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Changes in precipitation regime in the Baltic countries in 1966–2015

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Abstract The aim of the study was to analyse trends and regime shifts in time series of monthly, seasonal and annual precipitation in the eastern Baltic countries (Lithuania, Latvia, Estonia) during 1966–2015. Data from 54 stations with nearly homogeneous series were used. The Mann-Kendall test was used for trend analysis and the Rodionov test for the analysis of regime shifts. Rather few statistically significant trends ($p < 0.05$) and regime shifts were determined. The highest increase (by approximately 10 mm per decade) was observed in winter precipitation when a significant trend was found at the large majority of stations. For monthly precipitation, increasing trends were detected at many stations in January, February and June. Weak negative trends revealed at few stations in April and September. Annual precipitation has generally increased, but the trend is mostly insignificant. The analysis of regime shifts revealed some significant abrupt changes, the most important of which were upward shifts in winter, in January and February precipitation at many stations since 1990 or in some other years (1989, 1995). A return shift in the time series of February precipitation occurred since 2003. The most significant increase in precipitation was determined in Latvia and the weakest increase in Lithuania.

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1 Introduction

The Baltic Sea region has experienced a significant climate warming in the last half-century. During a long period (1871–2011), the annual mean air temperature has increased by 0.11 K per decade in the northern part of the region (north of 60°N) and by 0.08 K per decade in its southern part (BACC Author Team 2015). In the second half of the twentieth century and the beginning of the twenty-first century, the warming has been much higher (Casty et al. 2005; Lehmann et al. 2011). Climate projections show a continuous temperature increase until the end of the century (IPCC 2013).

Precipitation is another very important climatic variable. Projections of precipitation change corresponding to climate warming are more uncertain (IPCC 2013). General circulation models (GCMs) foresee more precipitation in northern Europe and less in southern Europe. Between these regions, there is a broad zone where only small changes are projected (Kjellström et al. 2011). This transition zone shifts southward in winter and northward in summer.

The Baltic Sea region will be characterised by a moderate increase in precipitation by the end of this century, especially during the cold half-year (BACC Author Team 2015), because warmer air is able to hold more moisture and can, thus, give more precipitation. Precipitation projections in the Baltic Sea basin for the summer season are ambiguous. For example, some results of GCM experiments show an increase in summer precipitation by the end of the century, while other models indicate a decrease in rainfall (Jaagus and Mändla 2014; BACC Author Team 2015).

Long-term trends and variations of precipitation based on empirical measurements have been investigated in many regions of the world. Precipitation is characterised by a very high spatial and temporal variability, which makes such kind of analyses quite complicated. One of the aspects that

complicate analyses is the fact that only a few long-time series of precipitation are really homogeneous. Inhomogeneity is caused by the improvement of precipitation gauges and measuring techniques, as well as by numerous relocations of observation sites. For example, the introducing of Tretyakov gauges in the former USSR since the beginning of the 1950s abruptly increased the measured solid precipitation amount in winter (Groisman et al. 1991; Groisman and Rankova 2001). Random extreme precipitation events at some stations can have a significant influence on trend values, causing large differences at neighbouring stations.

A wide overview on precipitation trends worldwide is presented by New et al. (2001). Different changes have been detected for different regions of Europe. Generally, the annual zonally averaged precipitation has increased by 7–12% between 30° and 85°N during the twentieth century (IPCC 2001). Such a trend revealed in Europe mostly in winter, autumn and spring but not in summer. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 with medium confidence before and high confidence after 1951 (IPCC 2013).

The second half of the last century is described by increasing precipitation in northern Europe and decreasing precipitation in southern Europe (Schönwiese and Rapp 1997; Hanssen-Bauer and Førland 2000), which could be explained by the prevailing of the positive phase of the North Atlantic oscillation (NAO) in the end of this period. In the Baltic Sea region, an increase in precipitation was observed in 1976–2000, compared to 1951–1975 (Beck et al. 2005; BACC Author Team 2008). The highest increase was observed in Sweden and on the eastern coast of the Baltic Sea in winter and spring. In Finland, no precipitation trends were revealed (Tuomenvirta 2004; Kilpeläinen et al. 2008), but an increase in summer precipitation was found for 1908–2008 (Ylhäisi et al. 2010). Similarly ambiguous results were obtained from Poland (Kożuchowski and Żmudzka 2003; Degirmendžić et al. 2004; Niedźwiedź and Twardosz 2004).

An increase of about 5% in annual precipitation in the European part of the former USSR was estimated since 1891 (Georgievsky et al. 1996; Bogdanova and Mescherskaya 1998; Groisman and Rankova 2001). Using the corrected precipitation data from 1936 to 2000, an increase in annual precipitation by 80–100 mm was observed in westernmost Russia (Bogdanova et al. 2010).

Several authors have studied precipitation changes in the Baltic countries — Lithuania, Latvia and Estonia. Kriaučiuniene et al. (2012) found 26–30-year variations in wet and dry periods in all three countries during 1922–2007.

A statistically significant increase (at nine from ten stations) by 80–180 mm was detected in annual precipitation in Estonia during the second half of the twentieth century (Jaagus 2006). The trend was mostly determined during the cold part of the year but not in summer.

