Response to the reviewers' questions and critical remarks made to our manuscript

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

by Jaak Jaagus, Mait Sepp, Toomas Tamm, Arvo Järvet and Kiira Mõisja

We thank both anonymous reviewers very much for their comments, suggestions and recommendations. We agree with them and we tried to improve our manuscript following their instructions. Here we answer to the questions and respond to every critical comment. We try to explain our preferences and improvements of the text. Our response is typed in blue colour. We also add the Word file of the improved manuscript where all our modifications are indicated in the Track Changes regime.

REVIEWER 1

General comments

The authors have published several papers on the same topic:

Jaagus, J. 2006. Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. TAC, 83, 77–88

Sepp, Mait, 2010. On regime shift in the general atmospheric circulation over the Baltic Sea region in winter. International BALTEX Secretariat Publication, 46, 46-47

Sepp, Mait, 2016. On Regime Shift in the General Atmospheric Circulation over the Baltic Sea Region. COST Action 733: Harmonization and Application of Weather Type Classifications for European Regions ; Final Scientific Report, 221?228.

Jaagus, J., Briede, A., Rimkus, E., Sepp, M. 2016. Changes in precipitation regime in the Baltic countries in 1966–2015. TAC, DOI: 10.1007/s00704-016-1990-8.

What is new in the present paper?

1. 15 years and 2 meteorological stations were added, but this did not change the conclusions drawn on temperature, precipitation and snow cover trends in (Jaagus 2006)

2. Trend analysis was complemented with regime shift analysis, but the conclusion that an abrupt change in the circulation over the Baltic Sea has taken place at the end of the 1980s only repeats the existing knowledge (Sepp 2010, Sepp 2016, Lehmann 2011, Soomere and Räämet 2014, Soomere et al 2015, etc)

3. The analysis of river runoff was added and this is new.

Therefore, the authors should make clear difference between the well-known facts, their own earlier conclusions and new information.

Response. Many thanks to the reviewer for these detail critical comments. It is true that we should stress much more to the novelty of our results. We should compare our results with the previous ones and leave these parts, which are more or less repetitions. We modified the text in the sections of introduction, results and discussions. Our more detail response is the following.

In the previous article (Jaagus, 2006) trend analysis for mean air temperature, precipitation and snow cover duration in Estonia was realised for the period 1951-2000. Results of trend analysis depend very much on the time frame, i.e. they are different for different periods. Therefore, it was important to look how much the results of trend analysis will change if we add data from 15 updated years. Continuous monitoring of climatic changes gives us valuable information about possible changes in the future. In the section of discussion we tried to put forward similarities and differences between the results of trend analysis between these two periods. In the paper on precipitation (Jaagus et al., 2016) there is a comparison of results of trend and regime shift analyses in three Baltic countries. But the period was shorter (1966-2015) than in the current article (1951-2015). Of course, here is an overlapping of results and partly a repetition. The main idea and novelty of our study was to make an integrated analysis of trends and regime shifts in time series of many inter-related and indicative variables of the climate system starting from the indices of the large-scale atmospheric circulation and ending with specific runoff of rivers. Therefore, we did not leave out the precipitation data from our study. We tried to explain all these aspects in the improved version of our manuscript.

Concerning the analysis of regime shifts we think that we have found new results and have not only repeated the existing knowledge. Mait Sepp (2010; 2016) has analysed time series of the frequency of different circulation types according to the classifications of large-scale atmospheric circulation, which are selected in the COST Action 733. He has not analysed the circulation indices, which were analysed in this study.

The famous article by Lehmann et al. (2011) used a wide range of data sources for the analysis of climate variability in the whole Baltic Sea region. They used mostly reanalysis data and regression, correlation, wavelet and cluster analyses. The detection of regime shifts was not the main task. They discussed shifts in the locations of the NAO centres of action but they also demonstrated that since 1987 the winter season (DJFM) of the Baltic Sea area has tended to be warmer, with less ice coverage and warmer SST, especially pronounced in the northern parts of the Baltic Sea. We would like to emphasise that when Lehmann et al. (2011) analysed climate variability in the regional scale then we have analysed trends and regime shifts in local scale, i.e. in Estonia. We showed that the most significant regime shift in Estonia has occurred exactly since the winter 1988/1989.

