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Trends and regime shifts in climatic conditions and river runoff in Estonia during 1951–2015

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Abstract. Time series of monthly, seasonal and annual mean air temperature, precipitation, snow cover duration and specific runoff of rivers in Estonia are analysed for detecting trends and regime shifts during 1951–2015. Trend analysis is performed using the Mann-Kendall test and regime shifts are detected with the Rodionov test (Sequential T-test Analysis of Regime Shifts). The results from Estonia are related to trends and regime shifts in time series of indices of large-scale atmospheric circulation. Annual mean air temperature has significantly increased at 12 observed stations by 0.3–0.4 K per decade. The warming trend was detected in all seasons but with the higher magnitude in spring and winter. Snow cover duration has decreased in Estonia by 3–4 days per decade. Changes in precipitation are not clear and uniform due to their very high spatial and temporal variability. The most significant increase in precipitation was observed during the cold half-year, from November to March. Time series of specific runoff measured at 21 stations has had significant seasonal changes during the study period. Winter values have increased by 0.4–0.9 l/s per km^2 per decade while stronger changes are typical for western Estonia and weaker changes for eastern Estonia. At the same time, specific runoff in April and May has notably decreased indicating the shift of the runoff maximum to earlier time, i.e. from April to March. All meteorological and hydrological variables are highly correlated in winter, determined by the large-scale atmospheric circulation. Correlation coefficients between the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) indices reflecting the intensity of westerlies, and the studied variables were 0.5–0.8. The main result of the analysis of regime shifts was the detection of coherent shifts for air temperature, snow cover duration and specific runoff in the late 1980s, mostly since the winter 1988/1989, which are, in turn, synchronous with the shifts in winter circulation. For example, runoff abruptly increased in January, February and March but decreased in April. Regime shifts in the annual specific runoff correspond to the alternation of wet and dry periods. A dry period started since 1964 or 1963, a wet period since 1978 and the next dry period since the beginning of the 21st century.

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1 Introduction

Climate warming in the Baltic Sea region including Estonia is estimated to be faster than the increase in the global mean temperature (Jaagus, 2006; BACC, 2008; 2015). Annual mean air temperature has increased by 0.11 K per decade in the northern part of the Baltic Sea basin, and by 0.08 K per decade in its southern part during 1871–2011 (BACC, 2015). The most significant warming was observed in spring and winter. Different methods of trend analysis are usually applied for the detection of climate changes. At the same time, there could be also abrupt changes, i.e. jumps or breaks, which divide a time series into sections with different statistical properties, called regime shifts. Initially, the term regime shift was used in marine ecology and it was inspired by abrupt changes in the climate of the North Pacific (Kerr, 1992) and salmon production around 1977 (Mantua et al., 1997; Rodionov, 2004). It means a large, abrupt and persistent change in the structure and function of a (natural) system (Biggs et al., 2009). In oceanography and climatology, a regime shift is characterized by an abrupt transition from one quasi-steady climatic state to another, and its transition period is much shorter than the lengths of the individual periods of each climatic state. The semantics and the essence of regime shifts are described in detail by Overland et al. (2008). There are several definitions of regimes (Rodionov, 2005; Overland et al., 2008). Here, we used only the concept of displacement, i.e. the inspection of time series over relatively short periods, where there can be sequential multi-year intervals with mean values in each interval which are statistically different, relative to their within regime variance.

As there are several definitions and methods to detect regime shifts, there are also numerous regime shifts in climate variables detected by different authors. For example, Swanson and Tsonis (2009) identified climatic regime shifts in global mean temperature in 1910–1920, 1938–1945, 1976–1981 and 2001–2002. A regime shift in the North Atlantic was observed in the 1920s and 1930s (Drinkwater, 2006). However, a number of studies have detected regime shifts in many parameters in the late 1980s, especially since 1989. For example, analysing wintertime sea-surface temperatures over the Northern Hemisphere during the 20th century, six regime shifts were detected, one of them in 1988/1989 (Yasunaka and Hanawa, 2002). An abrupt warming over the Northern Hemisphere in the late 1980s was examined by many authors (Rodionov and Overland, 2005; Tsunoda et al., 2008; Lo and Hsu, 2010; Kim et al., 2015). 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 shift of 1989 in that region was analysed also by Hare and Mantua (2000). In the late 1980s, regime shifts were also detected in the Arctic sea-level pressure (Walsh et al., 1996), the intensification of upper air polar vortex (Tanaka et al., 1996) and the decadal-scale atmospheric circulation (Watanabe and Nitta, 1999). This change is explained by a northward expansion of the Hadley cell, a poleward expansion and intensification of the Ferrel cell and a collapse of the polar cell (Kim et al., 2015). A thorough analysis of the regime shifts in the 1980s and their global impact on the biosphere was conducted by Reid et al. (2016).

There is also much evidence of regime shifts in the Northern Atlantic and European regions in the late 1980s. For example, a regime shift was reported from the Mediterranean Sea in this period, based on ecological, hydrological and climatic variables

(Conversi et al., 2010).The review article on regime shifts in marine ecosystems cites many studies that deal with the shift in the Northern Atlantic since 1989 (DeYoung et al., 2004). Hagen and Feistel (2005) determined the alternation of two climate regimes over the Baltic Sea by using long time series of the winter Baltic climate index (WIBIX) based on monthly values of the first principal component of winter anomalies (January – March) of the NAO index, sea level anomalies on Landsort (Sweden) and the maximum Baltic ice cover. The last period of mild winters started in 1988 (Hagen and Feistel, 2005). In marine ecosystems of the Baltic Sea, a regime shift was observed in the late 1980s. The phytoplankton biomass increased, the composition of phyto- and zooplankton communities changed conspicuously and the growing season was extended (Alheit et al., 2005; Möllmann et al., 2009; Dippner et al., 2012).

As the Baltic Sea is situated in the transition area between the Atlantic marine and Eurasian continental climate systems and influenced by air masses from arctic to subtropical origin, its climatic conditions are characterized by high spatio-temporal variations (BACC, 2008; Rutgersson et al., 2014). Thus, the Baltic Sea region poses a great challenge to the detection of regime shifts in the climatic, hydrological and ecological variables.

Estonia is located in the central part of the Baltic Sea region in the eastern coast of the sea. We suppose the climatic and hydrological changes here to be more or less typical for a much wider territory in the central part of the eastern Baltic Sea basin. As in the whole northern Europe, air temperature has increased in Estonia during the period of instrumental meteorological observations (Jaagus, 1998). The highest warming was detected during the second half of the 20th century when statistically significant trends were revealed for annual and spring mean temperature (Jaagus, 2006). Trend values for annual temperature were 0.2–0.3 K per decade, and for spring and winter temperature even 0.4–0.6 K per decade. At the majority of the studied Estonian stations annual and winter precipitation has also increased significantly. It was demonstrated that these climatic changes have been closely related to changes in the large-scale atmospheric circulation, precisely, to the intensification of westerly circulation over the Atlantic/European sector in winter (Jaagus, 2006).