Using precipitation data from 24 stations in Latvia during 1922–2003, no clear trends were distinguished (Briede and Lizuma 2007). An increasing tendency was observed in most of the analysed territory, but a statistically significant trend in annual precipitation appeared only at five stations. Single-month positive trends were found at several stations in January, February, March and June, while negative trends were revealed in September. Klavins and Rodinov (2010) did not find any statistically significant trends in annual precipitation at five stations in Latvia during 1948–2006, while long precipitation series from Rīga (1874–2006) have an increasing trend in winter, the cold season and annual values.

Precipitation has increased during the cold season and decreased during the warm season in Vilnius, Lithuania, during the second half of the twentieth century (Bukantis and Rimkus 2005). The number of days with heavy precipitation (above 10 mm) has increased in 1961–2008 (Rimkus et al. 2011). The same tendency was obtained in Latvia for the period 1948–2008, but the trend was significant only in a half of the studied time series (Avotniece et al. 2010).

Usually, climatic changes are analysed using different methods of trend analysis. Such analysis allows determining whether there is a statistically significant monotone increase or decrease in the studied time series. However, the assumption of monotone trends is often not justified. Abrupt changes can be found, i.e. jumps or breaks, which divide the time series into parts with different statistical properties. Such breaks in meteorological and hydrological time series are mostly caused by the inhomogeneity of the series (Heino 1994). Purely natural reasons for the breaks are also possible. Such natural changes are known as regime shifts.

Initially, the term "regime shift" was used in ecology. It means a large, abrupt and persistent change in the structure and function of a system (Biggs et al. 2009). Later, the term regime shift moved into climatology, where there is a variety of concepts for the definition of regimes. The semantics of regime shifts is described in detail by Overland et al. (2008).

Many studies have detected regime shifts in many parameters in the late 1980s, especially since 1989. For example, analysing the wintertime sea-surface temperatures over the Northern Hemisphere during the twentieth century, six regime shifts were detected, one of them in 1988/1989 (Yasunaka and Hanawa 2002). Oceanographic, climatological and biological time series from the Northern Pacific and the Bering Sea revealed regime shifts in 1977, 1989 and 1998 (Overland et al. 2008). The regime shift in that region since 1989 was thoroughly analysed by Hare and Mantua (2000). At the same time, a regime shift is well expressed in river runoff in Latvia, indicating a decrease in spring floods and an increase in winter discharge (Apsīte et al. 2013).

Using wind components at 850 and 500 hPa level over Estonia, an increase was detected in zonal circulation in February since 1987 (Keevallik and Soomere 2008). At the

end of the 1980s, a similar jump was found in the time series of cumulative wind stress calculated for December–January using data from Utö (Elken et al. 2014). During the period 1981–2010, an upward shift in the average airflow speed over the Gulf of Finland in January was detected in 1988 and a downward return shift in 1994 (Keevallik and Soomere 2014). Based on the data of two stations in Estonia, the majority of regime shifts in the end of winter were concentrated on the end of the 1980s. An abrupt increase in the zonal component of average air flow was observed from January to March, in air temperature in January and February and in precipitation in February (Keevallik 2011).

The main objective of this study is to evaluate changes in the precipitation regime in Lithuania, Latvia and Estonia, located on the eastern coast of the Baltic Sea, during the last decades, in 1966–2015. An attempt is made on trend analysis as well as the analysis of regime shifts.

We assume that the direction of future changes in precipitation should partly be evident already today. As air temperature has significantly increased during the last decades, the corresponding possible changes in precipitation should also have taken place during the same period. Therefore, it is really important to precisely determine the current climate changes, which can show the direction of possible precipitation changes in the future.

2 Data and methods

Monthly precipitation data from 54 stations in the Baltic countries — 19 stations both in Estonia and Latvia and 16 in Lithuania — in 1966–2015 were used in this study. The data were obtained from the Estonian Weather Service, the Latvian Environment, Geology and Meteorology Centre and the Lithuanian Hydrometeorological Service. The stations were located more or less evenly over the study area (Fig. 1). The measurements were made by the use of Tretyakov precipitation gauges twice or four times a day. The precipitation records include corrections for wetting — 0.2 mm (in case of liquid precipitation) and 0.1 mm (in case of solid precipitation) for each measurement. This correction was introduced starting from 1966. Summing up the monthly precipitation, the seasonal and annual values were obtained and analysed. The traditional seasons DJF, MAM, JJA and SON were used. The mean precipitation for each country was calculated by averaging the data from all stations for Estonia, Latvia and Lithuania.

The automated VRG-type gauges were introduced in Estonia starting from autumn 2010. In Latvia, the automated precipitation gauges were introduced in 2012 and in Lithuania, during the period from 2007 till 2011. Parallel measurements with manual and automated gauges gave very small and not systematic differences in measured precipitation

Fig. 1 Location of precipitation stations used in this study

(Alber et al. 2015). For this research, the stations were chosen assuming the homogeneity of the time series. There were no substantial relocations of observation sites at these stations.