We are very sorry that we have not referred the publications by Soomere and Räämet (2014) and by Soomere et al. (2015). The first one analysed wave properties of the Baltic Sea, which were simulated using the WAM model. They were related to annual mean components of air flow of the adjusted geostrophic wind. The second article also deals with wave and wind climatology of the Baltic Sea but it uses observation data at 8 stations in the eastern coast. A shift in simultaneity in annual mean wave length between the stations was detected since 1988. It was related to the observed shifts in the annual mean zonal and meridional components of air-flow of the adjusted geostrophic wind.

In conclusion, we can state that the three mentioned articles used completely different data sources, study areas, variables and methods for the analysis of regime shifts in comparison with our research, but they resulted in a similar result pointing out a significant regime shift in the end of the 1980s. In this sense, the main result of our paper is really a repetition of the results of the previous studies. We think that it is important to emphasise that this shift was a big change in the whole climate system in this region. We hope that our article could contribute into this study field. We tried to improve our manuscript in this sense in the introduction and discussion.

References: Lehmann A., Getzlaff K., and Harlaß J. 2011. Detailed assessment of climate variability in the Baltic Sea area for the period 1958 to 2009. Clim. Res., 46, 185–196. Soomere, T. and Räämet, A. 2014. Decadal changes in the Baltic Sea wave heights. J. Mar. Syst., 129, 86–95. Soomere, T., Bishop, S.R., Viška, M., Räämet, A. 2015. An abrupt change in winds that may radically affect the coasts and deep sections of the Baltic Sea. Clim. Res., 62, 163–171

Response. These articles are referred in the improved version of the manuscript.

Specific comments

An interesting part of the paper is regime shift analysis of large-scale circulation indices. Table 2 presents only trends and regime shifts are described very shortly in chapter 3.1. Figure 2 presents the time series of only one index. What about the others? What about return shifts?

Response. We agree that results of regime shifts in circulation indices are not well presented. Now, they are described more in details in the sections of results and discussion. We also added Table 3 and two figures (Figures 2b and 2c). Regime shifts appeared, first of all, in case of winter NAO indices. Shifts for the other indices were quite rare and random. Return shifts were detected for the NAO indices in February since 2004 (Figure 2b).

Table 3 shows trend and shift values for the whole Estonia, but text in chapters 3.2, 3.3 and 3.4 describes regional differences. This is not acceptable. The spatial distribution of these values should be presented in a more convincing way. E.g., there is a sentence "Generally, the trends and regime shifts at the coastal stations in western Estonia are weaker than at the inland stations of eastern Estonia". There are no numbers to prove this. Therefore, this sounds like belief, not knowledge.

Response. This result is presented more exactly in the section of results. In fact, we obtained a huge number of numeric results that is difficult to present in the article. We made a choice to present general results for the whole Estonia in tables, gave some typical time series on figures and described spatial differences within Estonia in the text. We added into the improved version the following sentences.

"For example, the changes by trend of annual, winter and spring temperature during the 65 years were in coastal stations – Vilsandi 2.2, 2.4 and 3.0, Ristna 2.0, 2.1 and 2.5, Tallinn 1.9. 2.4. 3.2 – and in inland stations of eastern Estonia – Võru 2.4, 2.4 and 3.4, Tartu 2.5, 2.9 and 3.7, Tiirikoja 2.3, 3.1 and 3.7 K, correspondingly. The values of regime shift in winter mean temperature since 1989 were the following; Vilsandi 1.9, Ristna 1.9, Tallinn 2.2, Võru 2.4, Tartu 2.7, Tiirikoja 2.7 K."

We do not agree with the assumption that this is a belief. This sentence mentioned by the reviewer is a generalisation of results confirmed by the concrete results of trend and regime shift analyses.

Trend values and regime shifts for precipitation shown in Table 3 do not coincide with the data in Tables 1 and 2 shown in (Jaagus et al 2016). This discrepancy should be clarified.

Response. The discrepancies were caused by different periods for the analysis: 1951-2015 in our case and 1966-2015 in case of the mentioned article (Jaagus et al. 2016).

Figures 3, 5, 6, 7 and 8 contain nearly no information, because they are drawn for some selected sites and simply illustrate how trends can be replaced by regime shifts. There is nothing new in comparison of these two methods.