Several studies have shown regime shifts in climate variables over the Gulf of Finland and in Estonia. An increase in zonal circulation since 1987 was detected in February (Keevallik and Soomere, 2008). A similar shift at the end of the 1980s 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 area in January was detected in 1988, and a downward return shift in 1994 (Keevallik and Soomere, 2014). Based on the data of two stations (Vilsandi and Tiirikoja, Estonia) an abrupt increase was observed in the zonal component of average air flow from January to March, in air temperature in January and February and in precipitation in February (Keevallik, 2011). Precipitation regime in the eastern Baltic region can be characterised by a very high spatial and temporal variability (Jaagus et al., 2010; 2016).

Long-term fluctuations in climatic parameters are reflected in the dynamics of river runoff which has a relatively short residence time. River runoff in Estonia is characterized by a significant seasonal and interannual variability. It is mostly caused by precipitation variations and snow conditions during the winter season and the melting period in spring. Runoff regime is also affected by hydrographical and hydrogeological characteristics, which have relatively large differences in Estonian catchment areas. Variability and trends in river discharge in the Baltic countries was analysed by many authors

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(Järvet, 1998; Reihan et al., 2006; 2007; Kriauciuniene et al., 2012). They found that during the 20th century, increasing trends in river runoff were characteristic only to the winter season. At the same time, the time series for Estonia were dominated by runoff fluctuations with the period of ca 30 years.

The objective of this study is a joint analysis of changes, i.e. trends and regime shifts in main climatic (temperature, precipitation, snow cover duration) and hydrologic (river runoff) variables and in the indices of large-scale atmospheric circulation in order to detect coherent changes. The study period 1951–2015 was chosen because it is the period with the highest number of stations with continuous time series available in Estonia. The novelty of this study in comparison with previous analyses is the use of the main parameters of large-scale atmospheric circulation as the drivers of regime shifts in climatic and hydrological time series.

2 Data and methods

Annual, seasonal and monthly mean air temperature and precipitation at 12 stations in Estonia (Figure 1) for 1951–2015 were used for the analysis. The measuring sites of the stations, except for two, had more or less remained at their original locations. In 1980, the Tallinn station was moved from Ülemiste (airport) to Harku, ca 12 km west. Thereby, the local placement of the measuring site on the limestone plateau several kilometres inland from the sea coast remained nearly the same. In 1997, the Tartu station was moved from Ülenurme to Tõravere, 15 km southwest. The analysis of time series did not reveal inhomogeneities due to these displacements (Sits and Post, 2006; Keevallik and Vint, 2012). Adding of the wetting correction to the measured precipitation at all stations since 1966 was the only important source of inhomogeneity that was not eliminated from the time series. The wetting correction amounts about ten per cent of monthly precipitation, which is difficult to detect. In addition, the time series of snow cover duration at five stations were analysed for better description of winter weather conditions.

For the generalization of the results, time series of spatial mean temperature and precipitation were also analysed. Mean temperature for Estonia was calculated by averaging the values of the 12 stations. Spatial mean precipitation for Estonia was calculated by averaging the gridded values, which were interpolated using all the available precipitation data (Jaagus, 1992).

We used specific runoff of rivers (in litres per second per square kilometre) because it allows comparing observation data from the river basins of different size and assessing the results of statistical analyses. We also used the monthly, seasonal and annual specific runoff values for 1951–2015 from all the 21 Estonian stations with various catchment areas, hydrological and hydrogeological conditions, which had available long series of measurements (Figure 1). Hydrological parameters of these river basins are presented in Table 1.

Large-scale atmospheric circulation is an important factor influencing local weather conditions. In this study, changes in circulation are analysed using the annual, seasonal and monthly values of Arctic Oscillation (AO) index, several North Atlantic Oscillation indices and teleconnection indices provided by the NOAA Climate Prediction Center. The AO index reflects the intensity of the circumpolar air vortex (Thompson and Wallace, 1998). North Atlantic Oscillation (NAO) describes the intensity of westerlies over the Atlantic/European sector (Hurrell, 1995). We applied several NAO indices: NAOG using SLP data from Gibraltar and Stykkisholmur/Reykjavik (Jones et al., 1997), NAOL using data from Lisbon and Reykjavik/Stykkisholmur (Hurrell, 1995) and NAOPC, which are calculated using the Principal Component Analysis (PCA) of SLP fields (Hurrell and Deser, 2009).

Teleconnection patterns have been defined as a result of PCA of SLP fields over the Northern Hemisphere (Barnston and Livezey, 1987). Here we use only these teleconnection patterns, which represent the atmospheric circulation in the Baltic Sea region. Monthly values are presented and updated by the NOAA Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). The North Atlantic Oscillation (NAOT), the East Atlantic (EA) and the Polar/Eurasia (POL) patterns mostly describe the zonal circulation while the East Atlantic/West Russia (EAWR) and Scandinavia (SCA) patterns describe the meridional circulation.

The Mann-Kendall test is used to detect trends in time series (Mann, 1945; Kendall, 1975). The reason for selecting this test is that the consistency with normal (Gaussian) distribution in case of hydrological parameters is usually not fulfilled. The trend slope is calculated using the Sen's method (Sen, 1968). Trends are expressed in changes per decade. They are considered statistically significant on the $p<0.05$ level.

Correlation coefficients are used for expressing the strength and direction of the statistical relationship between the time series of different climatic and hydrological variables. As the correlations are presented only for the illustration of the relationships, their statistical significance was not found.

The STARS (Sequential T-test Analysis of Regime Shifts) method, also known as the Rodionov test (Rodionov, 2004; Rodionov and Overland, 2005) was used to detect regime shifts in the time series of considered parameters. The identification of a regime shift is based on calculating the regime shift index (RSI), which represents a cumulative sum of normalized deviations of the time-series values from the hypothetical mean level for the new regime. This is the level for which the difference from the mean level for the previous regime is statistically significant according to Student's t test. If the RSI remains positive during a time period equal to the cut-off length, a shift is declared (Rodionov, 2004). Here, we used Excel macro developed by S.N. Rodionov, which is downloadable from the Bering Sea Climate website http://www.beringclimate.noaa.gov/regimes/. After numerous tests we decided to use the following relatively conservative set of parameters: cut-off length, $l = 10$ years; the significance level of the t-test $p = 0.05$; the Huber´s weight parameter, HWP = 1. HWP determines the weight of outliers in the calculation of mean values before and after the shift. No pre-whitening methods were used.

The output of the test is the year when a regime shift occurs (or years of shifts, if the time series contains multiple statistically significant shifts), i.e. the first year of the new level. The shift is expressed in RSI which represents a relative magnitude of the shift. The higher the value of RSI the more abrupt and statistically reliable the shift is. However, RSI does not present the shift in terms, for example, of degrees of Celsius or mm of precipitation. Thus, one output of the test is the difference between the weighted means which is used as a shift value for describing the magnitude of the shift.

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3 Results

3.1 Indices of large-scale atmospheric circulation

Statistically significant trends in the indices of the large-scale atmospheric circulation are comparatively rare (Table 2). The most remarkable feature is the significant increase in different NAO indices in winter (Figure 2). It means that negative NAO indices have started to occur less often and positive anomalies more often during the study period indicating the tendency of the intensification of westerly circulation over the Atlantic/European sector. Positive trends in NAO indices were observed in January, February and March while negative trends were found in June and October. The AO index has a statistically significant increasing trend only in March, November, spring and annually. It is interesting that the EA index can be characterized by an increasing tendency throughout a year. The EAWR, SCA and POL teleconnection indices have some, mostly negative, trends in single months (Table 2).