As a rule, the precipitation data are not normally distributed and are characterised by a positive skewness. Therefore, we used the nonparametric Mann-Kendall test for trend analysis. The slope was calculated using the Sen's method. Trend values are presented by changes per decade. Trends were considered statistically significant on the $p < 0.05$ level. While precipitation trend values vary a lot in the region, we additionally analysed cases when the Mann-Kendall test statistics are significant on the $p < 0.1$ level. Critical values of the Mann-Kendall test statistic for a 50-year time series are 2.01 in the case of significance level $p < 0.05$ and 1.68 for $p < 0.1$. Maps of trend values were composed to analyse the spatial variability of precipitation trends. As precipitation is characterised by a very high spatial variability, we assume that trend values also have a high spatial variability, i.e. they may differ substantially at neighbouring stations. Isolines are drawn using kriging interpolation.

Regime shifts were detected with the Sequential T-test Analysis of Regime Shifts (STARS) method, known also as the Rodionov test (Rodionov 2004; Rodionov and Overland

2005), which is widely used for that purpose. It is based on the sequential use of the Student's t test. In our study, we applied the macro for the STARS version 3.2 (http://www.beringclimate.noaa.gov/regimes/).

The user of the STARS can select a cut-off length (l), i.e. the length of the t test period, which is then moved over the time series in order to determine a point at which a statistically reliable shift takes place and also to determine the significance level (p) of the t test. The weights of the outliers can be controlled by the selection of an appropriate Huber's weight parameter (HWP). The STARS also enables the user, where necessary, to carry out a pre-whitening of a time series using three different methods. It can detect regime shifts in either the mean or the variance (Rodionov 2004; Rodionov and Overland 2005).

There are no exact guidelines for adjusting the STARS settings. The criteria for objectively differentiating between random and systematic changes remain uncertain. Rodionov advises to test different input parameters in order to find those which yield the most favourable outputs; if the desired output contains a relatively large number of regime shifts, then loose settings (short cut-off length, low significance level and high HWP value) should be applied. We decided to use in our study the following settings: l = 10, p = 0.05, HWP = 1. We use only the concept of displacement, i.e. the inspection of time series over relatively short periods, where there can be sequential multi-year intervals and mean values in each interval are statistically different, relative to their variance within the regime. No pre-whitening methods were used. Regime shifts, which occurred in the end of the time series (during last 5 years), were ignored as they are considered as artificial shifts caused by the peculiarities of the method.

3 Results

Results of the trend analyses using the Mann-Kendall test are presented in Table 1 in a generalised form. There are numbers of stations per country, which have a statistically significant trend on the p < 0.05 level as well as on the 0.05 < p < 0.1 level (in brackets), and trend values of country mean precipitation. If the mean trend value was positive, then also all trends at the stations were positive and vice versa. Changes in precipitation regime during the last 50 years are not large. It is evident that the highest changes in precipitation have taken place in Latvia and the least changes have occurred in Lithuania.

Results of the Rodionov test are presented in Table 2, displaying the years since which a statistically significant regime shift was detected. Upward shifts are in the column marked with "+" and downward shifts in the column "–". The number of stations in the country, where the regime shift was significant, is given in brackets after the year. If a shift was detected only at one station, then these stations are listed

Table 1 Numbers of stations with a statistically significant trend on the p < 0.05 level (left column for each country) as well as on the 0.05 < p < 0.1 level (in brackets) and trend values of country mean precipitation in millimetres per decade (right column)

	Estonia (19)		Latvia (19)		Lithuania (16)	
January	12 (5)	*4.4*	14 (4)	*5.2*	8 (4)	*4.3*
February	4 (2)	2.1	7 (2)	*3.3*	5 (2)	*2.8*
March	1 (1)	1.3	0 (0)	1.1	0 (0)	0.6
April	2 (1)	−2.7	0 (0)	−2.5	0 (1)	−2.3
May	0 (0)	0.5	0 (0)	2.0	1 (1)	1.6
June	9 (3)	*6.5*	3 (5)	*4.6*	1 (0)	2.3
July	0 (1)	−0.1	0 (0)	2.4	0 (1)	4.1
August	1 (1)	5.0	0 (0)	4.5	0 (2)	3.3
September	3 (6)	*−4.9*	3 (0)	*−4.7*	0 (0)	−1.8
October	0 (0)	−0.6	0 (0)	3.2	0 (0)	0.2
November	0 (0)	0.6	0 (0)	−1.3	1 (0)	−0.6
December	0 (1)	1.2	0 (0)	0.6	0 (0)	0.3
Year	0 (7)	12.5	6 (2)	*17.7*	3 (2)	*7.1*
Spring	0 (0)	−1.3	0 (0)	0.3	1 (0)	−0.8
Summer	4 (4)	12.3	4 (5)	*11.8*	0 (1)	9.2
Autumn	1 (3)	−6.9	1 (2)	−5.5	0 (0)	−2.9
Winter	14 (2)	*9.5*	16 (3)	*10.3*	7 (1)	*6.7*

Total number of stations for each country is indicated in brackets. Statistically significant trend values are italicized

in Table 2 only in the case when the time series of the country mean precipitation had the same shift. The years are underlined if the time series of the country mean precipitation had a significant regime shift since this year.

