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Precipitation pattern in the Baltic countries under the influence of large-scale atmospheric circulation and local landscape factors

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ABSTRACT: The main objectives of the study are to analyse the mean precipitation pattern in the Baltic countries (Estonia, Latvia, Lithuania) and the influence of local landscape factors on it, to derive a regionalization, i.e. select regions having coherent fluctuations in precipitation, and to analyse relationships between precipitation and characteristics of the large-scale atmospheric circulation. Monthly precipitation data from 123 stations in the Baltic countries from 1966 to 2005 are analysed in relation to 52 landscape variables and 13 circulation variables. The landscape variables characterize landscape around the meteorological stations: land cover, land surface elevation, distance from the sea coast, the proportion of water bodies and of forested area. Circulation is described using several circulation indices and frequencies of the main circulation types according to the Vangengeim-Girs and the *Grosswetterlagen* classifications. Maps depicting the mean annual and seasonal precipitation are created and analysed in the aspect of spatial and temporal autocorrelation. The Baltic Sea proved to be the main factor determining precipitation pattern in the study region. The presence of different precipitation zones parallel to the coastline is typical for the windward lowland region, whereas the belt of maximum precipitation is located at 10–60 km from the coast. Surface elevation is the second important factor causing higher precipitation on uplands. Rotated principal component analysis enabled to compose a regionalization of precipitation pattern in the Baltic countries. Four main precipitation regions having coherent fluctuations (south-western, south-eastern, north-eastern and north-western) are defined. Correlations between the variables of atmospheric circulation and precipitation are analysed. The intensity of westerlies is significantly positively correlated with the amount of winter precipitation, especially in the belt of maximum precipitation located at a moderate distance from the sea. Precipitation in the Baltic countries is less related to the meridional circulation types. Copyright © 2009 Royal Meteorological Society

KEY WORDS precipitation; atmospheric circulation; regionalization; landscape variables; Baltic Sea region

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1. Introduction

High spatiotemporal variability of precipitation is typical for the Baltic region (Heino *et al.*, 2008) having important impacts on natural environment and human activity. Precipitation extremes, extensive rainy periods and heavy rainfall events causing flooding as well as long drought periods are the main natural hazards causing economic losses in the Baltic countries, first of all in agriculture. A better understanding of factors influencing the precipitation pattern is of great scientific and economic importance.

Estonia, Latvia and Lithuania are located between 54 and 60°N at the eastern coast of the Baltic Sea in a transitional area from the maritime to the continental climate characterized by a strong westeast gradient in the continentality of climate and the distribution of precipitation. Climatic conditions are determined, first of all, by high cyclonic activity and the prevalence of westerlies. Precipitation regime in the Baltic countries has been studied separately, but not in the framework of the whole region.

The first research on precipitation in the region was carried out by Sresnewsky (1913). Kirde (1939) described the precipitation regime in Estonia using data from 1923 to 1935. Regularities in the spatial distribution of precipitation in Estonia were analysed using a simple statistical model, whereas four landscape parameters were used to describe the mean precipitation pattern (Jaagus and Tarand, 1988). Spectrum analysis of spatially averaged precipitation in Estonia for the period 1866–1990 revealed significant periodical fluctuations of 50–60, 25–30 and 6–7 years (Jaagus, 1992; Jaagus, 1998). Climatic changes in Estonia during the second half of the 20th century were analysed in their relationship with changes in large-scale atmospheric circulation in Jaagus (2006).

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Barloti (1932) described precipitation pattern in Latvia using data from the period 1922–1931. Analysis of seasonality and interannual fluctuations of precipitation in Latvia in 1990–2000 revealed that the total amount of precipitation can be low during any month, a high amount may occur only within a short period in summer (Krauklis and Draveniece, 2004). Long precipitation series in Latvia indicated that precipitation has increased both in the cold (NDJFM) and warm (AMJJSO) periods of the year with the maximum increase in January and March (Briede and Lizuma, 2007).

The first study on the climate of Lithuania presented an analysis of precipitation patterns dividing the Lithuanian territory into three main parts – western, central and eastern (Pakštas, 1926). Two determinant factors were the distance from the sea coast and topography. The Žemaičių Upland plays the main role in the redistribution of precipitation in western and central Lithuania, whereas the Baltic Upland is the most important factor in eastern Lithuania (Bukantis, 1994). The influence of forested areas and large water bodies (Bukantis, 1994; Galvonaitė *et al.*, 2007), different types of air masses (Kaušyla, 1964) and atmospheric circulation on precipitation have been analysed (Ignatavičienė, 1964; Bartkevičienė, 2002). An increase in winter precipitation was recorded in Lithuania during the 20th century related to more frequent advection of warm and humid air masses in winter (Kavaliauskas, 1995; Bukantis *et al.*, 2001; Bukantis and Rimkus, 2005). A trend analysis showed an increase in the number of days with precipitation above 1 mm (Bukantis and Valiuškevičienė, 2005).

Regionalization is an important stage of a climatological study. Usually, it is used to investigate regularities in precipitation patterns. Principal component analysis (PCA) enables to determine regions of coherent fluctuations. A detailed analysis of the patterns in the variability of rainfall in Australian districts at seasonal time-scales based on the rotated PCA was presented by Drosdowsky (1993). Various criteria were examined to determine the number of principal components to rotate. PCA has been applied for the regionalization and for the analysis of long-term changes in precipitation in many regions all over the world [e.g. Walsh *et al.*, 1982 (USA); Ehrendorfer, 1987 (Austria); Maheras, 1988 (Mediterranean); Gregory, 1989 (India); Ogallo, 1989 (Africa); Busuioc *et al.*, 2001 (Sweden)].

Precipitation is influenced by a combination of three groups of factors having different spatial, temporal and seasonal impacts. Atmospheric circulation affects large territories in the highest magnitude determining precipitation in winter. Local landscape peculiarities have a permanent influence on the precipitation pattern while different features have different impacts in different seasons. A large share of the precipitation pattern is related to random fluctuations caused by convective spells.

High temporal variability of precipitation is mostly related to variations in large-scale atmospheric circulation. The variation in circulation regimes may cause a difference in precipitation in different regions of the Baltic countries. Relations between circulation and precipitation in northern Europe have been examined in many studies. Hurrell and van Loon (1997) demonstrated that in case of the North Atlantic Oscillation (NAO) positive phase, wet conditions can be found in western Scandinavia, Denmark, Ireland and Scotland, and dry conditions on the Iberian Peninsula and the western Balkan.

Wibig (1999) studied the main circulation indices related to winter precipitation, based on the 500 hPa geopotential height data using PCA. There is a significant positive correlation between precipitation and the NAO index in northern Europe, and a negative one in the Mediterranean. She defined also the Scandinavia index, which 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).

Correlation between the frequencies of the main circulation forms W (westerlies), E (southerly, south-easterly and easterly circulation) and C (northerly airflow) according to the Vangengeim-Girs classification and European precipitation during the warm and cold half-years was studied by Kożuchowski and Marciniak (1988). They found that the frequency of W is positively correlated with precipitation in northern Europe and negatively in southern Europe, especially in winter. Frequency of C has a negative correlation in the Baltic Sea region and E – in northern Russia, especially in summer. Frequency of E has a positive correlation in southern Europe.

Higher precipitation over Sweden was related to stronger westerlies (higher NAO index) in Sweden (Busuioc *et al.*, 2001). The influence of the NAO on winter precipitation (DJFM) in northern Europe (Norway, Sweden, Finland, Denmark, North-Western Russia and the Baltic countries) was analysed by Uvo (2003). The highest correlation was detected in windward regions – Norwegian coast, northern Sweden and southern Finland. Precipitation on the leeward slopes of the Scandinavian Mountains in Sweden is mainly related to south-easterly winds (Uvo, 2003).