The AO index and NAO indices for winter demonstrate a statistically significant positive regime shift since the winter 1988/1989 (Figure 2), reflecting an abrupt intensification of the westerly circulation. The upward shift year 1989 was detected for the following indices: AO – in February, winter and annual time series, NAOL – February, NAOG – winter, NAOPC – February, March, winter, spring, annual; NAOT – February, winter. For NAOT, the shift year was 1988. Return shifts for NAO indices appeared starting from 2004. Other teleconnection indices had few regime shifts.

3.2 Surface air temperature

Results of the Mann-Kendall test show a large warming in Estonia during the period 1951–2015. Annual mean air temperature increased significantly at the studied stations by 2.0–2.5 K for the whole period or by 0.3–0.4 K per decade. Statistically significant warming was also detected for all seasons, while the trend values were higher than the annual mean in winter (Figure 3) and spring, and lower in summer and autumn. Among single months, statistically significant trends were detected during the study period in March, April, May, July, August, September and November (Table 3). No trends were observed in June and October. Notable warming in January, February and December was mostly insignificant due to a very high temporal variability of air temperature in winter.

Upward regime shifts are typical for air temperature (Table 3). Winter mean temperature has abruptly increased since 1988/1989 by 1.9–2.7 K at different stations. The highest shift value was recorded in Tartu (Figure 3). Generally, the trends and regime shifts at the coastal stations in western Estonia are weaker than at the inland stations of eastern Estonia.

A similar upward shift of even higher magnitude in monthly mean temperature was found in February, while some stations in southern Estonia had a downward shift since 2005. Stations in the continental part of Estonia had a downward shift in monthly mean temperature in January by 2.3–2.7 K since 1966, followed by an upward shift by 4.1–4.7 K since 1988. Statistically significant regime shifts in March and April temperature were found in two different years. In March, the upward shift by 3.2–3.9 K was revealed in the eastern half of the country since 1966, and by 1.9–2.3 K in the coastal region since 1989. In April, the shift to a higher temperature by 1.5–2.1 K occurred in the southern regions and the western coast in

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1989, while in northern Estonia the shift by 1.7–1.9 K was found since 1999. The time series of spatial mean temperature in Estonia has a shift in March since 1966 and in April since 1989 (Table 3).

Regime shifts in air temperature for the warm half-year were detected more than ten years later than for the cold half-year. Mean temperature in July had a jump by 2.0–2.4 K since 2001 (since 1999 at the island stations of Vilsandi and Kihnu); in August, the shift by 1.3–1.7 K was present since 2002 (since 1996 in Vilsandi and Kihnu) and in September, by 1.5–1.7 K since 2004. Mean temperature in spring had upward regime shifts in different years – since 1966, 1982 and 1989. Summer temperature shifted since 1999, 2001 or 2010 at different stations and autumn temperature since 2005. Annual mean temperature has a statistically significant increase by 1.2–1.5 K in 1988 (or 1989).

Interannual fluctuations in time series of air temperature are statistically related to the variations in the indices of large-scale atmospheric circulation. The indices describing the intensity of westerly circulation (AO and NAO indices) are highly correlated with winter temperature. Correlation coefficient is usually 0.6–0.7 or even higher. For example, the correlation between winter mean temperature in Tartu and Ristna with AO index in winter was 0.710 and 0.755, and with NAOPC 0.765 and 0.800, correspondingly (Figure 4). A higher correlation was clearly revealed in the coastal zone.

3.3 Snow cover duration

The warming in winter is closely related to the decrease in snow cover duration. The trend values were 4.0 days per decade in Pärnu, 3.6 in Tallinn, 3.4 in Tartu (Figure 5), 3.3 in Võru and 3.0 days per decade in Vilsandi. The change was statistically significant on $p<0.05$ level only in the first two stations. The low significance can be explained by a very high year-to-year variability of snow cover duration.

Time series of snow cover duration at all studied stations in the continental part of Estonia have a statistically significant negative shift by 16–20 days since the winter 1988/89 (Figure 5). An exception was detected at the Vilsandi station, which is located on the westernmost island under the direct influence of the Baltic Sea. A downward shift in snow cover duration by 31.9 days was observed in Vilsandi since 1988/1989, followed by an upward shift by 32.4 days detected since 2009/2010.

The correlation between winter mean temperature and snow cover duration is lower (r = -0.65 -0.75) in the inland regions of Estonia and much higher in the coast of the Baltic Sea (r = -0.88 in Vilsandi). Similar spatial differences appear in the correlation coefficients between snow cover duration and the indices describing the intensity of westerly circulation (AO, NAO indices) in winter. Their values are between -0.5 and -0.7.

3.4 Precipitation

Precipitation has an even higher spatial and temporal variability than snow cover duration. Generally, the correlations between precipitation and other climatic parameters are comparatively weaker. Trend values for stations are quite different. There are no months or seasons when a statistically significant trend was observed in all stations. Increasing trends in monthly precipitation up to 5 mm per decade were detected during the cold half-year (from November to March) and also in June (Table 3, Figure 6). The winter season has received significantly more precipitation with the exception of Vilsandi. The majority of stations have also experienced a significant increase in annual precipitation by 15–30 mm per decade. No changes were mostly observed during the warm half-year (except June). An insignificant decrease could be noticed at some stations in April, July and September. Generally, there is no correlation between air temperature and precipitation in Estonia, but a weak positive correlation (r = 0.30–0.35) can be found in winter and a negative correlation of the same magnitude appears in May, June and August.

Due to the extremely high temporal variability, regime shifts in time series of precipitation are not so clearly expressed as in case of temperature (Table 2). Several significant upward and downward shifts have been detected which express, first of all, the multi-annual fluctuations of precipitation and not so much the abrupt climatic changes. Upward shifts in annual precipitation by even more than 100 mm were detected at many stations during 1977–1986. They reflect the outset of the period of higher precipitation starting from 1977. Similar shifts for winter precipitation were observed later, starting with 1980/1981 and 1981/1982 at three stations, and ending with 1988/1989 and 1989/1990 at four of 12 stations, for example at Türi (Figure 6). Positive regime shifts in monthly precipitation were revealed at all stations during the cold season from November to March in the 1980s. In many cases they were followed by return shifts in 2003 (February) and 1996 (March). Downward shifts in September precipitation were detected at many stations mostly since 1998. Significant shifts in spring (7 stations) and autumn precipitation (2 stations) since 1966 can be explained by the wetting correction added to every measured precipitation.

