described more that 80% of the total variance. Seasonal precipitation had the highest level of data generalisation and, therefore, the highest cumulative eigenvalues (Table 1). Sequential monthly precipitation contained significantly more detailed information.

Seven significant components were detected for summer and autumn precipitation, while eight components were rotated in case of winter and spring precipitation (Table 1). Among the single seasonal precipitation the lowest eigenvalues of the first components appeared in the summer. This is logical because the summer rainfall is of the most random origin, caused mostly by local convective spells. Autumn and winter precipitation was characterised by the highest description of variance using the first components. This means that precipitation in these seasons was determined mostly by large-scale circulation factors and local factors had the least importance. In all seasons, the first four components described from 2/3 to 3/4 of the total variance of precipitation in the Baltic Sea region.

For regionalisation purposes, the first six principal components of sequential monthly precipitation and five components of sequential seasonal precipitation were rotated using varimax normalised rotation. As a result of the rotation, eigenvalues changed and they were not arranged in a descending sequence (Table 2). Four principal components were clearly expressed in both cases. They described 73% and 80% of the total variance, respectively. The share of the other components was much lower and they were not used in regionalisation. Precipitation in the Baltic Sea region was divided into four main regions, each of which corresponds to one of the four components.

As it was expected, the patterns of loadings of the four rotated principal components of sequential monthly and seasonal precipitations were very similar (Figs. 2 and 3), even though the component numbers were not the same. The maps indicate the regions where precipitation had a high correlation with the corresponding component. Thus, the first component (PC1) of the monthly precipitation and the third component (PC3) of the seasonal precipitation are related to precipitation variations in northern Scandinavia. The PC2 of monthly and the PC1 of seasonal precipitation distinguish the southern region (Poland, Lithuania, Belarus, Kaliningrad region). The PC3 of monthly precipitation and the PC2 of seasonal precipitation were highly correlated with precipitation in southern Scandinavia and over the Baltic Sea. The PC4 was in both cases related to precipitation in the eastern region (northwestern Russia, the eastern parts of Finland, Estonia and Latvia).

As a result, four clearly distinguished precipitation regions in the Baltic Sea drainage basin were defined. They could be named as the northern, southern, western and eastern regions, while the western region covered also the Baltic Sea itself. The regionalisation schemes based on two different data representations were similar

Table 1. Cumulative percentage eigenvalues of the significant non-rotated principal components of sequential monthly and seasonal precipitation, and of single seasonal precipitation.

Component	Months	Seasons	Spring	Summer	Autumn	Winter
1	51.9	62.0	41.8	37.0	42.8	43.7
2	62.9	73.0	54.3	50.0	60.4	58.0
3	70.3	78.8	61.7	59.7	68.4	67.1
4	75.1	82.3	66.4	65.8	72.9	71.7
5	78.0	84.8	70.0	69.7	76.9	76.0
6	80.4		73.4	72.5	79.8	79.4
7			76.2	75.3	82.2	81.9
8			78.8			84.3

Table 2. Percentage eigenvalues of the significant rotated principal components of sequential monthly and seasonal precipitation, and of single seasonal precipitation.

Component	Months	Seasons	Spring	Summer	Autumn	Winter
1	13.4	23.2	14.2	14.4	19.3	6.9
2	19.9	22.3	10.1	15.2	14.9	13.9
3	20.7	18.1	12.3	12.7	16.1	16.4
4	19.0	16.4	8.8	9.0	8.9	9.8
5	4.5	4.8	8.5	9.6	14.9	7.9
6	2.9		7.6	7.6	3.1	13.1
7			10.9	6.8	4.9	3.4
8			6.4			13.0