Response. These figures are really illustrations of the text. We do not imagine how we can describe trends and regime shifts in various time series without showing their graphical form. We tried to select the most typical examples. For example, data from the Tartu and Türi stations are more or less representative for describing climate variability in the whole continental part of Estonia. In the improved version we tried to change figures more informative and general. We merged Figures 3 and 5 showing the variability, trends and regime shifts in winter temperature and snow cover duration together on one figure. We draw Figure 6 showing coherent regime shifts in winter specific runoff in the majority of station.

Figure 4 is drawn for only one station and only one index, therefore, its informative value is low. Besides, positive correlation between NAO indices and temperature in winter is a trivial fact.

Response. We omitted the figure.

REVIEWER 2

General comments

In general the article is well prepared and worth to publish with minor revision.

Most of introduction is devoted to regime shift, while not enough attention was paid to previous investigations on climate parameters and especially on river runoff change.

Response. The analysis of regime shifts is quite new method in climatology and, therefore, it is more widely described in the introduction. Here we described nearly all investigations on climate changes in Estonia and referred also studies in the wider context (BACC, 2008; 2015). We added some other publications. But, unfortunately, studies on climate changes in river runoff in Estonia are only few. All they are referred.

Authors should to reveal novelty of their study too, i. e. to show if their study differs from the previously conducted in Estonia.

Response. This question is answered more exactly at the same comment made by the reviewer 1. We improved the sections of introduction and discussion.

I disagree that correlation coefficients can be provided in the article without evaluation of statistical significance. You can easily do that.

Response. The significance of the correlation coefficients is now evaluated. We added the following text into the section of data and methods: „As the length of the time series in this case is 65 years then the critical value of statistical significance on $p<0.05$ level is $r = 0.245$ and on 0.01 level $r = 0.318$. All correlation coefficients presented in this study are statistically significant at least on the $p<0.05$ level".

The reasons why "after numerous tests" certain set of parameters for regime shift detection was chosen should be described more clearly.

Response. We added the following text.

"As in case of many statistical methods, the STARS method has no strict rules for the selection of input parameters. The choice depends on the purpose of the study. For example, if there is a need to detect short-term variations in the time series then loose parameters – high HWP, short l and low significance. Our task was to study general changes in atmospheric circulation, climatic and hydrological variables. Therefore we used a relatively conservative set of input parameters …"

In some cases, very short periods (e. g. <10 years (line 234) or 6 years (line213)) were described as regime shift. It is not clear what is the difference between short-term fluctuations and regime shift.

Response. The text in the section of data and methods is improved and additional explanation is provided. We added the following text.

"One of the peculiarities of the STARS method is that it tends to find regime shifts at the rear years of time series. This characteristic of the method has been considered as an advantage that allows "to process data in real time, signalling the emergence of a potential shift and measuring changing confidence in the evidence for a shift as new data arrive" (Rodionov and Overland, 2005). Also, at the formal point of view, those RSI shifts are statistically reliable. However, it is understandable that in reality those shifts in rear years are meaningless and do not represent any substantial changes. Thus we have ignored shifts that occurred in last 5 years of the analysed time series."

Short-term fluctuations are typical for climatic time series. Regime shifts are more stable in time. But it is really difficult to define a clear difference between them.

The term "trend" can be used only in case of statistically significant changes. Otherwise increase, decrease, tendency or other terms should be used.

Response. We agree. We used this term only in these cases. We checked the text and made some corrections.

The purpose of section 3.1 remained unclear for me. There is a lot of different circulation indexes presented as well as a lot of regime shifts were found. However, it's difficult to understand significance of all this findings. For example, what mean negative trends in POL index values and how that relates to climate conditions in investigated area? I would suggest to remove this paragraph, while results of atmospheric circulation regime shift analysis can be used in other part of the text for explanation of tendencies of climate and runoff parameters.

Response. We added a sentence explaining the purpose of the section 3.1: As large-scale atmospheric circulation has close relationships with air temperature and precipitation in Estonia

(Jaagus, 2006), time series of its parameters were analysed as the main factors inducing climate variability. The Reviewer 1 thought that "An interesting part of the paper is regime shift analysis of large-scale circulation indices". He asked more detail description of these results. Therefore, we do not want to remove the section 3.1 but we presented more detail analysis in the text.