3.5 Specific runoff of rivers

The trend analysis of specific runoff of rivers demonstrated mostly an increase in annual values while statistically significant trend was detected only at five stations (Table 4). At the same time, increasing trends were revealed at all stations (except Vasknarva which is naturally regulated by Lake Peipsi) in the winter season and in the first three months of the year (Table 5). Trend values of specific runoff at single stations were quite different but mostly between 0.4–0.9 l/s per km^2 per decade, while lower values were obtained from eastern Estonia (Figure 7) and higher values from western Estonia. The highest increase was detected in the Uue-Lõve river basin on Saaremaa Island where the trend value of winter mean specific runoff was 1.1 l/s per km^2 per decade. The Vasknarva station is an exception due to its location in the outflow from Lake Peipsi to the Narva River whose runoff regime differs much from that of other rivers. It has a large basin area 66% of which lies outside of the territory of Estonia. A significant increasing trend was revealed there only in February and March.
Few significant trends were detected during other months. In southern Estonia (the Õhne, Väike-Emajõgi and Piigaste Rivers), runoff has increased also in June and in the Võhandu River (Räpina station) in July. This is related to the increase in precipitation in June. Mostly negative changes are typical for spring. In April, which is the most common month for spring flooding, the specific runoff has decreased by up to 1 l/s per km^2 per decade, but this trend was statistically significant only in the Õhne and Kasari Rivers. The decrease in May was significant in central and northern Estonia, at 8 stations out of 21. It is related to the shift in the spring runoff maximum caused by the melting of snow at the earlier time, i.e. in March. Annual mean specific runoff has significantly increased in some rivers of southern Estonia (in the Rivers of Emajõgi, Väike-

Emajõgi, Õhne and Halliste) by 0.2–0.3 l/s per km^2 per decade, and in the Uue-Lõve River in the West-Estonian archipelago by 0.47 l/s per km^2 per decade.

The relationship between climatic variables and runoff in Estonia is well exposed particularly in winter. High temperature, precipitation and shorter snow cover duration in winter are related to a higher winter runoff. The correlations between temperature and runoff in January, February and March are up to 0.7, between precipitation and runoff up to 0.6 and between snow cover duration and runoff up to -0.6. At the same time, the correlation between snow cover duration and specific runoff in April is strongly positive (r = 0.5–0.6).

Regime shifts in winter temperature in Estonia have caused shifts in specific runoff of rivers (Table 5). Warmer winters are naturally related to higher runoff in winter and an earlier maximum in spring after the snow melt which is typical for Estonia. Usually it is observed in April but during the last decades it has shifted to March. As a consequence, runoff in March has a positive shift which causes a negative shift in April. At 14 out of 21 stations, upward regime shifts in runoff appeared since the winters of 1988/1989 or 1987/1988 (Figure 5). The same shift was present also in January, February and March while the increase of more than two times in runoff in March was recorded at all stations. This has been the most significant change at all during the study period. The increase in runoff in March is closely related to the decrease in April since 1988/1989 with the return shift in the end of the time series since 2009 or 2010 (Figure 8). Practically no significant regime shifts were found in specific runoff during the other months.

Time series of annual mean runoff describe long-term alternation of wet and dry periods in Estonia (Table 3). Downward shift in 1963 or 1964, followed by upward shift since 1978 or 1981, mark the dry period in the middle of the whole study period. Some stations and some months show a decreasing runoff again in the beginning of the 21st century.

4 Discussion

It is rather natural that the elements of the climate system – air temperature, precipitation, snow cover, river runoff and indices of the large-scale atmospheric circulation – have close relationships. Changes in some parameters will induce corresponding changes in other parameters. We analysed correlations between them, similarities in their trends and regime shifts in Estonia. We suppose that our findings are relevant for a much wider territory in the Baltic Sea region.

The character of the large-scale atmospheric circulation is the main factor causing a very high interannual variability of weather conditions in the region. The highest role of circulation can be observed during the cold season when the role of solar radiation is negligible due to high latitude. The Atlantic Ocean is the only source of warm air for northern Europe in winter. Winter weather conditions in Estonia are largely determined by the intensity of westerly circulation over the Atlantic/European sector causing the advection of comparatively warm and moist air from the ocean. In case of weakening of westerlies, the influence of the ocean decreases and the weather is formed under the influence of a cold and dry continental air mass.

AO and NAO indices are appropriate variables for describing the intensity of westerlies. They have high correlations with winter climatic and hydrological parameters in Estonia. First of all, they determine winter temperature conditions. Snow cover duration is directly dependent on temperature while precipitation has more indirect relationships. Higher temperature in winter is caused by the cyclonic weather situation. It is related to cloudy, windy and rainy (snowy) conditions with higher precipitation. We detected increasing trends and upward regime shifts in AO and NAO indices in winter months and for the winter season as a whole. It reflects the intensification of the westerly circulation that has abruptly occurred since the winter of 1988/1989.

Changes in large-scale atmospheric circulation, trends as well as regime shifts, have naturally caused changes in other parameters. For example, the intensification of westerly circulation in winter during 1951–2015 has induced a significant increase in winter and spring temperatures, winter precipitation and river runoff, and a decrease in snow cover duration. It is expressed by linear trends and even better by coherent regime shifts since the late 1980s. 1989 proved to be the shift year for the majority of time series analysed in this study. This result lies in a good concordance with the previous investigations in the same region (Keevallik and Soomere, 2008; 2014; Elken et al., 2014).

The results of the trend analysis confirm the fact that climate warming in the Baltic Sea region has been faster than the global mean (BACC, 2015). Trend values 0.3–0.4°C per decade for annual mean temperature and the maximum more than 0.6°C in March show the existence of a very rapid change during 1951–2015. In the majority of cases with significant trends a regime shift was also detected. It allows to assume that climate change is not a monotone process but it consists of regime shifts. Several return shifts, i.e. shifts of an opposite direction were also found. In these cases the initial regime was more or less re-established. The shift value of about 2°C for winter temperature is practically the same as the total change by trend. It means that the whole winter warming during 1951–2015 can be described by the regime shift since 1988/1989.

It is important to emphasise differences between the coastal zone and the continental part of Estonia. The winter warming has been higher in the continental area and lower near the coast of the Baltic Sea. It can be explained by the thermal inertia of the sea and by the fact that in the case of stronger westerly circulation the advection of mild and moist maritime air mass into the continental parts of Estonia causes more substantial change in weather conditions than in the coastal zone. At the same time the correlation between the circulation indices and mean temperature is much higher in the coast.

Snow cover duration has a highly negative correlation with air temperature in winter. Therefore, the decrease by 3-4 days per decade as well as the downward regime shift by 16-20 days since the winter 1988/1989 follow the changes in temperature during the study period.

Various results of the analysis of trends and regime shifts for precipitation can be explained by its extremely high spatial and temporal variability. Mostly positive trends appeared in winter months. It is natural because the higher winter temperature in Estonia is related to cyclonic weather conditions that are also illustrated with higher cloudiness, wind speed and precipitation. Regime shifts in precipitation are not similar at different stations. They reflect long-term fluctuations. For example, the start of a rainy period in the end of the 1970s and in the beginning of the 1980s is characterised by an upward shift in annual precipitation detected at many stations.

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Discussion started: 20 March 2017

The response of river runoff to changes in climate parameters is more complicated. Annual mean runoff has not revealed any strong trends or shifts despite the increased precipitation and temperature. However, there are clear seasonal changes found in several earlier studies and confirmed in the current one. Specific runoff has significantly increased for the winter season and in all winter months separately from December to March. The highest increase has occurred in western Estonia. Due to the milder winter and earlier snowmelt the maximum spring runoff has moved from May and April to March. It could be considered as a logical consequence of climate warming which is projected for the end of this century (Jaagus et al., 1998; Jaagus and Mändla, 2014).