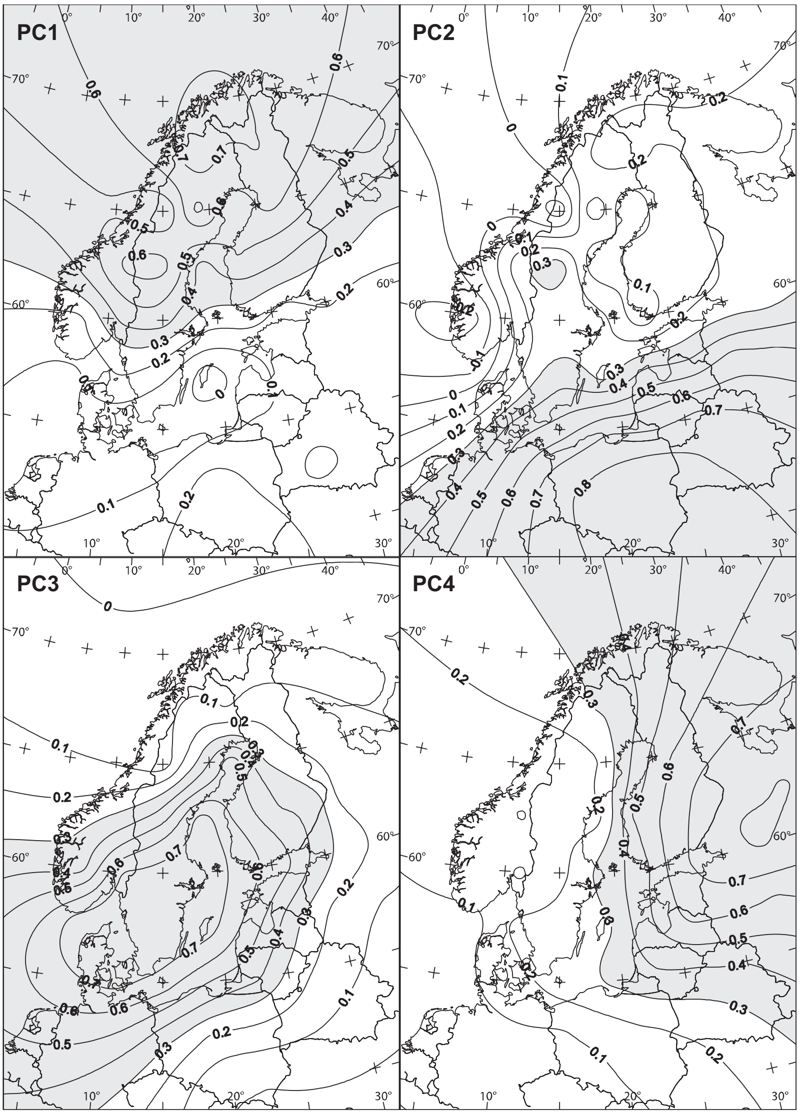

Fig. 2. Maps of loadings of the sequential monthly precipitation.

(Fig. 4). The southern region embraced the same grid cells in both cases. The eastern region was more extended to the west in case of sequential monthly precipitation.

The time series of sequential monthly and seasonal precipitation are not suitable for the analysis of relationships between circulation and precipitation because seasonal fluctuations are not eliminated there. The relationships may be different in different seasons. Therefore, seasonal precipitation was used for studying relationships between precipitation and atmospheric circulation. PCA of seasonal precipitation allows distinguishing specific regions for different seasons. Hereby, eight regions related to eight significant rotated components were distinguished for winter and spring, and seven regions for summer and autumn (Fig. 5).

Relationships with atmospheric circulation

The closest relationships between circulation and precipitation were characteristic for the winter and autumn seasons (Table 3). They were much