The months with a significant trend according to the Mann-Kendall test mostly have a significant regime shift as well. Positive trends and shifts were detected in winter months as well as in June. Negative regime shifts were revealed in April and September when a negative trend existed as well. In some cases, a second or a return shift was observed. For example, an abrupt increase in monthly precipitation in February occurred in the end of the 1980s and in the first half of the 1990s, while the return shift followed in 2003. In March, the corresponding years were 1988 and 1996. In August, some Estonian stations had a return shift since 1995 and in September, some Lithuanian stations since 1998. Such alternating shifts reflect natural variations in precipitation, the alternation of rainy and dry periods.

The majority of statistically significant trends have been detected in winter. January has become much wetter during the study period. An increase in monthly precipitation by approximately 25 mm per half-century is nearly equal to 50% of the long-term mean precipitation in January. A statistically significant regime shift was detected for the Latvian mean time series since 1990 (Fig. 2). Also, the highest trend value in January — 9.3 mm per decade — was obtained in Sigulda,

Table 2 Years with a statistically significant regime shift in precipitation time series

	Estonia		Latvia		Lithuania	
	+	−	+	−	+	−
January	1990 (3), 1982 (2)		*1990* (7), 1981 (3)			
February	*1995* (5), 1989 (3) 1987 (2)	2003 (8)	*1990* (7), 1989 (6)	*2003* (8)	1995 (6), *1990* (3)	2003 (4)
March	1989 (3), *1988* (2)	<u>1996</u> (4)	1988 (3)	1996 (2)		
April		<u>1979</u> (6)		1979 (3)		
May			*2010* (4)			
June	1976 (2)		1978 (2), 1980 (2) *1981* (1)		1980 (2), *1984* (1)	
July					2007 (2)	
August	1985 (2), 1986 (2) 1987 (2), 2005 (2)	1995 (2)				
September		<u>1998</u> (6)		1998 (2)	1984 (3), *1983* (2)	*1998* (2)
October						
November				1993 (2)		1983 (2)
December	2009 (3), 2008 (2)		2009 (3)			
Year	2008 (2)		2007 (7), *1977* (5)		1977 (3)	
Spring		1979 (2)				
Summer	*1985* (3), 2007 (3)		*1978* (3), 2007 (2)		2007 (2), 2009 (2)	
Autumn						
Winter	1981 (4), 1989 (2)		1981 (4), 1989 (2) 2007 (2), *1990* (1)		1981 (2)	

Number of stations in the country having a significant regime shift this year is presented in brackets. Years are italicized if the time series of country mean precipitation had a significant regime shift since this year

Central Latvia (Fig. 3). Other largest changes have taken place in the same region and in eastern Latvia, as well as in the central and western parts of continental Estonia. Trend values more than 5 mm per decade are also typical for the western coastal areas of Latvia and Lithuania (Fig. 3).

The same tendency of precipitation growth was also observed in February, but of less magnitude. Significant trends were detected at few stations. The area of maximum change is located in southern Lithuania and eastern Latvia. A positive
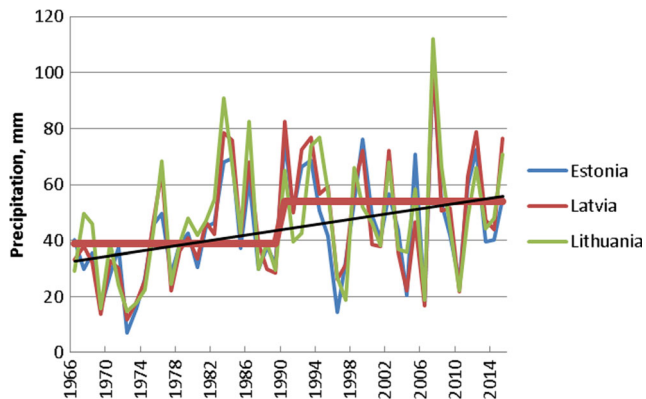

Fig. 2 Time series of country mean precipitation in January, their linear trend line and the regime shift in Latvian mean precipitation since 1990
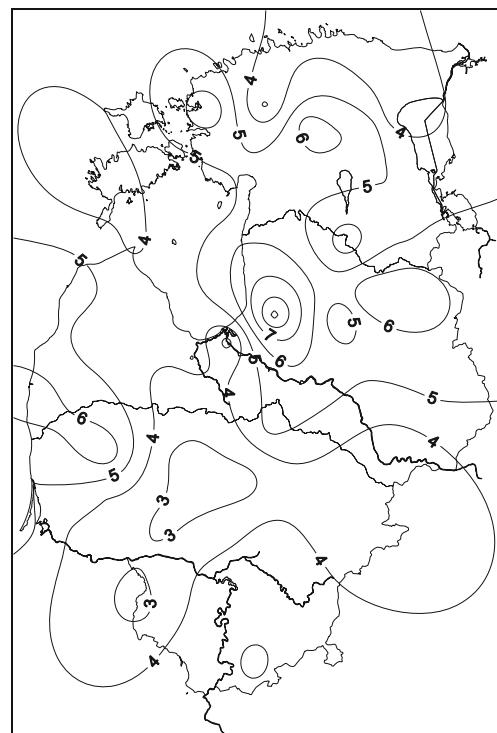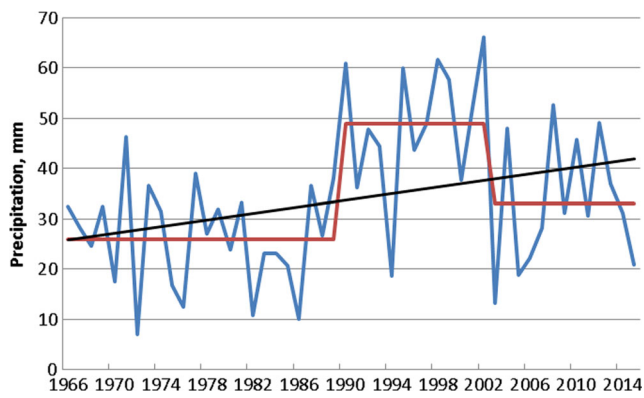