Specific comments

Page 1. Line 20-22. It is not clear for me if authors analyzed correlation between AO and NAO, while I didn't find such information in the following text. Moreover, what is a purpose of such correlation? From my point of view, it is not related with tasks of research.

Response. We apologise for the incorrect wording. We did not analyse correlation between AO and NAO. We wanted to say the correlations between the NAO and AO indices (from one side) and the studied variables (from another side) were 0.5–0.8. We corrected the sentence accordingly: "Correlation coefficients between the circulation indices reflecting the intensity of westerlies and the studied variables were 0.5–0.8.

Page 4. Lines 106-110. I suppose, that such detailed information about relocation of two stations isn't important. Only statement about data homogeneity can be left in the text.

Response. We omitted two sentences with detailed information.

Page 7. Line 221-223. Results presented in this part of text don't fully meet data in Table 3 (e.g. up to 5 mm in monthly precipitation). Moreover monthly data about changes in stations aren't presented in mentioned table.

Response. The text is modified significantly.

Page 10. Line 292. You mention that you detected regime shifts in NAO and AO indices, however in introduction you mentioned that such shifts were already discovered in other research.

Response. In the introduction, there were referred studies where regime shifts were detected in many parameters but not in NAO and AO indices.

Page 11. Line 321 and 337. Two statements about annual river runoff contradict each other.

Response. Unfortunately, there was a mistake in the first sentence. We replaced it with the following sentence: "Annual mean runoff has a statistically significant trend and regime shifts only in some stations".

Page 11. Line 326-327. In this paragraph you talk about already observed changes. So you don't need to wait the end the 21st century and consequently the last sentence of this paragraph have no sense.

Response. The last sentence of this paragraph was omitted.

Page 11. Line 338-339. What are the specific features of the last two distinguished groups of rivers?

Response. We added the following text:

The first one can be characterised by positive regime shifts in January and March and negative shift in April since the end of the 1980s. They have also significant negative trends in April and May. Rivers of southern Estonia have a general increase in specific runoff in January, February, March and June with positive shifts in the same months (except June) and negative shifts in April.

Page 12. Line 352. Do you think that March is winter month?

Response. In hydrology, March is an end of winter and the beginning of spring in Estonia. Due to the observed changes March has become more like a spring month with runoff maximum due to snowmelt.

Figure 1 should be improved with additional regional map where location of investigated area can be seen in more general context.

Response. We have improved the map and add a small map with the regional location of Estonia.

Technical corrections

Page 1. Line 19-20. The main idea of the sentence “All meteorological: : :” should be expressed more clearly.

Response. We replaced “All meteorological and hydrological variables” with “Air temperature, precipitation, snow cover duration and specific runoff of rivers”.

Page 4. Line 106. I would propose to use “station location” instead of “the measuring sites of the stations”.

Response. We agree and made this change.

Page 4. Line 112-113. The sentence “The wetting: : :” is difficult to understand.

Response. There was a term “wetting correction”. We rephrased the sentence writing “the correction for wetting of the walls of the gauge”. This correction was used all over the former USSR. We added the reference on Groisman et al. (1991).

Page 4. Line 95 and line 221. What mean “increasing trend”. Is it gradual change in trend values? I suppose that you should use the term “positive trend” or “significant increase of in river runoff” instead of.

Response. We replaced this term in the both cases.

Page 7. Line 195. The expression “had a jump by” isn’t usually used in English language.

Response. We replaced “jump” with “upward shift”.

Table 4. It isn’t clear if the regime shifts are upward or downward. Not always shifts sign correspond to general tendency.

Response. May-be, the presentation of the results in Table 4, now Table 5, is not the best. There have been up to three statistically significant regime shifts for some time series. Shift years in one column are related to shift values in the last column. For example, there were two shifts in the Tartu station: in 1964 there was a downward shift by 2.10 l/s per km^2 and an upward shift in 1978 by 2.85 l/s per km^2. We added the unit (l/s per km^2) into the heading of the table.

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 of trends and regime shifts during 1951–2015. Trend analysis is realised 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 the 12 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 have notably decreased indicating the shift of the runoff maximum to the earlier time, i.e. from April to March. All meteorological and hydrological variables Air temperature, precipitation, snow cover duration and specific runoff of rivers are highly correlated in winter determined by the large-scale atmospheric circulation. Correlation coefficients between the AO and 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 late 1980s, mostly since the winter 1988/1989, that 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 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.