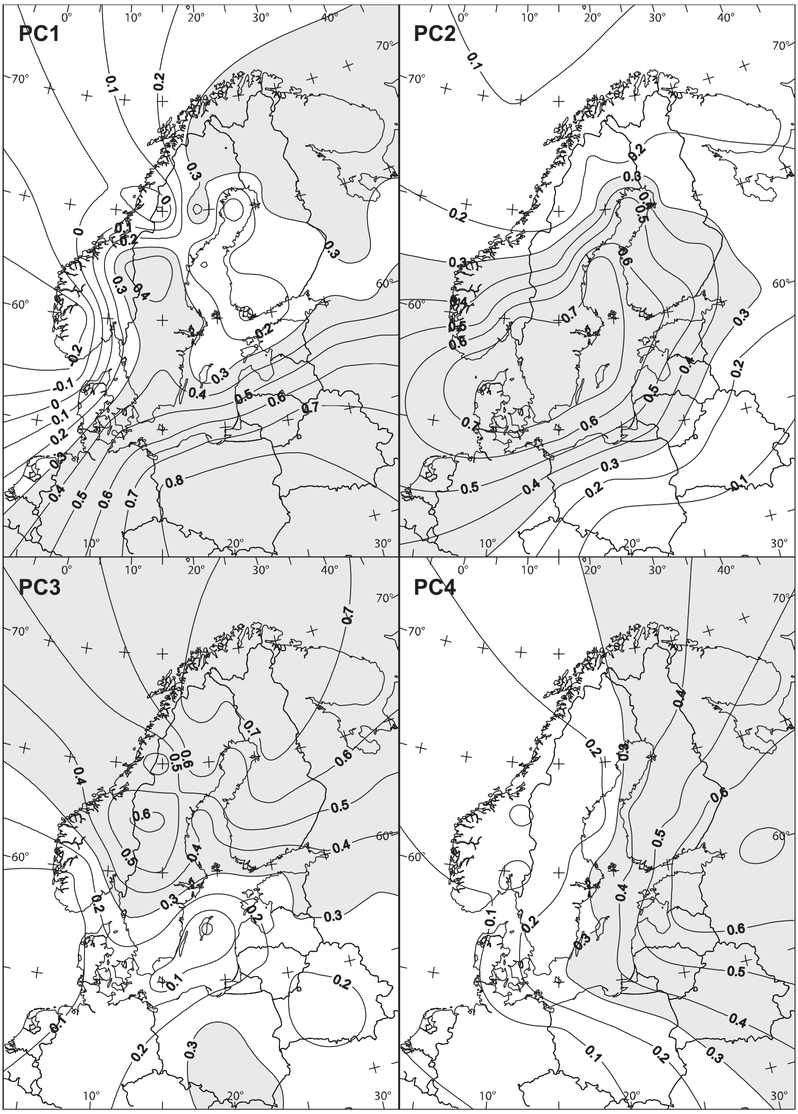

Fig. 3. Maps of loadings of the sequential seasonal precipitation.

weaker in summer and in spring. In winter, the highest values of correlation coefficient were for the PC4 (Scandinavian mountains, Lapland). A lot of precipitation was related to the zonal circulation form W and to the positive values of the NAO and AO indices (Fig. 6). A high correlation with the EAWR teleconnection pattern indicates more precipitation in case of north-westerlies and less precipitation with south-easterlies. A lack of precipitation was related to the meridional types of circulation (E, M) and to the Scandinavia teleconnection index positive phase (anti-cyclone over the Baltic Sea region). In conclusion, westerly and north-westerly airflow and prevailing low pressure over the region (negative SCA) brings moist air from the ocean to the Scandinavian mountains and Lapland where abundant precipitation is recorded. In case of the prevailing of high pressure (positive SCA) or meridional circulation, negative anomalies exist.

This result agrees with results of the previous studies. It has generally been suggested that the NAO index is positively correlated with winter precipitation in northern Europe (Hurrell 1995, Hurrell and van Loon 1997). A much more detailed analysis demonstrated that the relation-

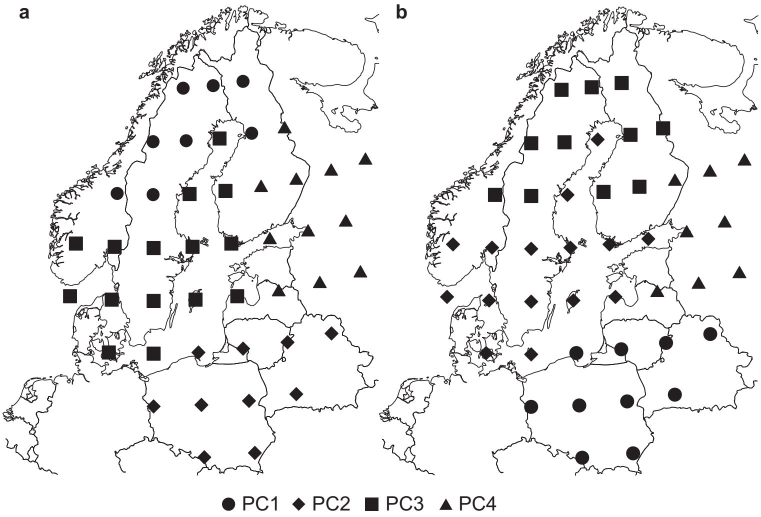

Fig. 4. Regionalisation of the Baltic Sea drainage basin using sequential monthly (**a**) and seasonal (**b**) precipitation.