The main objectives of this joint study were:

- to analyse the pattern of the mean precipitation in the Baltic countries;
- to analyse the influence of local landscape factors on the mean precipitation pattern;
- to compose a regionalization scheme for the precipitation in the Baltic countries, i.e. select regions having coherent fluctuations;
- to relate the precipitation time series and the characteristics of large-scale atmospheric circulation.

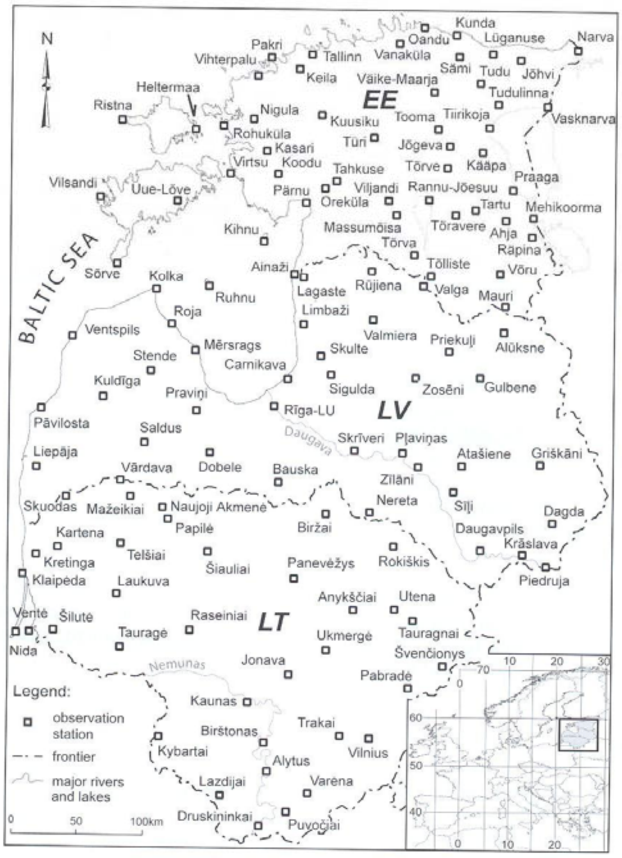

Figure 1. The location of precipitation stations in the Baltic countries – Estonia (EE), Latvia (LV) and Lithuania (LT), and their location in Europe.

2. Data

2.1. Precipitation data

The analysis is based on monthly, seasonal (spring – MAM, summer – JJA, autumn – SON, winter – DJF) and annual precipitation data measured at 123 stations all over the three Baltic countries during years 1966–2005. A total of 51 stations are located on the territory of Estonia, 37 in Latvia and 35 in Lithuania (Figure 1). The precipitation data are obtained from the national weather services of the three countries (Estonian Hydrometeorological Institute, Latvian Environment, geology and meteorology agency, Lithuanian Hydrometeorological Service).

The stations cover the study area more or less evenly. The stations were selected taking into account the existence of a full coverage of observations during the study period. At some stations (Kääpa, Sõrve, Virtsu, Rannu-Jõesuu, Massumõisa, Tudu, Kolka, Akmenė, Mažeikiai, Kartena, Alytus, Jonava, Ventė, Skuodas), the observation series had single gaps. Maximum amount of gaps allowed in this study was 2 years or 5% of the total observation period. The gaps were filled with values calculated using the ratio of precipitation at a neighbouring station having the highest correlation with precipitation at the particular station. The mean precipitation for the Baltic countries was calculated as the mean of the 123 stations.

The beginning of the study period in 1966 was chosen because wetting corrections were added to the measured precipitation values in the former Soviet Union starting from that year. After that, the measurement technique and instruments have not been changed. It allows considering the data nearly homogeneous.

The precipitation data from the study period express a high temporal variability. For example, the highest totals of monthly precipitation in August are 350 mm in Haanja (1987), 303 mm in Skuodas (1978) and 284 mm in Rīga-LU (1987). At the same time, no precipitation was measured at many stations in the months of August in 1994 and 2002.

2.2. Local landscape factors

A precipitation pattern is analysed in dependence on local landscape factors. Altogether 52 explanatory variables (locational features) were derived to characterize landscape around the meteorological stations. The following variables were used: Cartesian coordinates of the Transverse Mercator projection (central meridian 24E) in the westeast (longitude) and the southnorth direction (latitude); 26 variables characterize land cover diversity and the dominant land cover class; 11 variables reflect land surface elevation; 7 variables describe the distance from the sea coast and the share of water bodies, and 6 describe the share of forested area.

Two data layers were used to derive the locational features (excluding the coordinates): the Coordination of Information on the Environment (CORINE) land cover 2000 database (European Commission; http://terrestrial.eionet.europa.eu/CLC2000) and the global Shuttle Radar Topography Mission (SRTM) elevation model (US Geological Survey; http://edc.usgs.gov/products/elevation/srtmbil.html). The spatial indices calculated from the data layers included the number of categories, the index of dominance, the share of a particular category, the modal category and the reverse distance weighted modal category in the case of land cover; the mean value, aspect and quotient of variation were derived from the elevation model. Slope angle was not applied because the SRTM elevation model is not precise in details, and because the slope of land surface is predominantly close to zero in the Baltic countries.

The spatial indices were extracted from the raster format data layers at the precise location of the station (elevation, distance to coast), in the radii of 1, 10 and 20 km and in the southwest sector of the circular kernel using software LSTATS (Remm, 2005, http://www.geo.ut.ee/LSTATS/).

2.3. Large-scale atmospheric circulation data

A large number of variables characterizing atmospheric circulation in northern and central Europe are used in this study, including the circulation indices and the frequencies of circulation types according to two classifications. The NAO index expresses the intensity of the westerlies in the Atlantic/European sector. It is calculated as a difference between the standardized sea-level pressure anomalies between the Azores high and Icelandic low pressure areas (Hurrell, 1995). In this study, the monthly and seasonal NAO indices based on the data from Gibraltar and Stykkisholmur/Reykjavik are applied (Jones *et al.*, 1997). The second essential index is the Arctic Oscillation (AO) index, which describes the strength of circumpolar vortex in the Northern Hemisphere (Thompson and Wallace, 1998). The NAO is observed as a subset of the AO in Europe (Wallace, 2000).

Five teleconnection indices expressing atmospheric circulation conditions over Europe are applied in this study. These are defined by Barnston and Livezey (1987) using PCA of pressure fields in the Northern Hemisphere. Monthly indices were obtained from the web site of the Climate Prediction Centre, National Oceanic and Atmospheric Administration (www.cpc.noaa.gov/data/teledoc/telecontents.shtml). The teleconnection patterns of the North Atlantic Oscillation (NAOT), East Atlantic (EA) and Polar/Eurasia (POL) mostly describe the zonal circulation, whereas the patterns of the East Atlantic/West Russia (EAWR) and Scandinavia (SCA) describe the meridional circulation.

Frequencies of the main circulation forms W, E and C according to the Vangengeim-Girs classification (Girs, 1971) are considered the most appropriate for Estonia (Sepp and Jaagus, 2002). Form W represents the westerly circulation, form E denotes airflow from the east, southeast and south, and form C corresponds to circulation from the northern directions.