Fig. 3 Trend values of precipitation in January

Fig. 4 Time series of Latvian mean precipitation in February, its linear trend line and regime shifts since 1990 and 2003

Fig. 6 Time series of April precipitation in Jõhvi, September precipitation in Valga and Sigulda and their linear trend lines

regime shift was detected at the majority of stations since the end of the 1980s and in 1995, which was followed by a negative shift since 2003 (Fig. 4). In this case, the figure presents the low-frequency variability of precipitation rather than a general trend.

A remarkable increase in precipitation was observed also in June, but mostly in the northern part of the region (Fig. 5). The highest increase (more than 8 mm per decade) was determined in eastern Estonia (Narva) and eastern Latvia (Griškāni). It is interesting that in June, regime shifts practically did not appear in Estonia, but in Latvia and Lithuania they were observed at some stations since the beginning of the 1980s. For August, upward regime shifts were found at some stations in Estonia since the middle of the 1980s.
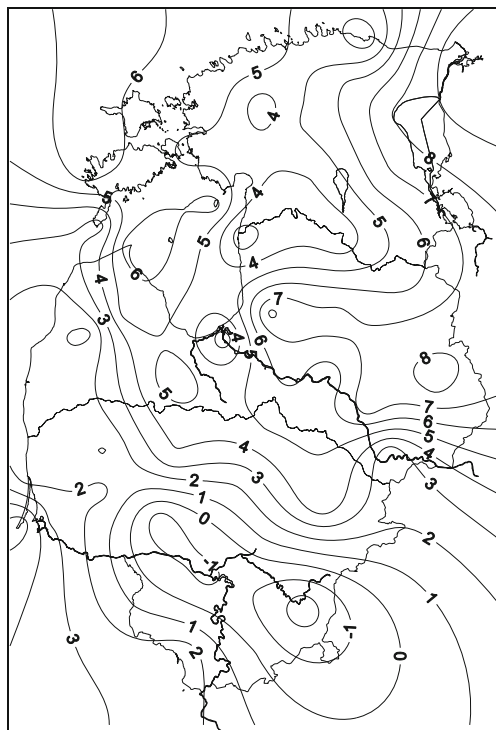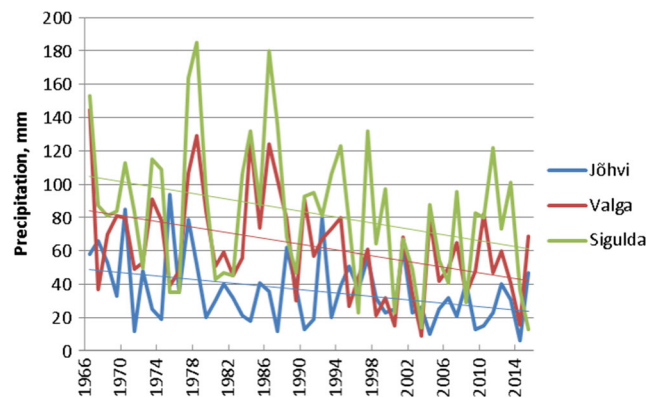
April and September are characterised by a prevailing decrease in precipitation that was significant at some stations in Estonia and Latvia (Fig. 6). The largest negative changes in April were recorded in north-eastern Estonia (Jõhvi), south-eastern Latvia (Daugavpils) and western Lithuania (Laukuva). In September, the area of the largest negative changes was concentrated in northern Latvia (Fig. 7). In April, downward shifts of precipitation regime were observed at some stations in Estonia and Latvia since 1979. A negative shift of precipitation in September has mostly occurred since 1998.

A general increase in precipitation is also reflected in the annual values. Some stations have a statistically significant trend, but the majority of them have not (Table 1). Time series
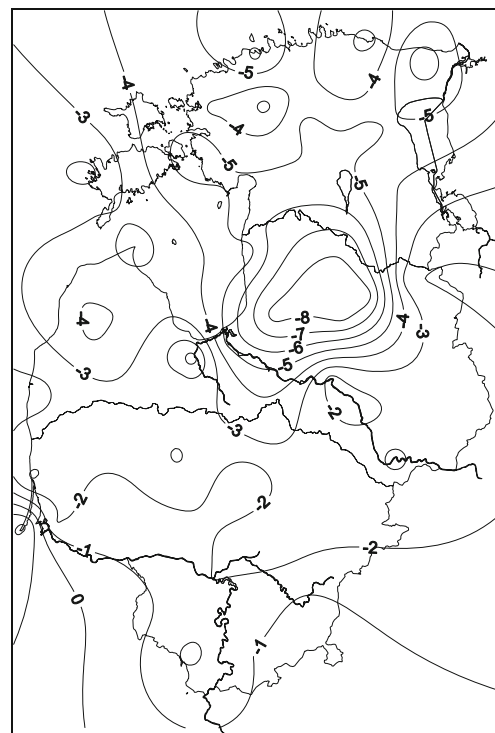