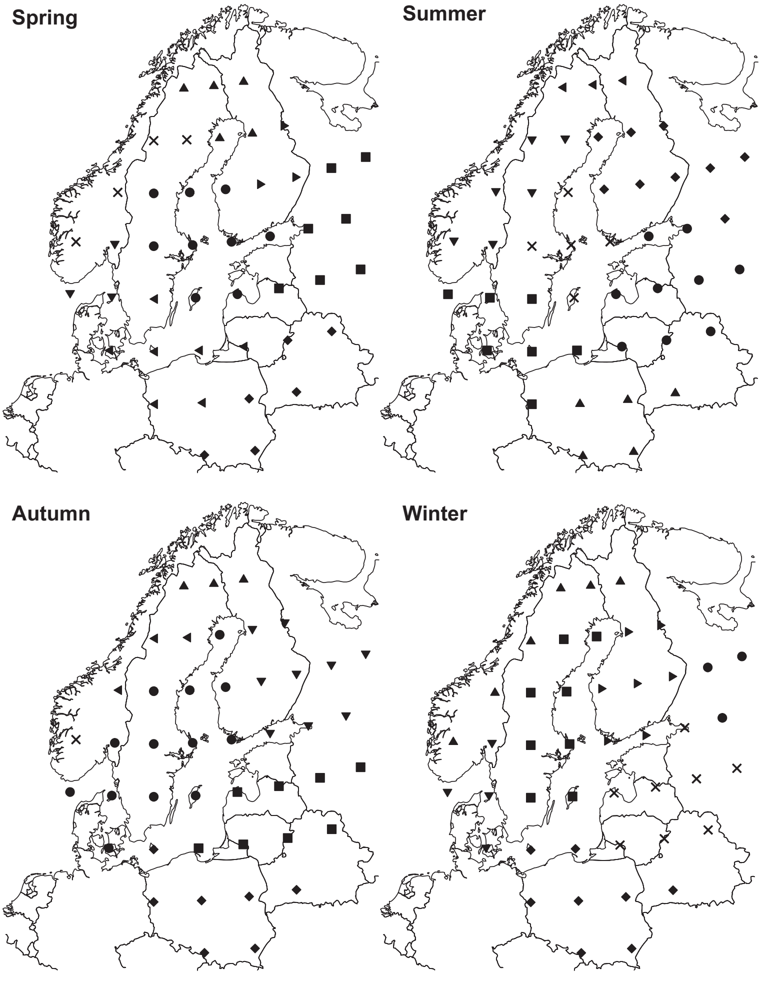

Fig. 5. Regionalisation of single seasonal precipitation.

ship is not uniform all over the region (Uvo 2003). The highest correlation with NAO was detected on the windward side of the Scandinavian mountains while low correlation revealed on the leeward side in the most of Sweden.

Winter precipitation correlations in Denmark and southwestern Sweden (PC5), Finland (PC8), the Baltic countries and northwestern Russia (PC6) were similar to those of the Scandinavian mountains (PC4) but of much lower magnitude.

Table 3. Correlation coefficients between the seasonal circulation variables and the six first PCs of precipitation. Correlations greater than 0.3 are set in boldface. They are statistically significant at $p < 0.01$, except the teleconnection indices (NAOT, EA, POL, EAWR, SCA), which are significant at $p < 0.05$.