There are quite obvious differences in regime shifts in Estonia. The Vasknarva station on the Narva River reflects runoff fluctuations in a much wider area than the territory of Estonia. Therefore, they are not well comparable with shifts at other stations. Much less statistically significant regime shifts in specific runoff were detected in northern Estonia (the Jägala, Valgejõgi, Kunda and Purtse Rivers) than in the other parts of Estonia. Upward shifts were there revealed only in March since 1989. Rivers in northern Estonia are also characterised by strong negative trends in specific runoff in May.

The second group consists of the Vihterpalu, Leivajõgi and Keila Rivers in north-western Estonia where shifts were detected also in January, February and in winter as a whole. Rivers in western Estonia (Kasari, Pärnu, Lõve) have the strongest regime shifts. The Kasari and Lõve Rivers have extremely high values of the shifts, which exceed 11 l/s per km2 in January and February. Positive shifts at these stations were also revealed in annual runoff. Two other groups of rivers were distinguished in central Estonia (the Pedja, Põltsamaa, Navesti) and southern Estonia (the Võhandu, Piigaste, Väike-Emajõgi, Õhne, Halliste).

5 Conclusions

The main result of this study was the detection of coherent regime shifts in many climatic and hydrological parameters in Estonia that mainly occurred since the winter 1988/89. This significant change was caused by an abrupt intensification of westerlies, described by AO and NAO indices, which brought bigger amount of warm air from the North Atlantic to the Baltic Sea region. As a consequence, winter air temperature increased significantly and the duration of snow cover decreased. Due to the thermal inertia, mild winters are followed by early and warmer springs. The warming trend has been mentioned throughout a year but it is the highest in winter and spring. The shift value of about 2°C for winter temperature and up to 20 days for snow cover duration, detected in the end of the 1980s, is nearly similar to the total change by trend in 1951–2015.

Precipitation can be described by a moderate increase observed during the cold season (from November to March) and June, and by various regime shifts. Annual precipitation has had shift years since 1977 at some stations, and winter precipitation since the end of the 1980s.

Changes in climatic parameters were reflected in runoff of rivers. Winter runoff has increased significantly, especially in March. Runoff maximum caused by snowmelt has shifted from April to March and runoff in April has decreased. Few changes were found in specific runoff during the warm half-year.

Acknowledgements

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Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-24, 2017
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 20 March 2017

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Table 1: The list of hydrological stations used in this study, their catchment areas and characteristics of annual mean specific runoff (l/s per km^2).

River	Station	Area, km^2	Annual mean	St. deviation	Annual maximum	Annual minimum
Narva	Vasknarva	47800	6.85	1.83	10.88 (1990)	3.37 (1973)
Emajõgi	Tartu	7840	7.44	1.89	11.32 (1990)	3.71 (1996)
Pedja	Tõrve	776	7.85	2.19	13.25 (1981)	3.92 (1996)
Põltsamaa	Pajusi	1030	9.23	2.49	15.03 (1962)	4.38 (2006)
Piigaste	Piigaste	11.5	8.94	2.71	16.04 (1978)	4.01 (1965)
Võhandu	Räpina	1130	7.28	1.73	11.43 (1990)	4.17 (1996)
Väike-Emajõgi	Tõlliste	1050	7.90	1.97	14.31 (1978)	4.28 (1996)
Õhne	Tõrva	269	8.87	2.50	18.41 (1978)	4.74 (1965)
Halliste	Riisa	1880	9.27	2.66	16.50 (1978)	4.13 (1996)
Navesti	Aesoo	1008	9.13	2.77	17.22 (1981)	4.06 (1996)
Pärnu	Tahkuse	2080	9.92	2.81	18.16 (1981)	5.40 (1964)
Pärnu	Oore	5160	9.62	2.76	17.05 (1981)	4.95 (1996)
Lõve	Uue-Lõve	134	10.65	3.34	19.52 (2012)	5.40 (1976)
Kasari	Kasari	2640	9.62	2.79	15.74 (2012)	5.02 (2003)
Vihterpalu	Vihterpalu	474	9.29	2.84	19.19 (2012)	3.59 (2003)
Keila	Keila	635	9.78	3.02	16.83 (2012)	4.77 (2006)
Leivajõgi	Pajupea	83	8.12	2.54	14.26 (1981)	3.63 (2006)
Jägala	Kehra	903	8.23	2.41	15.86 (1981)	3.37 (1996)
Valgejõgi	Vanaküla	404	8.65	2.34	15.51 (1981)	4.12 (2006)
Kunda	Sämi	406	10.77	2.66	17.44 (1962)	5.45 (2006)
Purtse	Lüganuse	784	8.35	2.65	15.66 (1981)	3.08 (1964)

Table 2: Trend values of monthly, annual and seasonal indices of the large-scale atmospheric circulation. Statistically significant trends on p<0.05 are typed in bold.

	AO	NAOL	NAOG	NAOPC	NAOT	EA	EAWR	SCA	POL
Jan	1,12	**1,95**	1,13	**1,40**	**1,02**	**2,03**	-0,04	0,09	**-1,19**
Feb	1,16	**1,85**	1,25	**1,36**	**1,23**	0,86	0,41	0,37	-0,99
Mar	**1,18**	**1,82**	1,05	**1,63**	**1,58**	1,04	-0,22	-0,24	**-1,09**
Apr	0,44	-0,11	-0,41	0,26	0,46	**1,42**	0,61	-0,75	-0,20
May	0,61	0,62	0,02	0,40	-0,21	0,90	-0,68	-0,46	-0,08
Jun	-0,11	**-1,60**	**-1,84**	-0,49	-0,75	0,53	**-1,52**	**-1,00**	0,35
Jul	-0,18	-0,76	-1,09	-0,40	-0,66	**1,65**	-0,42	0,26	0,65
Aug	0,24	0,29	-0,48	-0,07	-0,03	**1,76**	-0,96	-0,77	**1,13**
Sep	0,32	-0,54	**-1,86**	-0,06	0,10	0,59	-0,85	0,09	0,23
Oct	-0,50	-1,47	**-1,69**	**-1,16**	**-1,52**	**1,39**	**-0,85**	-0,66	-0,48
Nov	**1,10**	1,08	0,14	0,72	0,59	**1,62**	0,17	-0,56	-0,11
Dec	0,53	-0,14	0,81	0,57	0,84	**1,81**	-0,11	-0,36	**-0,95**
Year	**0,43**	0,42	-0,26	0,38	0,25	**1,18**	-0,35	**-0,32**	**-0,35**
Spring	**0,69**	0,55	0,06	**0,75**	**0,64**	**0,97**	-0,11	**-0,51**	**-0,74**
Summer	0,00	-0,60	**-1,25**	-0,27	-0,49	**1,33**	**-0,91**	-0,39	0,58
Autumn	0,27	-0,25	**-0,91**	-0,19	-0,24	**1,04**	**-0,56**	-0,39	0,12
Winter	0,79	**1,13**	0,84	**1,11**	**0,99**	**1,50**	0,06	0,02	**-1,00**

Table 3: Trend values, shift years and shift values of spatially averaged monthly, annual and seasonal mean air temperature and precipitation in Estonia during 1951–2015. Statistically significant trends on $p<0.05$ are typed in bold. A significant downward regime shift for temperature by -2.5 K was detected only in January since 1966.