Fig. 5 Trend values of precipitation in June

Fig. 7 Trend values of precipitation in September
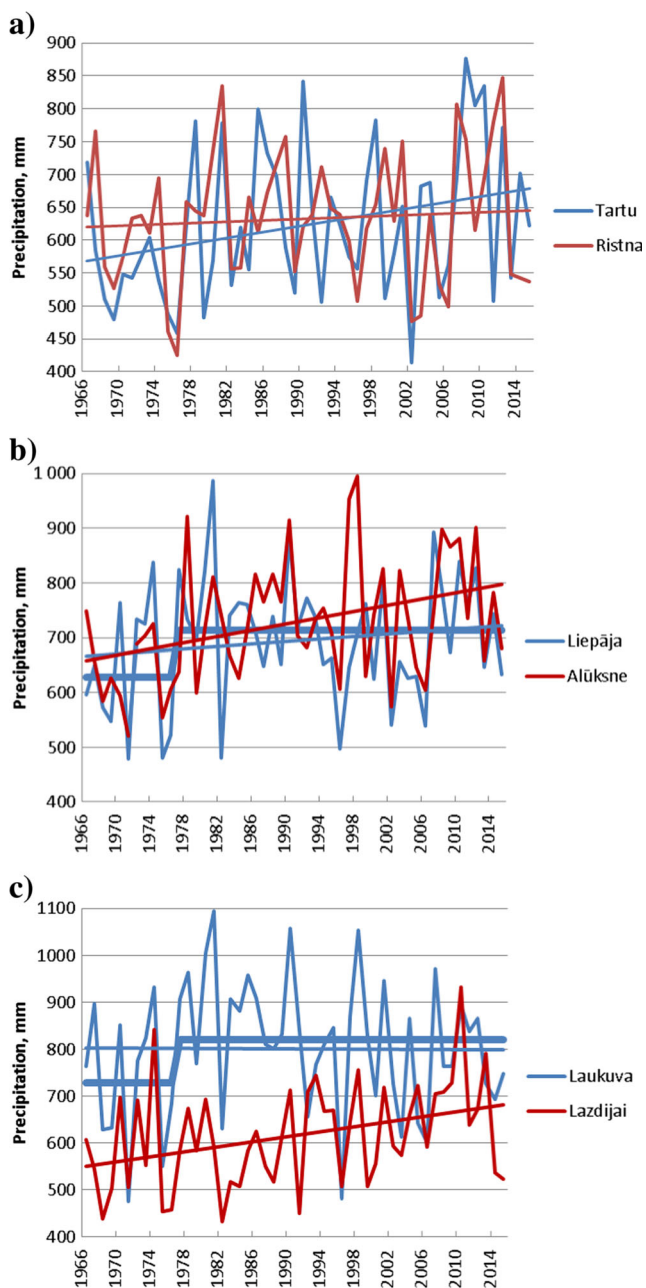
a)

b)

c)

Fig. 8 Time series of annual precipitation, their different trend lines and regime shifts (if they are statistically significant) at two stations in Estonia (**a**), Latvia (**b**) and Lithuania (**c**)

Fig. 9 Trend values of annual precipitation

of annual precipitation at different stations are presented in Fig. 8, presenting two stations from each country, one of which has a trend and the other does not have it. It can also be seen that the precipitation fluctuations are not much coherent between the stations, reflecting the random behaviour of the rainfall pattern.

The map of trend values of annual precipitation is rather complicated (Fig. 9). Lower values are clearly concentrated to Lithuania, where even an area of slightly negative changes can be found around the Šilute and Laukuva stations. Lower trend
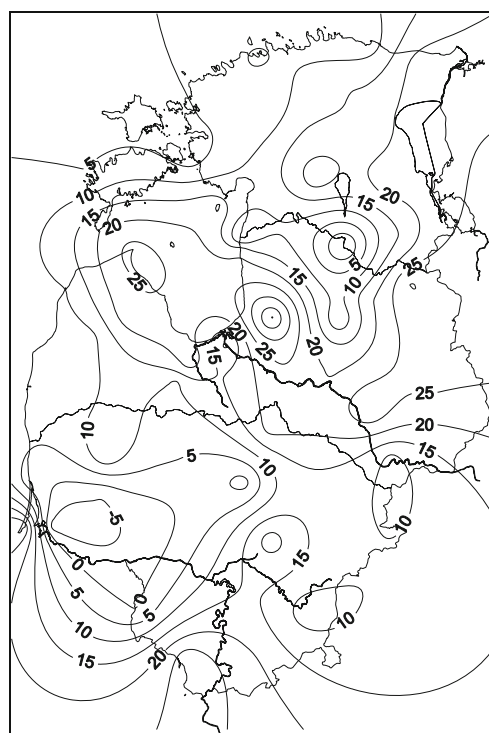
values (less than 10 mm per decade) are also typical for the north-western part of Estonia. This change is statistically insignificant. At the same time, trend values of annual precipitation exceeding 20 mm per decade can be found in eastern and central Latvia and in eastern Estonia, as well as at some stations in Lithuania. There were few statistically significant regime shifts in the time series of annual precipitation. Mostly, they are present in Latvia, where mean precipitation has significantly increased since 1977. This shift in Liepaja and Laukuva is indicated in Fig. 8.