The *Grosswetterlagen* classification by Hess and Brezowsky (Gerstengarbe *et al.*, 1999) consists of 29 weather types subjectively determined using daily synoptic maps. The prevailing airflow is analysed with respect to central Europe. The weather types are drawn together into three groups. The zonal circulation group Z expresses only the westerly patterns, the half-meridional group ZM represents the south-westerly and north-westerly flows, and the meridional group M includes northerly, north-easterly, south-easterly and southerly airflows.

3. Methods

Mean annual and seasonal values at the stations were mapped using point kriging for spatial interpolation in Surfer (Golden Software, Inc.). The linear variogram model was applied using precipitation data from all stations. The interpolated precipitation field was smoothed by spline smoothing.

Spatial autocorrelation of the mean values of precipitation at the observation stations characterizing the spatial structure of the means was described by Moran's I statistic (Moran, 1950). Positive values of spatial autocorrelation indicate that the values of a variable tend to be less variable within the pairs of observations located at a particular distance than the overall variance of the observations. Calculation of the spatial autocorrelation function has a presumption of spatial homogeneity and isotropy of the precipitation pattern, i.e. the correlation between the stations depends only on the distance between the stations but not on their location and orientation. Envelopes of the expected probability in case of the null-model of spatial randomness were obtained by 1000 iterative random replacements of the measured values between the stations. A Moran's I value was considered statistically significant at $p < 0.05$ if it was outside the envelope of 95% of the Moran's I values calculated from the iterations with randomly replaced values.

Spatial correlation between the interannual dynamics of precipitation at the stations in every month was also calculated. Based on the correlation matrix of precipitation and the matrix of distances between the stations, a correlation surface was constructed where the value of correlation according to the Pearson *R* is dependent on the month and distance between stations. It is calculated via averaging of the single correlation coefficients by month and distance intervals. The interval of distance zones was 20 km.

The locational features more closely related to the mean values of precipitation at the observation stations were selected and organized using the Feature Selection and Variable Screening (FSVS) module in Statsoft STATISTICA 8 Data Miner (http://www.statsoft.com/products/dataminer.html#feature). This module was applied to select a subset of the ten best predictors for each dependent variable. Search in the FSVS module is performed predictor-by-predictor, i.e. using a first-order search of potential predictors of the outcome variables of interest. Thereby, intercorrelations between the explanatory variables are not taken into consideration.

The Chi-squared Automatic Interaction Detector (CHAID) algorithms (Kass, 1980) implemented in the FSVS module select continuous and categorical predictor variables that show a relationship of the continuous or categorical dependent variables of interest, regardless of whether that relationship is simple (e.g., linear) or complex (nonlinear, nonmonotone). Hence, the program does not bias the selection in favour of any particular model that can be used to find the final best rule, equation, and so on for prediction or classification.

Time series of sequential monthly precipitation and of single seasonal precipitation were used for regionalization of the territory of the Baltic countries. Differences in the seasonal distribution of precipitation serve as important criteria for the classification of the stations. The S-mode PCA (Richman, 1986) is usually applied for regionalization, indicating that spatial units (stations) are the variables and temporal units (months) are the cases in the initial data matrix.

Correlation matrix was calculated and normalization to unity was used for PCA, applied in the STATISTICA 8 software. To put forward the regions of coherent fluctuations in precipitation, rotation of the main components using the varimax normalized technique was applied. The number of principal components to rotate was determined according to the Kaiser criterion, i.e. the eigenvalue of the last component to rotate should be equal to 1 or above.

The significant rotated components were selected for regionalization according to their share in the total variance that ought to be significantly (many times) higher than the share of the other components. Precipitation at each station is related to one of the significant components that has the highest correlation between the time series of its scores and of precipitation at this station. Groups of stations related to the same component form one precipitation region. Stations having similar correlation coefficients with many components were not classified and were considered located in a border zone between the regions.

Correlation analysis was applied to compare the relationships between precipitation and atmospheric circulation. Because of the fact that the relationship between a variable of atmospheric circulation and precipitation can change within a year, monthly and seasonal values were used. Correlation coefficients above 0.30 are statistically significant at the level $p < 0.05$ when the length of time series is 40 years.

4. Results

4.1. Spatial variability of the mean precipitation pattern in the Baltic countries

The precipitation maps were created by the interpolation of the station data from 1966 to 2005 excluding the locational features. Usually, lower precipitation (even below 600 mm per year at some coastal stations in Estonia) is observed in the coastal zone and on islands (Figure 2). It is caused by the comparatively cold sea surface in spring and in the first half of summer, hindering air convection and the formation of clouds. Minimum precipitation is the most pronounced in the coastal regions of Estonia. On the western coasts of Latvia and Lithuania, annual mean precipitation is much higher.

There are two belts of maximum precipitation expanding from the south to the north nearly parallel to the coastal line at the medium distance (10–60 km) from the sea. One of them is located in the western parts of Lithuania and Latvia, in Žemaitija and Kurzeme regions, and

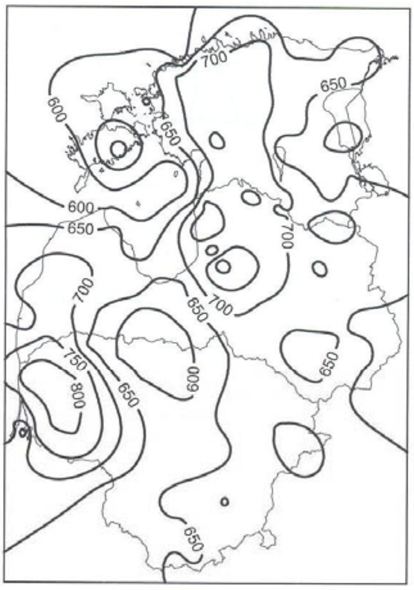

Figure 2. Mean spatial distribution of annual precipitation pattern in the Baltic countries in 1966–2005 as interpolation of data from stations in Figure 1.

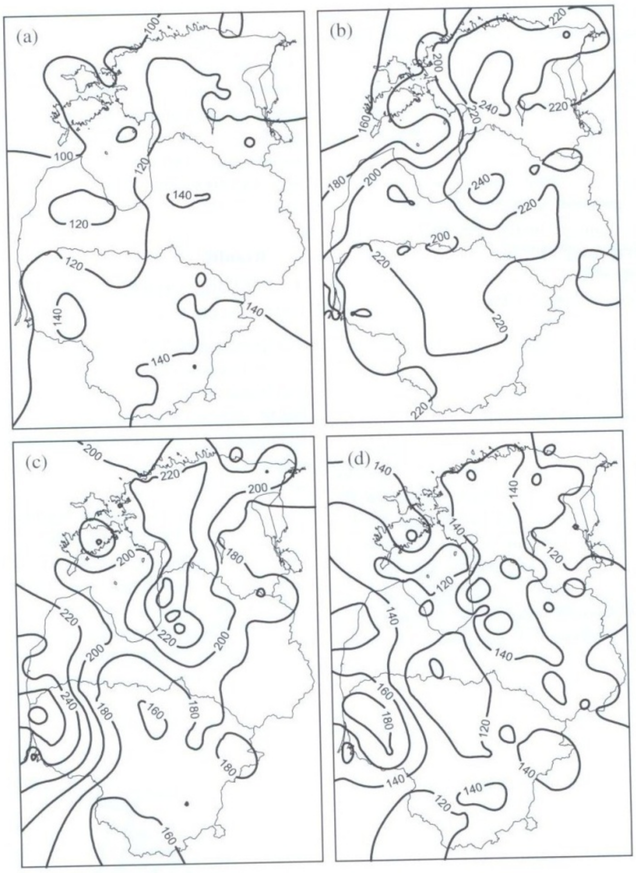

Figure 3. Mean spatial distribution of seasonal precipitation pattern in the Baltic countries in 1966–2005; interpolation of data from stations in Figure 1: (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), (d) winter (DJF).

the other in the western part of continental Estonia and in Central Latvia east of the Gulf of Rīga. The majority of air masses bringing rainfall are moving from the Baltic Sea to the continent, i.e. coming from the south-western and western directions.