	Temperature			Precipitation				
	Trend (K per decade)	Upward shift year	Shift value (K)	Trend (mm per decade)	Upward shift year	Shift value (mm)	Downward shift year	Shift value (mm)
Jan	0.37	1988	4.0	**2.0**				
Feb	0.54	1989	2.3	1.0	1995	24.0	2003	-21.7
Mar	**0.62**	1966	3.4	**1.3**	1988	23.4	1996	-18.6
Apr	**0.43**	1989	1.9	-0.3				
May	**0.34**			0.7				
Jun	0.06			**3.0**				
Jul	**0.35**	2001	2.2	-0.5				
Aug	**0.27**	2002	1.4	1.1				
Sep	**0.27**	2004	1.6	-1.7			1998	-18.9
Oct	0.05			1.6				
Nov	**0.28**			**1.9**	1969	19.2		
Dec	0.36			1.3	2009	20.2		
Year	**0.33**	1988	1.4	**12.7**	1977	85.5		
Spring	**0.48**	1983	1.5	1.1	1966	19.2		
Summer	**0.25**	1999	1.2	-0.4				
Autumn	**0.26**	2005	1.6	3.3	1977	32.1		
Winter	**0.39**	1989	2.3	**4.7**				

Table 4: Trend values, years of regime shifts and corresponding shift values of annual mean specific runoff.

Station	Trend values	Shift years	Shift values
Vasknarva	0.05	1964, 1978, 2000	-2.70, 3.43, -1.46
Tartu	**0.19**	1964, 1978	-2.10, 2.85
Tõrve	0.07	1963	-0.86
Pajusi	0.00	1964	-1.49
Piigaste	0.17	1963, 1978	-3.53, 3.90
Räpina	0.10	1964, 1978	-2.00, 2.64
Tõlliste	**0.16**	1964, 1981	-1.88, 2.35
Tõrva	**0.34**	1981	2.61
Riisa	**0.26**		
Aesoo	0.20		
Tahkuse	0.23	1981	2.82
Oore	0.22	1981	2.40
Uue-Lõve	**0.47**	1978	3.71
Kasari	0.21	1984, 1996	2.82, -1.90
Vihterpalu	0.16		
Keila	0.22		
Pajupea	0.06	1984	1.37
Kehra	0.11		
Vanaküla	0.10		
Sämi	0,15		
Lüganuse	0,11		

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-24, 2017
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 20 March 2017

Table 5: Trend values of mean monthly, annual and seasonal specific runoff averaged over the 21 stations in Estonia. Statistically significant trends on $p<0.05$ level are typed in bold. Shift years, mean shift values and numbers of stations with statistically significant regime shifts in specific runoff.

		Upward shift			Downward shift		
	Trend	Year	No. of stations	Value	Year	No. of stations	Value
Jan	**0.78**	1988	14	7.1			
Feb	**0.41**	1989	10	6.6	2003	4	-8.7
Mar	**0.68**	1989	19	7.0	2003, 2009	6	-7.9
Apr	-0.50	2009, 2010	14	11.2	1989	8	-11.8
May	-0.31						
Jun	0.08						
Jul	0.04						
Aug	0.02						
Sep	-0.01						
Oct	-0.08				1964	3	-3.5
Nov	0.13	1977	3	7.7	1992	3	-6.4
Dec	0.29	2003	6	8.8	1963	3	-3.2
Year	0.17	1978, 1981	9	2.9	1964	8	-2.0
Spring	-0.13	2010	5	4.7	1963	4	-4.4
Summer	0.05						
Autumn	-0.02						
Winter	**0.65**	1988, 1989	14	5.0			

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-24, 2017
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 20 March 2017

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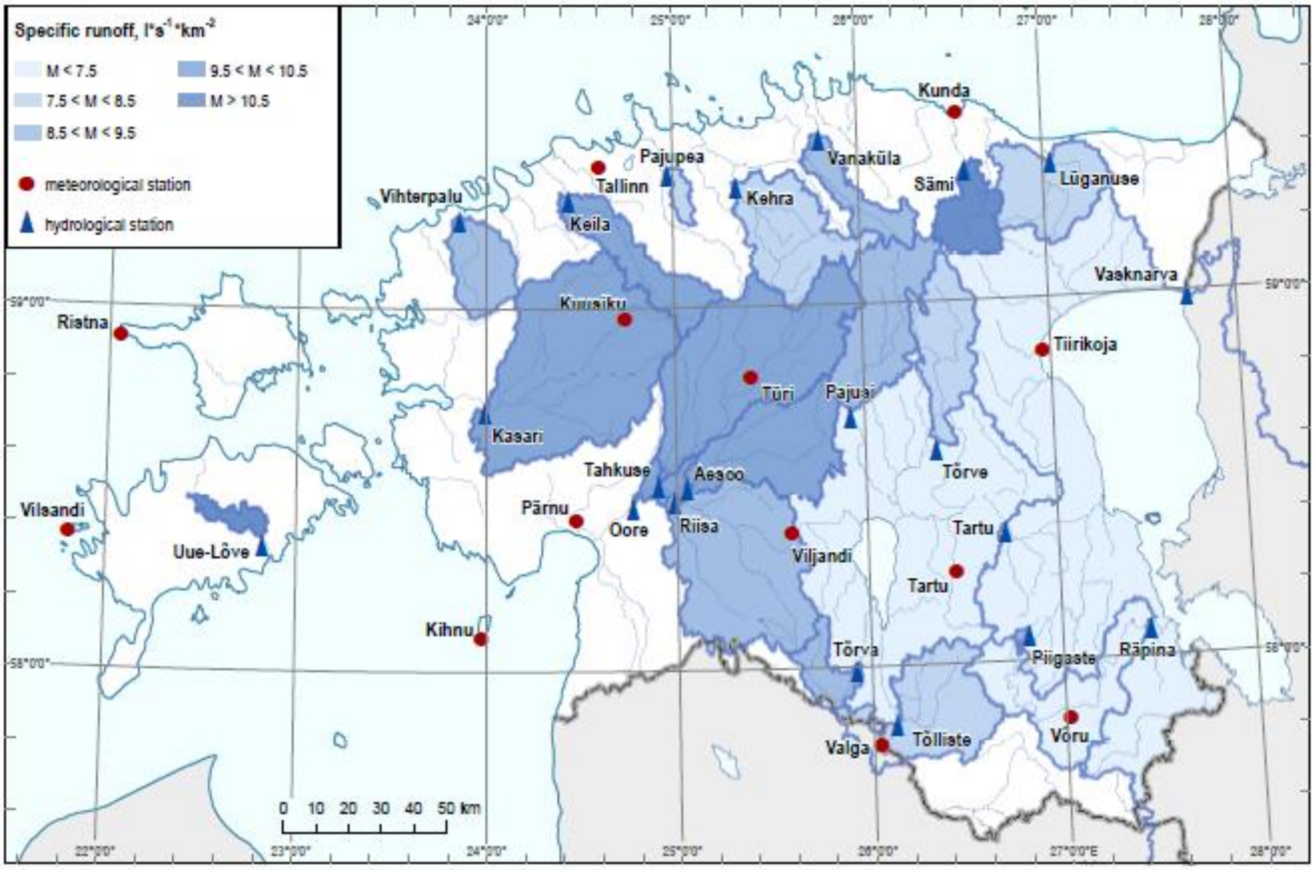


Figure 1: Map of Estonia with meteorological and hydrological stations, and the annual mean specific runoff of the studied river basins.