The tendencies in seasonal precipitation are different. The precipitation amount has increased in summer and winter, while in winter it was statistically significant at the majority of stations. Positive trends in summer precipitation on 0.05 or 0.1 significance levels were found only at few stations in Latvia and Estonia. In spring and autumn, there were no positive trends, but negative trends were observed in few stations. The highest increase in summer precipitation by about 15 mm per decade was revealed around the Gulf of Riga (Fig. 10). Maximum trend values above 20 mm per decade were detected in Sigulda and Kolka. Regime shifts in summer precipitation were detected at some stations starting from different years. A significant shift occurred in Estonia since 1985 and in Latvia since 1978.

The most obvious increase in precipitation in the Baltic countries during the last 50 years has taken place in winter (DJF). A statistically significant trend in the mean
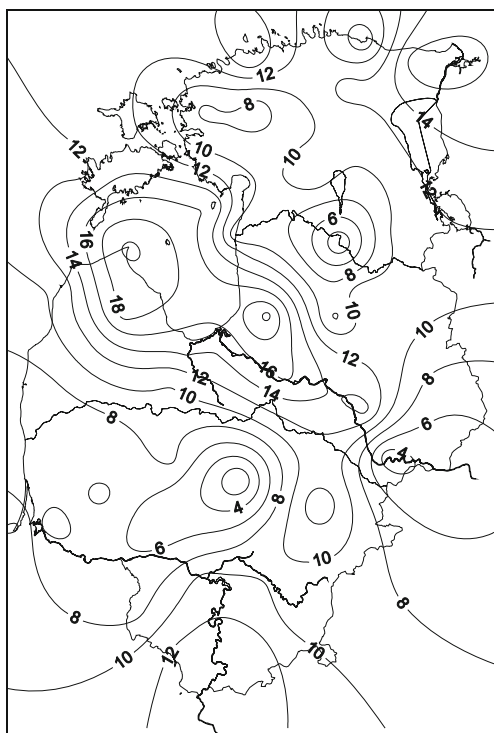
Fig. 10 Trend values of summer precipitation

precipitation amount was found in all three countries (Table 1), and it was also recorded at the large majority of meteorological stations. Trend values for winter precipitation
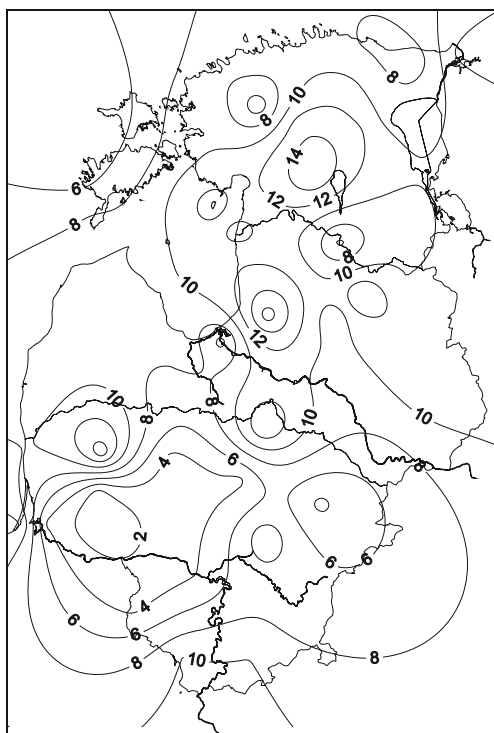

Fig. 11 Trend values of winter precipitation

are more similar between stations, being about 10 mm per decade (Fig. 11), but they tend to be higher in Estonia and Latvia and lower in Lithuania. The highest trend values were determined for Sigulda (17.0 mm per decade) and Viljandi (16.3 mm per decade).

Regime shifts in winter precipitation were observed at different years — since 1981, 1989, 1990 and 2007. They were the most typical for Latvia. The country mean winter precipitation in Latvia had a significant regime shift since 1990, which is the same as in January (Fig. 2).

4 Discussion and conclusions

Precipitation time series are extremely variable. Maximum and minimum values of monthly precipitation differ many times. Precipitation data are so randomly distributed that it is very complicated to determine statistically significant trends and regime shifts. Even quite high trend values are not significant due to the large variability. Using the significance level $p < 0.05$, we suppose that the possibility of I type errors is minimised. At the same time, there is a rather high risk of II type errors, i.e. not detecting a trend when, in reality, there is a change in the time series of precipitation. To avoid this, we used also the significance level $p < 0.1$ to detect less prominent trends or tendencies in the time series. Generally, we did not detect many additional trends on that level. It confirms that the significance level $p < 0.05$ was not too high for the II type errors.