Sea surface is rather even and makes only a minor obstacle to the air moving above it. Coming from the sea towards the land surface, the friction resistance of the ground surface against the moving air increases by many times. The dynamic and thermal turbulences of the air moving above the land surface increase rapidly, inducing vertical movement of the air, formation of clouds and precipitation on the medium distance from the sea coast. Further towards the hinterland, precipitation slowly decreases.

Topography is an important factor determining mean precipitation. Higher elevation generally causes more precipitation. Although absolute heights are relatively low in the Baltic countries, where only the highest peaks are above 300 m, topography significantly affects the formation of the precipitation pattern. The highest values of annual mean precipitation (above 800 mm) have been observed in regions where the belt of maximum precipitation at the medium distance from the sea coast is combined with higher areas – in the Žemaičių Upland in western Lithuania and in the Vidzeme Upland in central Latvia. A higher amount of precipitation is observed also in the south-easternmost Estonia and north-easternmost Latvia on the Haanja-Alūksne Upland, which is the highest upland in the Baltic countries.

The highest precipitation values are typical for the windward (south-western and western) sides of the uplands, whereas their leeward sides (north-eastern, eastern) are much drier. A wide belt of minimum precipitation is extended on the Central Lithuanian and Central Latvian Lowlands, and in the eastern coast of Kurzeme Peninsula. It is induced by the combination of a low altitude and the leeward side of uplands. Ascending of

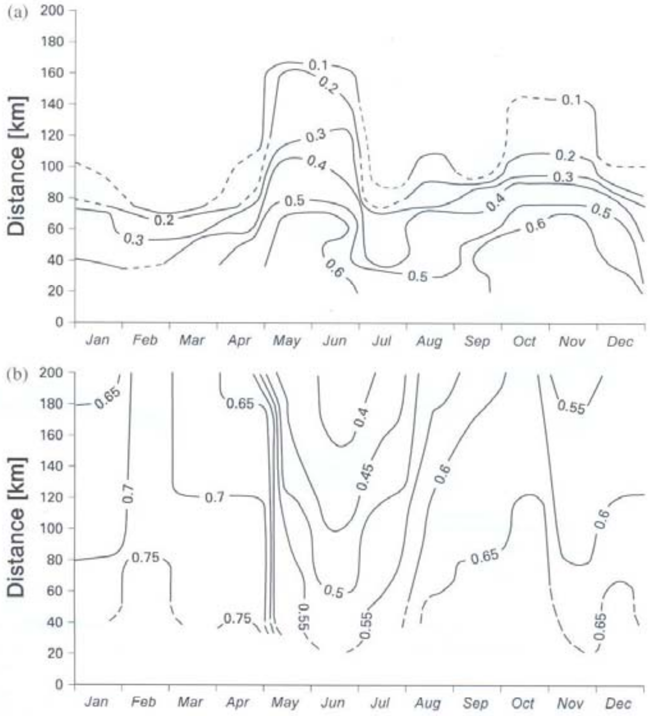

Figure 4. Spatial autocorrelation and correlation of the monthly mean precipitation at stations: (a) spatial autocorrelation as isolines of statistically significant positive Moran's I values: continuous lines indicate $p < 0.01$, dotted lines $0.01 \leq p < 0.05$. (b) interannual similarity according to Pearson R related to the distance between stations.

the moving air causes more precipitation and descending reduces it.

There are significant differences in the spatial distribution of seasonal precipitation in the Baltic countries. Spring precipitation is higher in the south (Lithuania) and lower in the north (Estonia), especially in the coastal regions (Figure 3(a)). The latter is caused by low sea surface temperature in spring, which induces temperature inversion, lack of convective spells, clouds and precipitation above the sea. Summer is the rainiest season in the Baltic countries. The least rainfall has been measured on the West Estonian islands and over the Gulf of Rīga (Figure 3(b)). The highest precipitation has been detected in some continental parts of Estonia and Latvia. The maximum of autumn precipitation is shifted close to the western coastal zone, especially in western Lithuania (Figure 3(c)). A large part of the moisture originated above the sea surface falls down there. Eastern regions of the Baltic countries have much less precipitation in autumn. The pattern of precipitation in winter is rather similar to that in autumn (Figure 3(d)).

Spatial structure of the mean monthly precipitation is expressed using autocorrelation by Moran's I (Figure 4(a)). Regions having similar mean precipitation are wider and more homogeneous in May and June and of lesser extent also in October and November. During the rest of months, spatial variability of the monthly mean precipitation is more complicated – differences in the mean precipitation between closely located stations are higher. The number of station pairs at small spatial intervals is low. Spatial autocorrelations at distances less than 40 km are statistically not significant and therefore are not depicted on Figure 4. Much more closely located stations are needed to describe the pattern of precipitation in further spatial details.

Annual curve of the spatial correlation functions of monthly precipitation is presented using isocorrelates. Isocorrelates are isolines linking the distances of the same correlation at different months. Spatial correlation functions indicate how correlation changes with the increasing of the distance between the stations. Spatially extending high positive correlation values indicate similar precipitation fluctuations over a large area. Correlations sharply decreasing to zero at a relatively low distance indicate that the annual precipitation patterns measured at neighbouring stations are not much related. The latter case is typical for summer months when the showers from small convective spells are frequent. The most extensive

Table I. Ten main landscape variables related to annual, seasonal and monthly precipitation.

Period	Rank									
	1	2	3	4	5	6	7	8	9	10
Annual	*D20*	W10	W20sw	W1sw	W20	W10sw	W1	F10	*D10*	*D10sw*
DJF	**W-E**	F1sw	W20sw	A20	A10	DC	*wML20*	EV1	F10	W10
MAM	E	W10	DC	W20	*wML*20	ES20	ES10	W10sw	*D20*	EV10
JJA	W10	W20	W10sw	W20sw	*wML20*	EV20	*D20*	W1sw	ES20	*ML10*
SON	DC	**W-E**	EV1	EV20	W20sw	ES	ES1	ES20	ES10	E
Jan	**W-E**	F1sw	DC	EV1	W20sw	F10	*D10*	*D10sw*	F1	EV20
Feb	*wML*20	*ML10*	E	*ML20*	W10	A10	*D20*	*D10*	F1sw	F10
Mar	*wML*20	W10	**S-N**	*ML10*	E	A20	A10	*D20*	W20sw	**W-E**
Apr	*wML20*	E	W20	W10	**S-N**	DC	W10sw	EV20	ES20	*D20*
May	DC	E	ES20	W20	ES10	W10	EV20	EV10	ES1	ES
Jun	W20	W10	ES20	ES10	EV20	DC	ES1	ES	W10sw	EV10
Jul	W10	W20	W20sw	W10sw	W1sw	*wML*20	EV20	W1	ES20	*ML20*
Aug	W20	*D10sw*	*D20*	W20sw	*D20sw*	W10	F10sw	W10sw	W1sw	W1
Sep	DC	W20sw	EV1	**W-E**	EV20	ES1	W20	ES	ES20	*D10sw*
Oct	DC	**W-E**	EV1	EV20	W20sw	ES20	ES	ES1	E	ES10
Nov	DC	**W-E**	EV1	EV20	W20sw	ES	ES20	ES1	ES10	E
Dec	**W-E**	DC	A20	EV1	W20sw	A10	*NC10*	*T20*	*ML10sw*	F1sw

W, share of water bodies; DC, distance to the sea coast; W-E, longitude; S-N, latitude; E, elevation; F, share of forest; ES, elevation according to the SRTM model; EV, quotient of variance of elevation; A, dominating slope aspect; T, share of artificial surfaces; ML, modal land cover category; D, index of dominance of land cover categories; NC, number of land cover categories; sw, in southwest sector; wML, reverse distance weighted modal land cover category.