1 Introduction

Different methods of trend analysis are usually applied for the detection of climate changes. For example, using regression analysis ~~C~~climate warming in the Baltic Sea region including Estonia is estimated to be faster than the increase of 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. The most dramatic changes in the Baltic Sea region have taken place just during the last decades (Lehmann et al., 2011).

The North Atlantic Oscillation (NAO) strongly affect Northern Hemisphere surface temperatures with patterns often reported to be similar to the global warming trend (e.g. Hurrell 1995, Rodwell et al. 1999). Also, several studies show the evidences for ongoing intensification of the global water cycle, including increasing river runoff (Labat et al. 2004, Huntington 2006). ~~Different methods of trend analysis are usually applied for the detection of climate changes.~~ However, it is known, that trend analysis, especially linear trends, have certain limitations. Linear regression analysis disregards the internal variability of the time series. At the same time, those internal alterations provide a lot of important information on climate changes. ~~t~~

In addition to linear trends, there could be also abrupt changes, i.e. jumps or breaks, which divide a time series into parts with different statistical properties, called regime shifts. Initially, the term regime shift was used in marine ecology and was inspired ~~in~~ by ~~abrupt~~ changes in 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 details by Overland et al. (2008). There are several concepts of the definition 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 that 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 1920s and 1930s (Drinkwater, 2006). However, a number of studies have detected regime shifts in many parameters in 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 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). Regime shifts in late 1980s have been detected also in the Arctic sea-level pressure (Walsh et al., 1996), intensification of upper air polar vortex (Tanaka et al., 1996) and a 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 1980s and their global impact on the biosphere was conducted by Reid et al. (2016).

There are also many evidences of regime shifts in the North Atlantic and European region in late 1980s. For example, a regime shift on this period was reported from the Mediterranean Sea based on ecological, hydrological and climatic variables (Conversi et al., 2010). In the review article on regime shifts in marine ecosystems many studies are referred where the shift since 1989 in the Northern Atlantic was found (DeYoung et al., 2004). Using long time series of winter Baltic climate index (WIBIX) based on monthly values of the first principal component of winter anomalies (January – March) of NAO index, sea level anomalies on Landsort (Sweden) and maximum Baltic ice cover, Hagen and Feistel (2005) determined the alternation of two climate regimes over the Baltic Sea. The last period of mild winters started at 1988 (Hagen and Feistel, 2005). In marine ecosystems of the Baltic Sea a regime shift has been observed in 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 of Atlantic marine and Eurasian continental climate systems and influenced by air masses from arctic to subtropical origin, the climatic conditions here are characterize by high spatio-temporal variations (BACC, 2008; Rutgersson et al., 2014). Thus, the Baltic Sea region poses great challenge for the detection of trends and 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 (Figure 1). We suppose the climatic and hydrological changes here are more or less typical for much a 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 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. In the majority of the studied stations annual and winter precipitation has also increased significantly in Estonia. 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). It will be important to monitor if these trends have continued also in the beginning of the 21st century.

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). 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). Dynamics of wave properties of the Baltic Sea were analysed by Soomere and Räämet, (2014), which were simulated using the WAM model. They were related to annual mean components of air flow of the adjusted geostrophic wind. A shift in simultaneity in annual mean wave length between 8 stations in the eastern coast of the Baltic Sea was detected since 1988 (Soomere et al., 2015). It was related to the observed shifts in the annual mean zonal and meridional components of air-flow of the adjusted geostrophic wind. During the period 1981–2010 an upward shift in 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) abrupt increase was observed in the zonal component of average air flow from January to March, in air temperature for January and February and in precipitation for February (Keevallik, 2011). However, the Pprecipitation regime in the eastern Baltic region can be characterised by a very high spatial and temporal variability and thus there are few reliable trends in time series of precipitation (Jaagus et al., 2010; 2016).