Component	1	2	3	4	5	6	7	8
Spring								
W	0.13	–0.03	0.16	–0.12	–0.08	**0.30**	0.08	0.16
E	0.08	–0.07	–0.06	0.20	**0.35**	–0.23	0.06	–0.07
C	–0.26	0.11	–0.09	–0.14	**–0.38**	–0.02	–0.16	–0.11
M	–0.09	–0.12	–0.20	–0.14	–0.15	**–0.47**	–0.13	–0.12
H	0.18	–0.02	0.17	0.15	0.02	**0.46**	0.04	0.11
NAO	–0.08	0.03	0.15	–0.08	0.22	**0.50**	0.05	0.02
AO	–0.07	–0.10	0.01	–0.09	0.02	**0.58**	–0.10	0.23
NAOT	0.07	–0.03	–0.06	–0.08	0.17	0.21	–0.14	**–0.34**
EA	0.17	–0.18	–0.04	0.06	0.21	0.20	**0.34**	0.21
POL	–0.22	–0.06	–0.20	–0.06	–0.20	0.25	0.00	**0.51**
EAWR	**–0.38**	–0.12	0.10	–0.07	–0.03	0.06	–0.02	–0.21
SCA	–0.03	–0.12	**–0.35**	–0.26	–0.08	–0.23	–0.02	–0.25
Summer								
C	–0.02	–0.21	**–0.31**	–0.15	–0.26	–0.11	–0.27	–
Z	0.13	0.07	**0.35**	0.04	0.22	0.23	0.04	–
NAOT	**–0.39**	–0.17	**–0.61**	–0.13	–0.09	–0.05	0.10	–
EA	0.13	–0.12	0.28	–0.01	**0.42**	0.10	0.20	–
POL	**–0.40**	–0.16	–0.08	–0.19	–0.28	–0.27	–0.10	–
EAWR	**–0.37**	**–0.44**	–0.21	0.11	–0.15	–0.24	–0.16	–
SCA	–0.13	**–0.30**	–0.22	**0.44**	–0.16	–0.04	–0.01	–
Autumn								
E	**0.40**	0.15	–0.22	–0.01	–0.19	–0.22	–0.04	–
C	**–0.43**	–0.06	0.07	–0.22	–0.05	0.07	0.03	–
Z	**0.38**	0.05	**0.43**	0.18	0.22	0.26	0.12	–
M	–0.17	0.13	**–0.34**	–0.19	–0.27	–0.29	–0.18	–
NAO	**0.30**	–0.24	0.00	0.20	0.20	**0.39**	–0.06	–
AO	–0.01	–0.29	0.11	0.24	0.09	**0.51**	0.17	–
NAOT	–0.21	**–0.31**	0.03	0.27	–0.27	0.24	0.08	–
EA	**0.52**	–0.24	–0.14	–0.05	0.06	–0.03	0.06	–
POL	–0.25	–0.07	**–0.38**	0.18	0.04	**0.45**	–0.04	–
EAWR	**–0.33**	–0.29	–0.17	–0.23	–0.13	0.19	**0.37**	–
SCA	0.21	0.05	–0.25	–0.15	**–0.45**	–0.16	**–0.34**	–
Winter								
W	0.09	–0.06	**–0.32**	**0.43**	0.11	**0.31**	0.16	0.21
E	–0.17	0.05	**0.35**	**–0.48**	0.10	–0.27	–0.16	0.04
C	0.16	0.01	–0.15	0.20	**–0.31**	0.02	0.04	**–0.33**
Z	0.15	0.26	0.23	0.21	**0.38**	0.25	0.00	0.24
M	–0.16	–0.10	–0.09	**–0.43**	–0.29	–0.25	–0.01	**–0.42**
H	0.03	–0.15	–0.15	**0.31**	–0.05	0.04	0.02	0.26
NAO	0.11	–0.07	–0.13	**0.44**	**0.55**	0.08	0.14	**0.31**
AO	0.05	–0.20	–0.29	**0.62**	0.29	0.08	0.14	0.22
NAOT	0.13	–0.01	–0.03	**0.46**	**0.49**	0.11	0.16	**0.33**
EA	0.05	–0.10	0.13	–0.17	**0.34**	0.29	–0.20	0.01
EAWR	–0.06	–0.11	–0.21	**0.55**	–0.20	0.12	0.07	–0.22
SCA	**–0.37**	–0.20	0.19	**–0.58**	0.17	**–0.36**	–0.17	–0.23

They had the same exposition to the sea where westerly winds bring maritime air. This feature was also drawn out by Uvo (2003).

It is logical that the circulation characteristics expressing airflow from the ocean to the continent on the higher latitudes (AO, W, EAWR) have higher correlation with the PC4 (Scandinavian mountains, Lapland), while the variables expressing westerlies on midlatitudes (Z, NAO, NAOT, EA) have higher correlation with PC5 (Denmark, southwestern Sweden). The frequency of the zonal circulation group Z and the East Atlantic teleconnection pattern (EA) describe westerlies mostly in central Europe.