Number indicates the radius of calculation. Features related to water bodies have grey background, coordinates are in bold, share of forest underlined, land surface elevation in regular text, land cover in italics.

spatial correlation is observed during the cold half-year (Figure 4(b)).

4.2. Influence of landscape variables on mean precipitation pattern

Many of the landscape variables are intercorrelated. For example, distance from the Baltic Sea is characterized by the following features: distance to the sea coast, geographic coordinate in the westeast direction (longitude), the proportion of water bodies in a given radius and the index of dominance of land cover units in a given radius. The features based on the same index of landscape pattern calculated in different radii are naturally also intercorrelated. Therefore, the features in Table I include similar indicators and should be interpreted in a generalized manner.

The ten most important landscape variables for annual, seasonal and monthly precipitation are presented in their ranking order (Table I). The main landscape variables related to the mean precipitation are seasonally different. The mean amount of precipitation depends mainly on the distance from the Baltic Sea during the period from September to January (Figure 5(a)). The distance to the coast and longitude were ranked as the highest during this period. Both features involve effects of larger distances (distance to the coast and longitude) in contrast to the

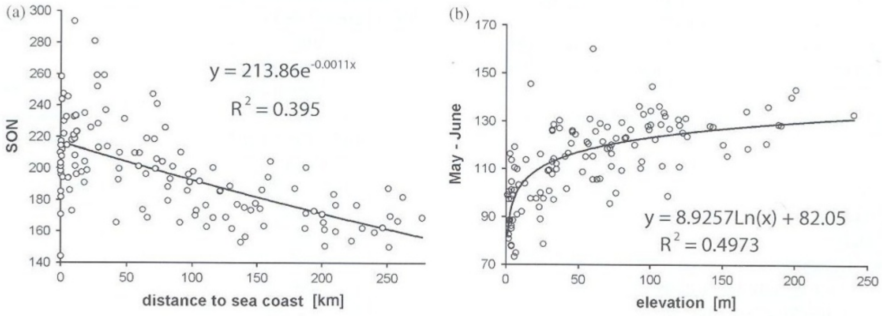

Figure 5. Mean amount of precipitation (mm); (a) – in September-October-November (SON) at stations according to the distance to the sea coast, (b) – in May-June according to the elevation of stations.

amount of water bodies that was calculated up to the distance of 20 km only. The effect of the open sea extends over the distance of 20 km. The sea surface cools down slower than the inland waters.

The mean amount of precipitation correlates first of all with the share of water bodies in the vicinity of an observation station in June, July and August. The Baltic Sea usually acts as a cold surface in summer. Colder air above the sea surface stays stable – it is not forced to ascend. Therefore, clouds are not frequent and precipitation is low above the sea and in the coastal zone in summer.

Among features derived from the land cover, in addition to the share of water bodies, the modal land cover category within 20 km is closely related to mean precipitation. The modal land cover category within 20 km most often involves either coniferous forests (63 stations), the sea (31 stations) or arable land (approximately 23 stations). These are the most frequent options regardless of the way the modal class is calculated – in the distance weighted mode or in southwest sector. In general, the locational features calculated in different radii are intercorrelated. Preference of one or another seems to be largely casual in different months.

Although the differences in land surface elevation are modest in the Baltic countries, elevation is related to the mean amount of precipitation, especially in May and June. As a rule, higher elevated areas have higher precipitation (Figure 5(b)). Land forms are more complicated on uplands. Uneven heating of different parts of the surface causes high thermal turbulence inducing intense convection, formation of clouds and precipitation. Uplands also cause an increase in dynamic turbulence. A small increase in the elevation of land surface induces a large increase in the air flow.

Slope aspect fell into the ten most indicative variables only during winter months. The features calculated in the SW sector, in general, did not correlate better with the mean amount of precipitation than the features calculated in a circular kernel.

4.3. Regionalization of mean precipitation schemes

Precipitation in the Baltic Sea region is mostly related to cyclones moving from the Atlantic to the continent in the East (Jaagus, 2006; Heino *et al.*, 2008). Because of different cyclone tracks, the precipitation patterns differ over the Baltic countries.

Results of the rotated PCA of sequential monthly precipitation revealed four significant components describing 72.3% of the total variance (Table II). The share of other single components was negligible.

Each of the rotated components has a high correlation with precipitation in a certain region. The first component represents precipitation fluctuations in western Lithuania and south-western Latvia located close to the Baltic Proper. The highest correlation is observed at Klaipėda, Kretinga and Kartena (Figure 6(a)). The second component corresponds to the precipitation regime in southern and central Lithuania having maximum correlation at Varėna, Puvočiai and Vilnius (Figure 6(b)). The third component is significantly correlated with precipitation in north-eastern Latvia and eastern Estonia – maxima at Tiirikoja, Vasknarva and Praaga located on the coast of Lake Peipsi (Figure 6(c)). The last significant component describes precipitation fluctuations in north-western Estonia (Figure 6(d)). Thereby, the stations at Heltermaa, Vihterpalu and Keila have the highest correlation with loadings of the fourth component. As a conclusion, four precipitation regions were distinguished in the Baltic countries (Figure 7). The above-mentioned stations can be considered the most typical stations for each region. We named the regions according to their position as south-western, south-eastern, north-eastern and north-western.

Table II. Percentage eigenvalues of the first eight rotated principal components of sequential monthly precipitation and of single seasonal precipitation.

Component	Months	Spring	Summer	Autumn	Winter
1	13.4	19.1	20.6	21.0	30.1
2	20.0	17.4	16.3	20.7	22.8
3	21.8	16.3	20.9	20.9	15.3
4	17.4	19.2	12.7	7.2	11.5
5	3.8	3.6	5.6	9.6	1.2
6	2.9	2.1	1.8	1.8	3.2
7	3.2	1.8	2.2	1.6	1.4
8	1.1	2.2	1.8	2.6	1.7

Estonia and Lithuania are divided between two precipitation regions, one representing a more continental and the other a more maritime climate. The precipitation regime in Latvia, located in the middle, is the most complicated. It is divided between four precipitation regions. The northern parts of Latvia lie in the same regions with Estonia and the southern parts with the Lithuanian regions.

The north-western region extends only to the northernmost coastal area of Latvia. The rest of Kurzeme belongs to the south-western precipitation region. Precipitation fluctuations in Zemgale are similar to the south-eastern region and in Vidzeme to north-eastern region. Eastern Latvia is divided between these two precipitation regions.

The area near Rīga has the lowest correlation with the four significant principal components. Five stations (Rīga-LU, Carnikava, Mērsrags, Skulte, and Stende) have correlations below 0.5. The components weakly describe precipitation fluctuations at that area located between the four precipitation regions in the Baltic countries.