We analysed trends together with regime shifts in time series of precipitation. They are highly inter-related. If there was detected a positive (or negative) trend, then, in many cases, a positive (or negative) regime shift was also found. In some cases, even two statistically significant shifts were observed — the first one was a jump to a higher precipitation level and the second was a breakdown to a lower level after a decade or a longer period. In these cases, we cannot talk about trends but about the low-frequency variability of precipitation.

It is natural to relate precipitation to large-scale atmospheric circulation. Transport of atmospheric moisture from the ocean is the main source of precipitation in the continental regions. The Atlantic Ocean is the most important source region from where water vapour is transported to Europe. Westerly circulation prevailing in midlatitudes brings moist maritime air far into the Eurasian continent. The North Atlantic oscillation (NAO) reflecting the intensity of westerly circulation from the North Atlantic to Europe is expected to be the main circulation factor (Barnston and Livezey 1987; Kożuchowski and Marciniak 1988; Hurrell 1995; Jones et al. 1997; Wibig 1999).

Previous studies on the influence of atmospheric circulation on air temperature and precipitation in the Baltic Sea regions have proved the leading role of NAO (BACC

Author Team 2008). The highest values of the correlation coefficient between precipitation and circulation (above 0.60) in Estonia were revealed with the NAO index in winter (Jaagus 2006), while in Lithuania, such correlation is much weaker (Bartkevičienė 2005). In the latter case, it was found that correlation coefficients are statistically significant (0.3–0.4) only in individual months (mostly in January and March). In Latvia, the period from the mid-1980s is described by the increased westerly circulation accompanied by higher temperatures and precipitation in winter. It was found that changes in the precipitation amount in Rīga were well correlated with the NAO index (Klavins and Rodinov 2010). Detailed correlations between circulation and precipitation together with their spatial variability in the Baltic countries in 1966–2005 were analysed in our previous study (Jaagus et al. 2010).

The results of trend analysis in this study are more or less similar to other estimations of precipitation changes in northern Europe, indicating a weak increasing tendency which mostly appears in winter (Beck et al. 2005; BACC Author Team 2008, 2015). It can easily be related to the general climate warming which has also been the most notable in the cold season (IPCC 2013). Higher winter temperatures in the Baltic Sea region are caused by cyclonic weather conditions. They are directly related to cloudy, windy and rainy weather. Many studies have demonstrated that cyclonic activity has increased in northern Europe during the last decades (Lehmann et al. 2011; BACC Author Team 2015; Chang and Yau 2015). At the same time, the storm track has shifted northwards (Sepp et al. 2005; Wang et al. 2006; Lehmann et al. 2011). It favours the advection of warm and moist maritime air from the North Atlantic to the Baltic Sea region.

The largest change detected during this study is the increase in winter precipitation by 10 mm per decade in the average in 1966–2015. A statistically significant increasing trend was revealed at the large majority of stations in Latvia and Estonia. Such changes were weaker and not so obvious in the southern part of the eastern Baltic region, i.e. in Lithuania. January and to a lesser extent February contributed to the rise of winter precipitation. Statistically significant regime shifts in winter and in January precipitation were detected in a much smaller number of stations in comparison with the number of stations where the trend was detected. At the same time, clear positive shifts in precipitation regime, mostly since 1990, were found in February, with the return shift since 2003. We suppose that these changes in winter precipitation are directly related to changes in air temperature and in large-scale atmospheric circulation in northern Europe and the Baltic Sea region (Niedźwiedź and Twardosz 2004; Bukantis and Rimkus 2005; Bartkevičienė 2005; Jaagus 2006; Klavins and Rodinov 2010; BACC Author Team 2015).

Although the increase in winter precipitation has occurred at the majority of stations during the last half-century, we cannot assume that the annual precipitation amount has generally increased in the Baltic countries. Trends at least on the $p < 0.1$ significance level appeared in the case of 42.1% of stations in Latvia, 36.8% in Estonia and 31.3% in Lithuania. This result is in line with other studies which mostly did not find statistically significant trends in precipitation in different parts of the Baltic Sea region during different time frames (Tuomenvirta 2004; Briede and Lizuma 2007; Kilpeläinen et al. 2008).

Precipitation changes during other seasons are not clearly evident. An increasing tendency was found in summer and a very weak decreasing tendency in spring and autumn. The increase in summer is related only to positive trends in June, which have occurred in the north-eastern part of the study region, i.e. in Estonia and eastern Latvia. Negative trends were revealed at some stations in April and September.

Our experiences demonstrated that, generally, the analysis of regime shifts is not well suitable for the time series of precipitation, at least using relatively conservative settings of the STARS method implemented here. High natural variability of precipitation makes it very complicated to analyse shifts. As a result, no shifts are similar and present at the majority of stations. Statistically significant regime shifts were determined at a few stations in different years. We can conclude that we did not find clear and overall regime shifts in the time series of precipitation, except the shifts in winter.

We assumed that precipitation variability and trends in the Baltic countries behave similarly to those in much wider areas. We suggested that the increase in precipitation is the weakest or even absent in the southern parts of the study region and the strongest in the northern part. This suggestion is partly affirmed in this study. Trends and regime shifts in Lithuania were really comparatively weak and were found only at a few stations. But the highest increase was recorded not in the northernmost country but in Latvia, located between Lithuania and Estonia. We cannot explain this result otherwise than with the high natural variability of precipitation.

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