Quite an opposite exposition to the sea was typical for Sweden (PC3). Most of precipitation arrived there from the east and south-east, i.e. from the Baltic Sea. This feature was expressed as a positive correlation with the frequency of the circulation form E and in a negative correlation with the westerly and north-westerly circulation. This regularity has been mentioned in literature before (Busuioc *et al.* 2001, Uvo 2003), but has not been analysed using empirical data on atmospheric circulation. The southern region (PC2 — Poland, Belarus) had practically no significant correlations between the circulation variables and precipitation components.

In autumn, relationships between circulation and precipitation were mostly the same as in winter, but certain differences appeared (Table 3). The highest correlation coefficients appeared for the PC1 (Denmark, southern and central Sweden, western coast of Finland). An even higher than in winter correlation was found with the frequency of the meridional circulation form E according to the Vangengeim-Girs classification. This means that a large part of precipitation at that region originates from the Baltic Sea. At the same time, a high positive correlation was observed also with the circulation variables expressing south-westerlies in midlatitudes (EA, Z, NAO). Less precipitation or lack of it was related to the variables expressing northerlies (C). The highest correlation with westerlies (AO, POL, NAO) in the autumn season was presented in the mountains of southern Norway (PC6). In other parts of the Baltic Sea region relationship between circulation and precipitation was much lower than in winter.

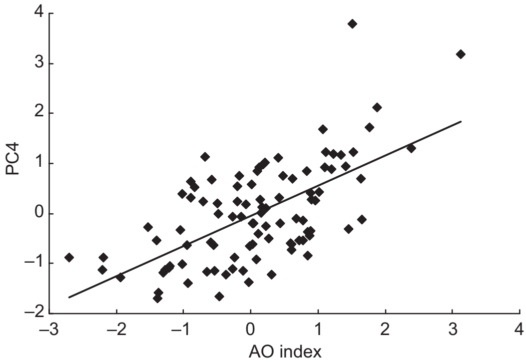

Fig. 6. Scatter plot of the AO index and PC4 of precipitation in winter ($r = 0.62$, $p < 0.01$).

The influence of circulation on precipitation in spring was much lower. Only one region — the Scandinavian mountains (PC6) — had more or less the same relationships as in the winter season. In other regions only some higher correlations were revealed.

Some specific features were detected for the summer precipitation. The majority of precipitation in the summer season was related to local convective spells. The role of atmospheric circulation was much lower. Correlation coefficients between the circulation indices and time series of principal components in Table 3 were not related to circulation itself but to locations of highs and lows in case of different synoptic situations. For example, the NAO teleconnection index (NAOT) had a high negative correlation with precipitation in a wide belt between 50°N and 60°N (PC1, PC3) (Fig. 7). The prevalence of high pressure over this area corresponds to high positive NAOT values. The same effect explains the close negative correlation with POL pattern in the eastern Baltic region (PC1) where positive sea-level pressure anomalies occurred as well. In case of positive EA values, the Scandinavian mountains (PC5) are located under the influence of a low air pressure area centred near Scotland. Mostly negative correlations with the EAWR teleconnection pattern in Finland (PC2) and the Baltic countries (PC1) indicate rainfall with south-easterlies and dry weather with north-westerlies.

It is reasonable to summarise and discuss the relationships also by circulation variables. It is evident that westerly circulation causes

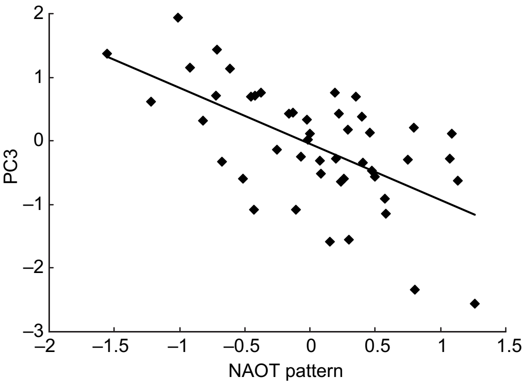

Fig. 7. Scatter plot of the NAOT teleconnection pattern and PC3 of precipitation in summern(r = –0.61, $p < 0.05$).

much precipitation in the Scandinavian mountains, Lapland and other windward coastal regions: Denmark, southwestern Sweden, the Baltic countries, Finland, northwestern Russia. The intensity of westerlies is characterised using different variables — frequencies of circulation form W and of the zonal circulation group Z, the NAO and AO indices, and the NAOT, EA and POL teleconnection indices. Mostly, they are positively correlated with precipitation in winter and, of less magnitude, in autumn and spring.