Precipitation in different regions is presumably governed by different synoptic factors. For example, the north-western region is mostly affected by cyclones having a northern trajectory. These move from the Northern Atlantic to northern Scandinavia bringing precipitation mostly in the north-western region. Western cyclones of more southerly track give maximum precipitation to the south-western region. Lows located over northern Russia influence mostly the north-eastern region and southern

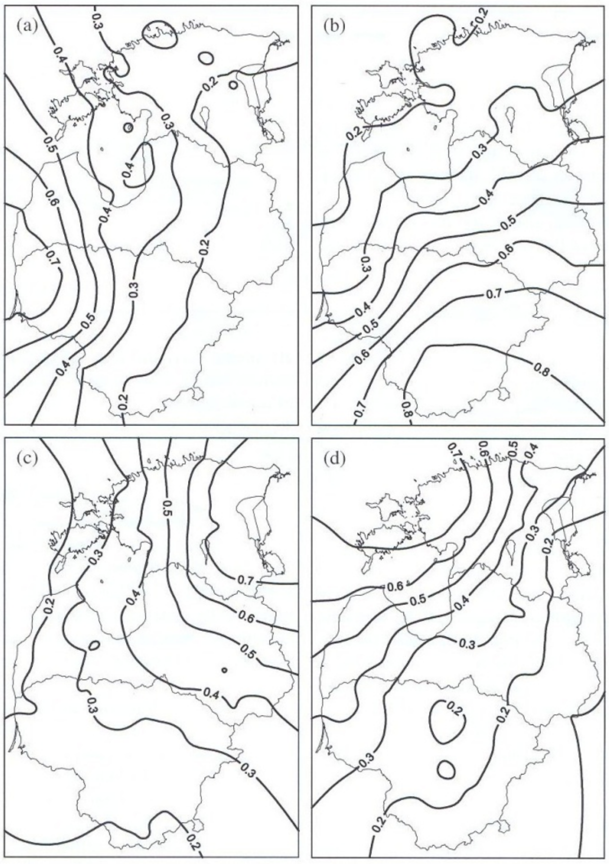

Figure 6. Spatial distribution of loadings of four rotated principal components as a result of PCA from sequential monthly precipitation in the Baltic countries during the period 1966–2005, interpolation of station data (see Figure 1): (a) PC1, (b) PC2, (c) PC3, (d) PC4.

lows bring precipitation, first of all, to the south-eastern region.

Precipitation regions for single seasons were determined using PCA from seasonal data. Four significant components were used for spring, summer and winter precipitation, whereas five components were used for autumn precipitation (Table II).

Precipitation regions for seasonal precipitation (Figure 8) are more or less similar to those for sequential monthly precipitation (Figure 7). The similarity is the highest in spring and summer (Figures 8(a) and 8(b)). The south-western, south-eastern, north-eastern and north-western precipitation regions are presented by PC3, PC1, PC4 and PC2 in spring and by PC1, PC2, PC3, and PC4 in summer, respectively.

PCA revealed five precipitation regions in autumn (Figure 8(c)). The north-western region (PC1) extends to central Estonia. The north-eastern region is divided into two parts – north-eastern Estonia (PC4) and south-eastern Estonia/north-eastern Latvia (PC3). The south-western region (PC5) is rather small in comparison with the south-eastern region (PC2). Winter precipitation regions are located differently than in other seasons (Figure 8(d)). Eastern Latvia and eastern Estonia are related to PC1. Practically, the whole Lithuania belongs to one region related to PC2. The north-western region is more or less the same (PC3). A new region appeared in central Latvia (eastern Kurzeme, western Zemgale, Rīga region), which is related to the PC4.

4.4. Relationships between precipitation and large-scale atmospheric circulation

The results of correlation analysis of relationships between monthly and seasonal values of circulation variables and precipitation revealed significant dependencies (Table III). Three circulation variables expressing the

Figure 7. Precipitation regions in the Baltic countries determined by PCA of time series of sequential monthly precipitation during 1966–2005: ● – south-western, ◆ – south-eastern, ■ – north-eastern, ▲ – north-western, ○ – nonclassified stations located between two regions.

intensity of westerlies – NAO, AO, NAOT – have more or less similar relationships with precipitation characterized by high positive correlation during the cold period, mostly $R = 0.3$–0.6, and a weak negative correlation for the warm period. The highest correlation, which was statistically significant at nearly all stations, revealed for the NAO index in winter. Correlation was the highest in the regions exposed to the Baltic Sea in the western parts of Lithuania and Latvia, and in the continental part of western Estonia (Figure 9(a)). These regions have also the highest mean precipitation. Much lower correlation was observed in the leeward belt in central Latvia and Lithuania, approximately between Rīga and Kaunas, and also on the coasts of the Gulf of Finland and of Lake Peipsi in Eastern Estonia. Rather similar correlation pattern is typical also for the AO index and the NAOT teleconnection index, but the mean correlation is lower.

Correlation between precipitation and the NAOT teleconnection index in summer is mostly negative, especially in the south-eastern region (Figure 9(b)). It is related to the prevalence of a high pressure area over Central Europe in the case of a positive NAOT and a low in the case of a negative NAOT. The EA teleconnection index, reflecting the intensity of westerlies on more southern latitudes than NAOT, generally has a weak correlation with precipitation in the Baltic countries. Significant correlations for annual values revealed mostly in eastern Lithuania. The POL teleconnection index is mostly negatively correlated with precipitation, first of all, during summer. It means that the north-westerly flow is related to less precipitation and the south-easterly flow to higher precipitation. South-easterlies are often related to the southern cyclones.

Relationships between precipitation and the NAO, AO and NAOT indices are higher in Estonia and Latvia, and between precipitation and the EA and POL teleconnection patterns – in Lithuania. Significant correlations of the opposite sign between the NAO index and precipitation in July were revealed in Estonia and Lithuania.

Table III. Correlation coefficients between average precipitation in the Baltic countries during 1966–2005 and the monthly, annual and seasonal circulation variables.

	NAO	AO	NAOT	POL	EAWR	SCA	W	E	C	Z	M
Jan	**0.54**	**0.40**	**0.51**	−0.14	−0.06	**−0.64**	**0.44**	**−0.32**	−0.08	**0.60**	**−0.53**
Feb	**0.51**	**0.40**	**0.31**	−0.23	0.01	**−0.74**	**0.69**	**−0.55**	−0.18	**0.44**	**−0.55**
Mar	**0.52**	**0.34**	**0.40**	−0.28	−0.15	**−0.45**	0.27	−0.10	−0.19	**0.38**	**−0.55**
Apr	0.18	0.12	−0.26	0.26	**−0.33**	**−0.34**	0.19	0.18	**−0.41**	**0.38**	−0.13
May	−0.16	−0.18	**−0.41**	0.21	**−0.30**	−0.09	0.14	−0.02	−0.08	0.09	0.10
Jun	**−0.31**	**−0.39**	**−0.61**	−0.22	**−0.36**	**−0.41**	**0.31**	0.19	**−0.47**	**0.43**	−0.12
Jul	0.02	−0.19	**−0.37**	**−0.52**	**−0.43**	0.03	0.21	0.22	**−0.52**	**0.38**	−0.19
Aug	−0.07	−0.19	−0.27	**−0.43**	**−0.30**	**−0.48**	0.16	0.10	−0.27	0.28	−0.19
Sep	0.18	−0.06	−0.11	**−0.44**	0.27	**−0.60**	**0.47**	−0.28	−0.20	**0.63**	**−0.46**
Oct	−0.03	−0.12	−0.27	**−0.31**	−0.19	**−0.49**	**0.32**	−0.13	−0.27	**0.30**	−0.28
Nov	0.11	0.22	−0.18	0.17	−0.28	**−0.45**	**0.47**	**−0.41**	0.07	**0.52**	**−0.41**
Dec	0.25	0.23	**0.50**	0.01	−0.18	−0.28	**0.43**	−0.13	**−0.31**	**0.59**	**−0.40**
Year	0.15	0.01	0.02	**−0.46**	−0.22	**−0.43**	0.16	−0.02	−0.17	**0.46**	**−0.41**
Spring	0.28	0.09	−0.12	0.01	−0.27	**−0.36**	0.25	−0.01	−0.29	0.19	**−0.38**
Summer	−0.16	**−0.36**	**−0.53**	**−0.54**	**−0.63**	**−0.36**	0.23	0.17	**−0.47**	0.26	−0.26
Autumn	0.12	0.07	0.02	−0.27	0.12	**−0.53**	**0.32**	−0.27	0.08	**0.36**	**−0.41**
Winter	**0.58**	**0.47**	**0.52**	−0.17	0.10	**−0.74**	**0.55**	**−0.48**	0.06	**0.64**	**−0.63**

Statistically significant correlations ($p < 0.05$) are in bold.