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-24, 2017
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 20 March 2017

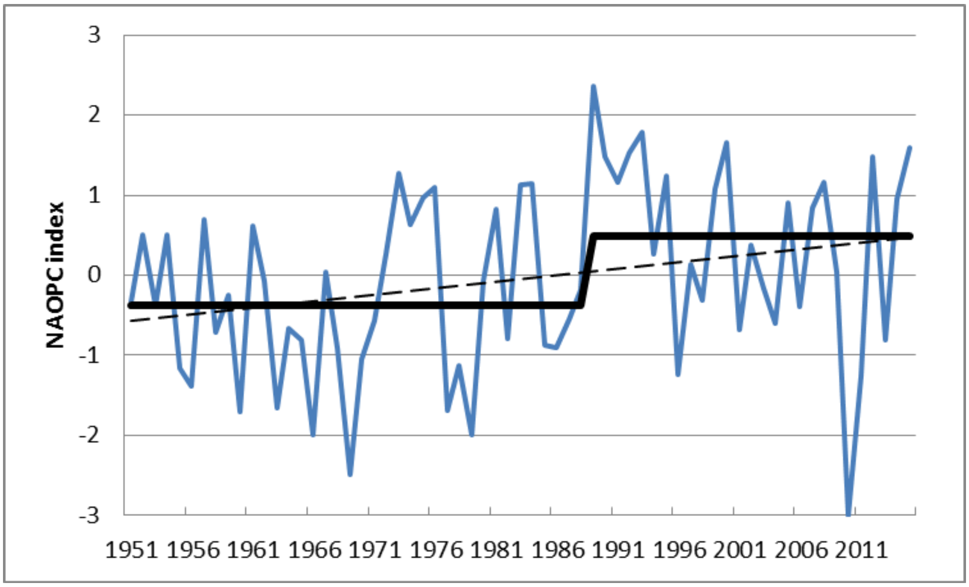


Figure 2: Time series of NAOPC index in winter (DJF) during 1951–2015, its regime shift since 1989 (wide line) and the linear trend (dashed line).

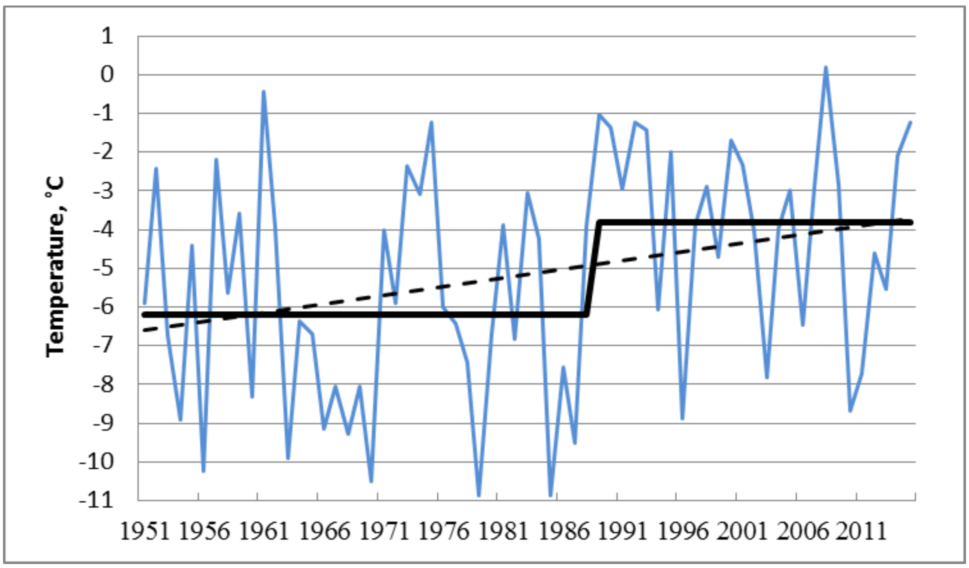
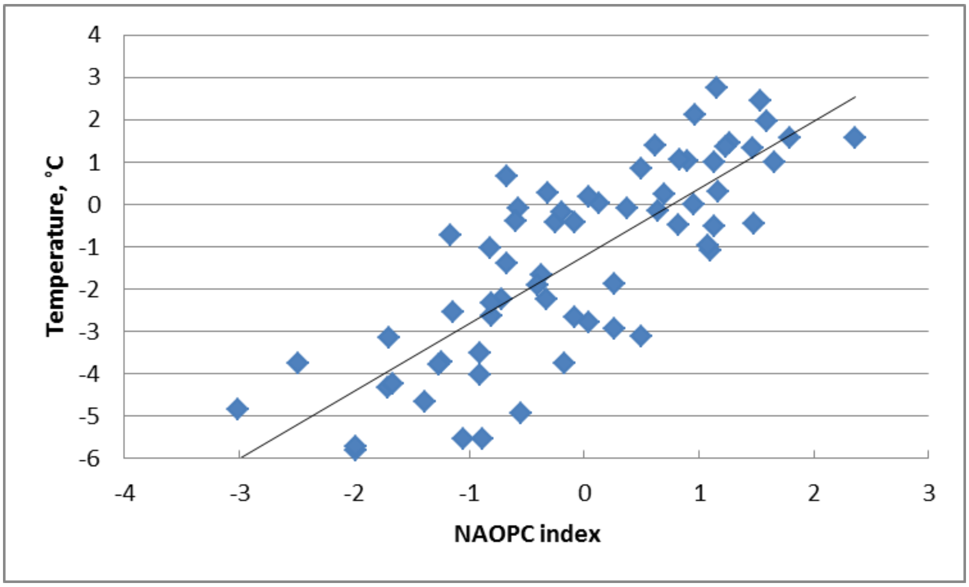
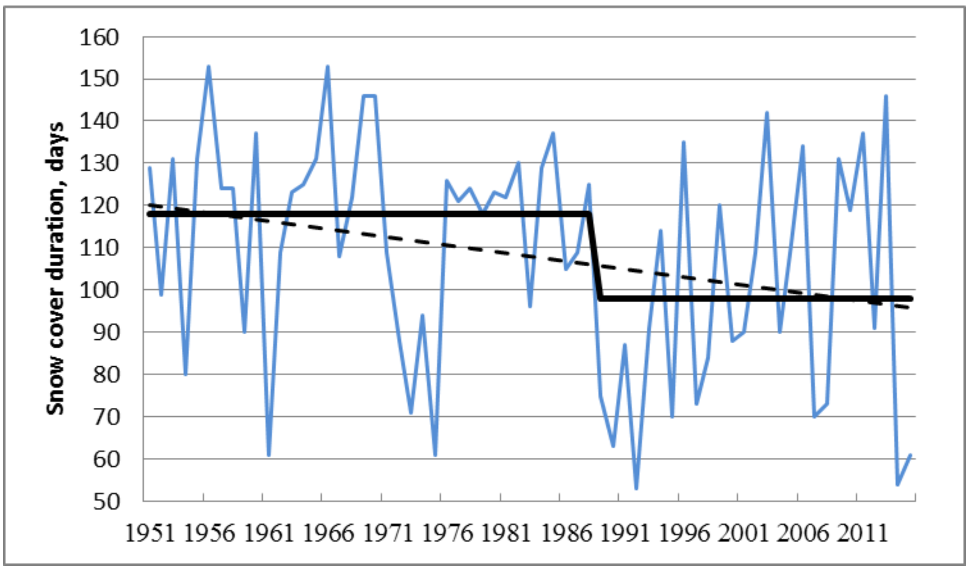


Figure 3: Time series of winter (DJF) mean air temperature (°C) in Tartu during 1951–2015 (blue line), its regime shift since the winter 1988/89 (wide black line) and the linear trend (dashed line).