Precipitation on the leeward side (most of Sweden) had no correlation with westerlies. Easterly, south-easterly and southerly circulations (form E) were positively correlated with precipitation in Sweden due to the fact that these directions are windward sides, i.e. exposed to the Baltic Sea. This result is in agreement with the previous studies (Busuioc *et al*. 2001, Uvo 2003). The circulation form C represents airflow from the northern directions in the Baltic Sea basin. Its frequency was usually negatively correlated with precipitation.

The East Atlantic teleconnection pattern (EA) describes westerlies on more southern latitudes than NAO does. The main EA airflow comes from the Biscayan to central Europe. It is related to precipitation in the southern part of the Baltic Sea region. High correlation with the EA index was revealed in Denmark and southern Sweden in all seasons except summer. In spring, the EA influence appeared also in western Poland.

The East Atlantic/West Russia (EAWR) teleconnection pattern expresses the north-westerly (positive) and south-easterly airflow (negative). Generally, it has a negative correlation with precipitation, especially in central and eastern parts of the Baltic Sea region. This means that south-easterly circulation brings rainfall. The only exception was the Scandinavian highland that had a positive correlation with the EAWR index, first of all in winter. North-westerly winds from the ocean bring precipitation to the mountain area.

The Scandinavian (SCA) teleconnection pattern reflects a high pressure area over the Scandinavian Peninsula in its positive phase and a low pressure area in the opposite phase. Therefore, the SCA index was negatively correlated with precipitation, especially in the eastern part if the Baltic Sea basin (the Baltic countries, Russia) where weak northerlies prevail in case of positive SCA. The only exception was the summer when a significant positive correlation was observed between the SCA index and precipitation in the southern region (Poland, Belarus).

The Polar/Eurasia (POL) teleconnection pattern had a few significant correlations with precipitation. A positive relationship in Finland was revealed in spring and a negative relationship in the Baltic countries and in northwestern Russia in summer and autumn. The latter was caused by the prevailing of high pressure in POL positive values.

Conclusions

A regionalisation scheme for precipitation in the Baltic Sea drainage basin was created using principal component analysis. Based on sequential monthly and seasonal precipitation, four main regions were defined: the northern, eastern, southern and western. The last region embraces also the central part — the Baltic Sea. Regionalisation of a single seasonal precipitation revealed different and detailed patterns with seven to eight regions for each season.

Precipitation pattern in the Baltic Sea drainage basin was remarkably determined by large-scale atmospheric circulation, first of all in winter but also in autumn and spring. Summer precipitation was mostly induced by local convective spells and is not related to circulation.

High correlation with some circulation indices in summer can be explained through air pressure anomalies.

Significant correlations existed between the variables indicating the intensity of westerlies (frequency of the zonal circulation form W and group Z, the NAO and AO indices, the NAOT, EA and POL teleconnection indices). The highest correlation was characteristic for the Scandinavian mountains. The same relationship wasobserved also in other windward regions: Denmark, southwestern Sweden, Lithuania, Latvia, Estonia, Finland and northwestern Russia.

Different relationships were found on the leeward side of the Scandinavian Mountains in most of Sweden, where precipitation was negatively correlated with westerly circulation. Rainfall in Sweden was related to airflow from the eastern and southeastern directions i.e. from the Baltic Sea. This circulation was expressed by the frequency of the circulation form E. Northerly circulation usually causes little precipitation in the Baltic Sea basin.

The teleconnection patterns NAOT, EA, POL, EAWR and SCA have significant influence on precipitation fluctuations in the Baltic Sea region, but it is specific in different locations and seasons. Generally, precipitation is more determined by circulation in the northern and western parts of the Baltic Sea region and less in the southern and eastern parts.

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