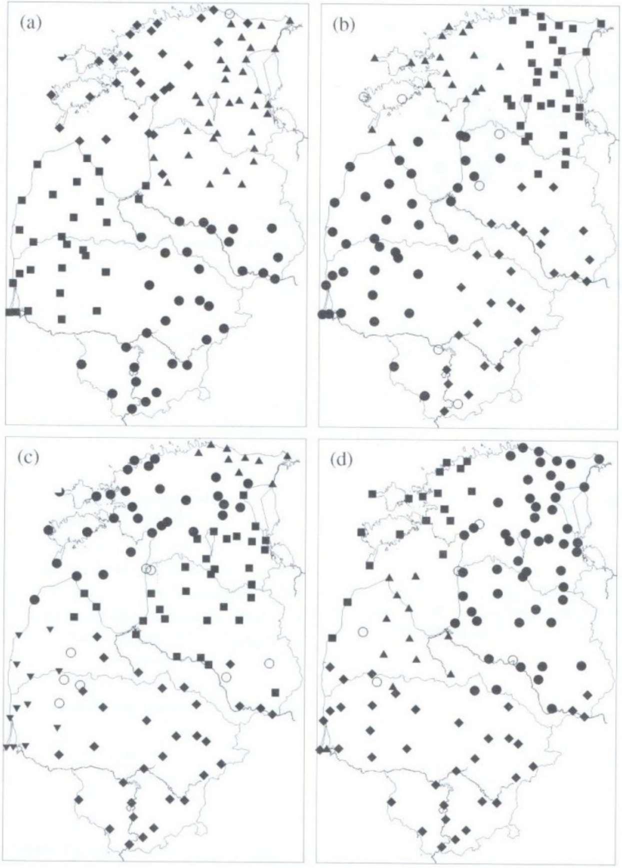

Figure 8. Seasonal precipitation regions in the Baltic countries determined using PCA from time series of seasonal precipitation during 1966–2005: ● – PC1, ◆ – PC2, ■ – PC3, ▲ – PC4, ▼ – PC5, ○ – nonclassified stations located between two regions; (a) spring, (b) summer, (c) autumn, (d) winter.

The EAWR teleconnection pattern expresses meridional circulation over the Baltic Sea region. In the case of a positive EAWR, the area of lower sea-level pressure (SLP) is located over Russia and higher SLP over the British Isles. This synoptic situation causes northerlies over the Baltic countries, which is negatively correlated with precipitation (Table III). The closest negative relationship is observed in the summer season (Figure 9(c)), a higher correlation being in northern Estonia.

The SCA teleconnection pattern reflects air pressure conditions over Scandinavia and the Baltic Sea region. A positive SCA index denotes high pressure conditions; negative values correspond to low pressure. Not surprisingly, the SCA indices have a high negative correlation with precipitation, especially during winter and autumn. Higher correlation areas are located in the regions of higher precipitation and vice versa (Figure 9(d)). Generally, the negative correlation is lower in Lithuania than in Estonia and Latvia, especially in summer.

Frequency of the main circulation forms according to the two circulation classifications is closely related to precipitation in the Baltic Sea region. As a rule, frequency of the zonal circulation forms (W, Z) are positively correlated with precipitation, and frequency of meridional circulation forms (E, M) has a negative correlation. The relationships are the highest in winter and the lowest in summer (Table III). The circulation forms according to the Vangengeim-Girs classification have typically a higher correlation in the northern part of the observed area (Figure 9(e)), whereas the *Grosswetterlagen* classification is more informative in the southern part, i.e. in Lithuania. In winter, the circulation form E is related to a cold high over Russia and a cold

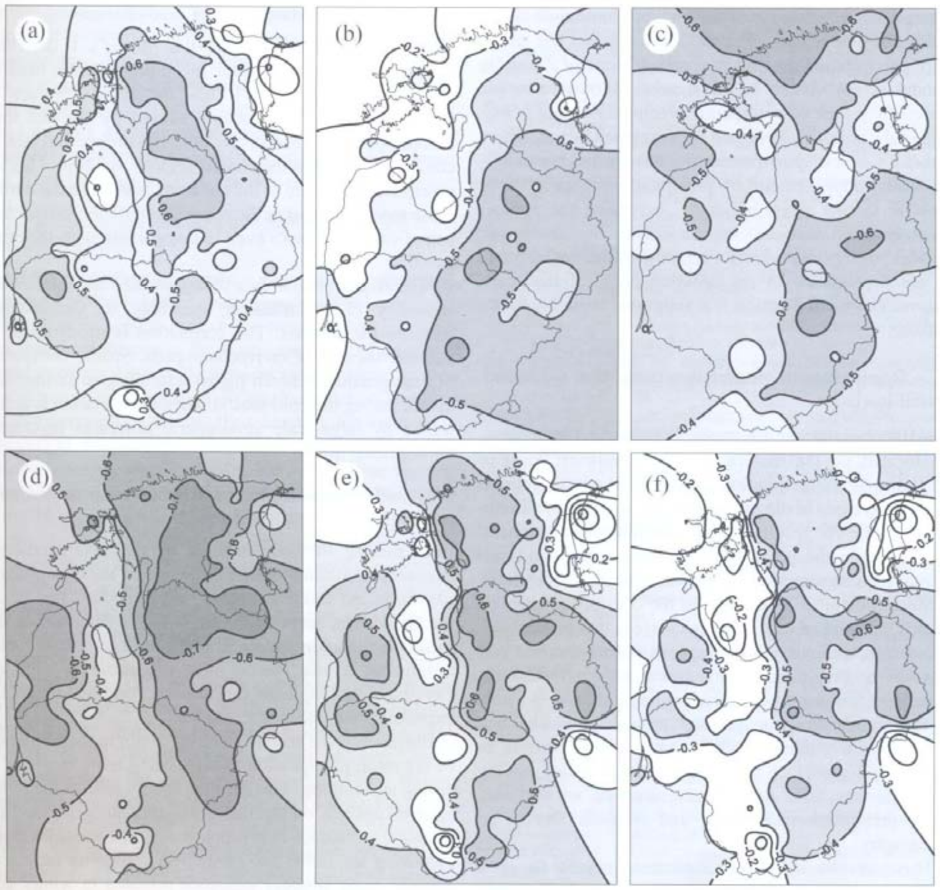

Figure 9. Spatial distribution of the correlation between circulation variables and precipitation in the Baltic countries during 1966–2005: (a) NAO index in winter, (b) NAOT teleconnection index in summer, (c) EAWR teleconnection index in summer, (d) SCA teleconnection index in winter, (e) frequency of the circulation form W in winter, (f) frequency of the circulation form E in winter. Statistically significant area correlation is grey.

airflow from the east, southeast and south where dry weather prevails. Stronger negative correlation is located in eastern Latvia (Figure 9(f)). The circulation form C has a weaker correlation with precipitation, especially in winter.