520 **Figure 4:** Scatter plot of winter mean NAOPC index and winter mean temperature in Ristna (r = 0.800).



525 **Figure 5:** Time series of snow cover duration in Tartu during 1951–2015 (blue line), its regime shift since the winter 1988/1989 (wide black line) and the linear trend (dashed line).

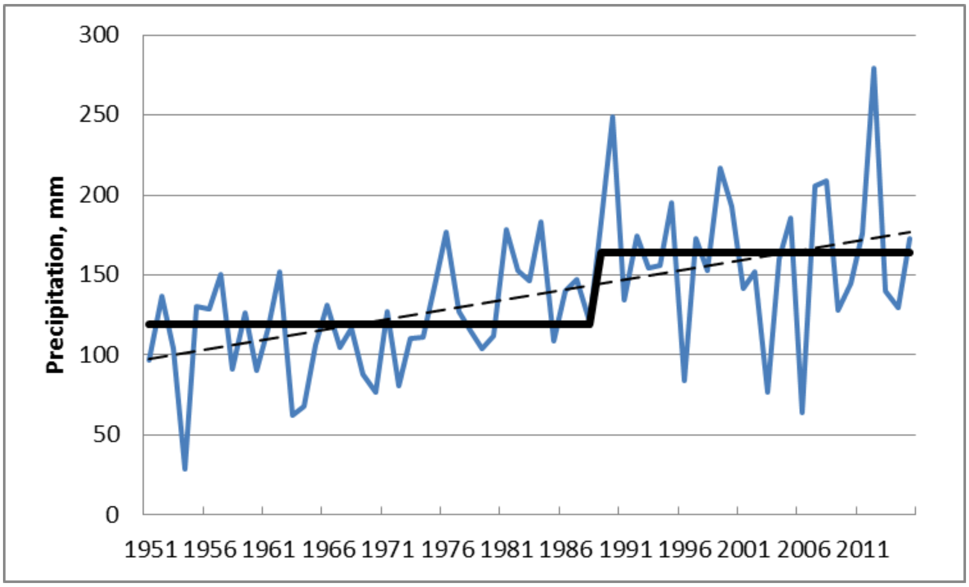


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Figure 6: Time series of winter precipitation (DJF) in Türi during 1951–2015 (blue line), its regime shift since 1989 (wide black line) and the linear trend (dashed line).

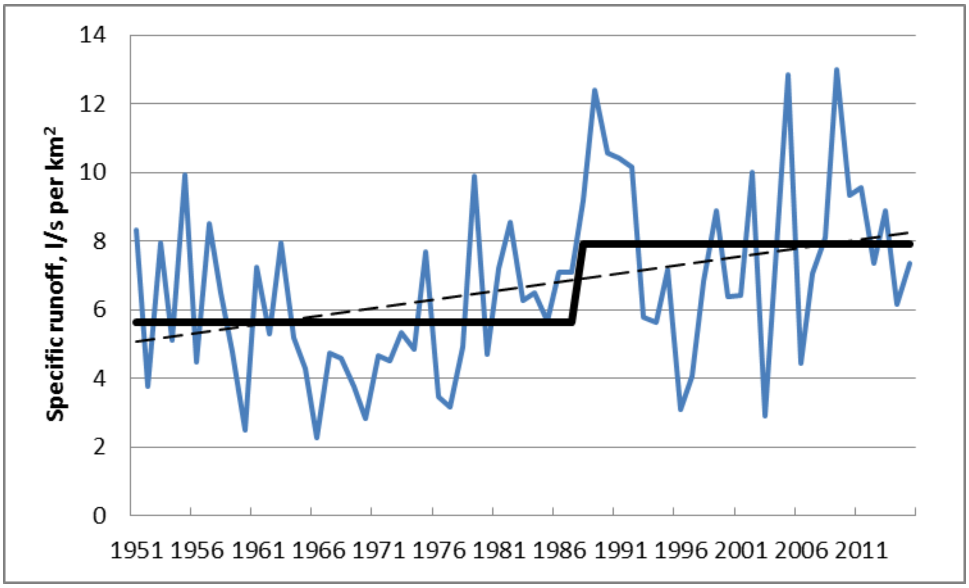

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Figure 7: Time series of specific runoff (l/s per km2) in winter at the Tartu station on the Emajõgi River during 1951–2015, its regime shift since 1987/1988 (wide line) and the linear trend (dashed line).

Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-24, 2017
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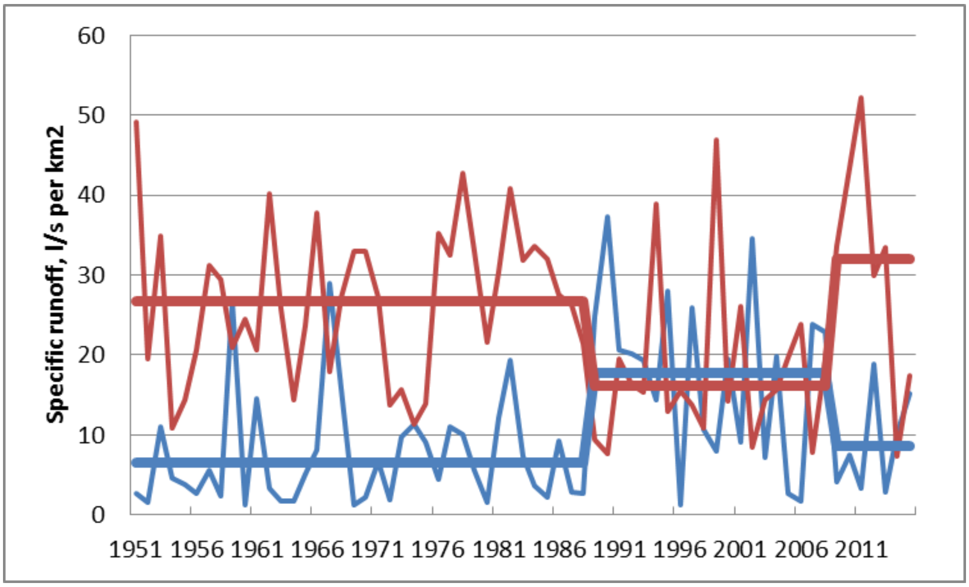

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Figure 8: Time series of specific runoff (l/s per km^2) in March (blue) and April (red) at the Riisa station on the Halliste River during 1951–2015 and their regime shifts of opposite sign since 1989 and 2009 (wide lines).