There are few circulation variables having statistically significant relationships with precipitation during the spring season. It is the period when local factors have the largest influence on precipitation formation and distribution.

5. Discussion and conclusions

5.1. Quality of the precipitation maps

Using data from a number of stations from the three countries allows an improved presentation of the precipitation patterns compared with results of the former studies, which were composed separately for single countries (Jaagus and Tarand, 1988; Ziverts, 2004; Galvonaitė *et al.*, 2007). Now, discrepancies at the borders have been eliminated.

The precipitation maps were created by interpolation of the station data, which inevitably includes artefacts because of generalization and some interpolation errors. The share of artefacts would be less if the network of stations were denser.

Some biases in the precipitation maps are caused by the unavailability of continuous observations in the research period. For example, the higher precipitation rate on the Otepää Upland (southern Estonia) and in the hinterland parts of Saaremaa and Hiiumaa islands has been proved (Jaagus and Tarand, 1988) but does not reveal in

Figures 2 and 3 because of the lack of continuous observations at that regions. For the same reasons, the maximum precipitation amount in southern slope of Žemaičių Upland is not visible in the figures. Another example caused by a lack of continuous precipitation data is evident in the south-western part of Kurzeme Upland, where higher amount of precipitation (>800 mm) is typical.

Further improvement of precipitation maps will be possible in two ways, either by increasing the number of observation stations, i.e. increasing the density of network, or by constructing a reliable spatial model based on the dependence of precipitation on local landscape factors. The second option is a suggested topic for future studies.

5.2. Regularities in precipitation patterns in windward coastal lowlands

The Baltic countries – Estonia, Latvia and Lithuania – are located on the eastern, i.e. the windward coast of the Baltic Sea. Precipitation in windward coastal regions rapidly increases in the mountains, e.g. in Norway (Tveito *et al*., 2001). The results of this study indicate that general regularities in the precipitation pattern in the windward coastal regions are clearly presented also on the lowland.

Mean precipitation is lower in the coastal zone and on islands, because of the colder sea surface that prevents air convection, especially in spring and during the first half of summer. Precipitation increases significantly towards hinterland forming a belt of higher precipitation, oriented in southnorth direction parallel to coastline. The belt is present in summer and becomes even stronger in autumn and winter. A big share of the moisture moving from the sea falls down there. Further to the east, mean precipitation decreases and depends mostly on topography.

These results on the precipitation pattern lie in a good concordance with the previous studies (Jaagus and Tarand, 1988; Bukantis, 1994; Briede and Lizuma, 2007; Galvonaitė *et al*., 2007). Precipitation pattern on the Baltic Sea drainage basin (Heino *et al*., 2008) also demonstrates that the belts of higher precipitation parallel to the coastline in the Baltic countries are areas of the highest precipitation over the whole region. Mean precipitation in spring is higher in the southern parts of the study area (Lithuania) and lower in the northern parts (Estonia; Figure 3). This relation changes in summer when the mean precipitation amounts in Lithuania are usually lower than in continental Estonia.

Longitudinal precipitation zones are well presented in Latvia and Lithuania. Their western areas, Žemaičių and Kurzeme Uplands, usually receive much higher precipitation. Mean precipitation in the coastal zone west of the uplands is lower. The next zone east of the uplands (Central Lithuanian and Central Latvian Lowlands, eastern coast of the Kurzeme Peninsula) is located in the leeward side characterized by much lower precipitation. Higher precipitation is again observed on the uplands of eastern Lithuania and central Latvia.

5.3. Spatial autocorrelation of precipitation

Spatial autocorrelation using the Moran's I describes the statistical structure of the mean precipitation patterns in a generalized way. It has the highest values in May and June. It is probably caused by the fact that, because of the comparatively cold sea surface and lack of convective spells in the coastal regions, the belt of higher precipitation parallel to the coastline does not exist during those months. It makes the mean precipitation pattern less complicated and more even in comparison with the other months.

Spatial correlation function indicates an interannual similarity of precipitation according to the distance between the stations. The correlation is much lower in summer because of convective spells. Spatial correlation of precipitation is much higher extending to further distances during the cold season when precipitation is determined by large-scale atmospheric processes (cyclones, atmospheric fronts).

5.4. Influence of landscape variables on precipitation pattern

Data mining methods enabled to rank the landscape variables according to their influence on the precipitation pattern in the Baltic countries. Water bodies, first of all the Baltic Sea, serve as the main factor determining the mean precipitation pattern. It is the most important factor throughout a year, being most influential in summer. Geographical longitude can also be considered a factor expressing the distance to the sea.

Elevation is the second affecting factor in the formation of the mean precipitation pattern, being more essential in spring and autumn. This result probably reflects the influence of uplands on thermal turbulence in spring and on dynamic turbulence in autumn. Landscape variables characterizing the forest and land cover categories have less impact. Their stronger influence revealed in winter and spring. Expectedly, further investigations will improve the knowledge of how the local landscape factors influence the formation of the meso-scale and micro-scale precipitation patterns.

5.5. Regionalization of precipitation

Regionalization of precipitation in the Baltic countries using the PCA enabled to distinguish regions with coherent fluctuations. Four clear precipitation regions were defined. The main sources of precipitation in the Baltic countries are cyclones moving from the Northern Atlantic from the west to the east towards the continent, although peculiarities are still evident in different regions.

Precipitation in the north-western region (western Estonia, northern Kurzeme) is presumably, first of all, determined by cyclones located over the Norwegian Sea and moving from the west to the east in Northern Scandinavia. The south-western region (western Lithuania, western Latvia) is more affected by the cyclones having southern trajectories, especially by cyclones over the Baltic Sea region. Precipitation in the north-eastern region (eastern Estonia, eastern and central Latvia) is, probably, more affected by eastern cyclones over the Russian territory, which move from the west and also from the northern and southern directions. At the same time, precipitation in the south-eastern region (central and eastern Lithuania, south-eastern Latvia) is more related to the southern cyclones moving north from the Mediterranean, the Black Sea and the Caspian Sea regions.

5.6. Relationships between atmospheric circulation and precipitation

Analysis of correlation between precipitation and circulation variables revealed quite significant relationships. These can be summarized in the most general way saying that precipitation in the Baltic countries is related to zonal circulation (westerlies), especially in winter, and to low pressure conditions. Meridional circulation and high pressure conditions are mostly related to dry weather. In the case of meridional airflow during the warm half-year, southerlies and south-easterlies have a positive correlation with precipitation and northerly airflow – a negative correlation. Precipitation in Estonia and Latvia has a higher correlation with the variables describing circulation conditions in Northern Europe, whereas precipitation in Lithuania is more related to the circulation variables for central Europe (the *Grosswetterlagen* classification, EA teleconnection pattern).

Results of this study lie in a general correspondence with regularities detected in the previous studies. Winter precipitation is determined by the intensity of westerlies expressed by many circulation variables (NAO, AO, NAOT, W, Z). The same for the whole northern Europe is elucidated for the NAO index (Hurrell, 1995; Hurrell and van Loon, 1997; Wibig, 1999) and for the frequency of the circulation form W (Kożuchowski and Marciniak, 1988). The area of the highest correlation between the variables of the intensity of westerlies and precipitation is located on the windward belts of higher precipitation not far from the sea coast. The same result was obtained also by Uvo (2003), who analysed relationships between the NAO index and precipitation in the Nordic countries.

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