Long-term fluctuations in climatic parameters are reflected in the dynamics of river runoff that has 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 affected also by hydrographical and hydrogeological characteristics where we can find relatively large differences in Estonian catchment areas. Variability and trends in river discharge in the Baltic countries is analysed by many authors (Järvet, 1998; Reihan et al., 2006; 2007; 2012; Kriauciuniene et al., 2012). They found that increasing trends of river runoff were characteristic only in winter season during the 20th century. At the same time, runoff fluctuations with the period of ca 30 years are dominating in the time series for Estonia. Using the water balance model WATBAL changes in river runoff in Estonia were modelled for the case of continuous climate warming (Jaagus et al., 1998). The results indicated an increase of runoff in winter and decrease in spring, which could leave to drought conditions in the end of spring and beginning of summer.

The objective of this study was 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 indices of large-scale atmospheric circulation to detect coherent changes. The study period 1951–2015 was chosen as it is the period when the highest number of stations with continuous time series is available in Estonia. The main idea and novelty of this study in comparison with the previous ~~analyses~~ ones ~~i~~was to realise an integrated analysis of trends and regime shifts in time series of many inter-related and indicative variables of the climate system starting from the indices of the large-scale atmospheric circulation and ending with specific runoff of rivers. ~~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 have been used for the analysis. No significant relocations of the measuring sites have been taken place at these stations except two stations. In 1980, the Tallinn station was moved from Ülemiste (airport) to Harku ca 12 km west. Thereby, the local placement on the limestone plateau several kilometres from the sea coast remained nearly the same. Since 1997 the Tartu station has moved from Ülenurme to Tõravere by 15 km southwest. Analysis of time series did not revealed 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 is not eliminated from the time series. The wetting correction takes about ten per cent of monthly precipitation, which is difficult to detect. In addition, time series of snow cover duration at five stations are analysed to better describe winter weather conditions.

For 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 available precipitation data (Jaagus, 1992).

We used specific runoff of rivers (in litres per second per square kilometre) because it allows comparing observ~~ation~~ed data from river basins of different size and assessing results of statistical analyses. Monthly, seasonal and annual specific runoff values in 1951–2015 have been used from all 21 stations with various catchment areas, hydrological and hydrogeological conditions where the long series of measurements is available in Estonia (Figure 1). Seasons were defined by three months as usual in climatological studies: spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Hydrological parameters of these river basins are presented in Table 1.

Large-scale atmospheric circulation is an important factor influencing on local weather conditions. In this study changes in circulation are analysed using 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 have used 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 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), East Atlantic (EA) and Polar/Eurasia (POL) patterns describe mostly zonal circulation while the East Atlantic/West Russia (EAWR) and Scandinavia (SCA) patterns describe the meridional circulation.

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

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).

The Mann-Kendall test is used to detect trends in time series (Mann, 1945; Kendall, 1975). The reason for selecting the 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 statistical relationship between time series of different climatic and hydrological variables. As the length of the time series in this case is 65 years then the critical value of statistical significance on $p<0.05$ level is r = 0.245 and on 0.01 level r = 0.318. All correlation coefficients presented in this study are statistically significant at least on the $p<0.05$ level. ~~As the correlations are presented only for the illustration of the relationships, their statistical significance is not found~~.

The STARS (Sequential T-test Analysis of Regime Shifts) method, known also as the Rodionov test (Rodionov, 2004; Rodionov and Overland, 2005) was used for the detection of regime shifts in 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 with 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 and is downloadable from the Bering Sea Climate website http://www.beringclimate.noaa.gov/regimes/. As in case of many statistical methods, the STARS method has no strict rules for the selection of input parameters. The choice depends on the purpose of the study. For example, if there is a need to detect short-term variations in the time series, then loose parameters can be used – high Huber´s weight parameter (HWP), short cut-off length (l) and low significance level of the t-test (p). Our task was to study general changes in atmospheric circulation, climatic and hydrological variables. Therefore we used a relatively conservative set of input parameters – ~~After numerous test experiments 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, ~~Huber´s weight parameter,~~ HWP = 1. HWP determines the weight of outliers in calculation of mean values before and after the shift. No pre-whitening methods were used.

The output of the test is a year, when a regime shift occur (or years of shifts, if the time series contain 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, as one output of the test is the difference between the weighted means that is used as a shift value for describing the magnitude of the shift.

One of the peculiarities of the STARS method is that it tends to find regime shifts in the end of time series. This characteristic of the method has been considered as an advantage that allows "to process data in real time, signalling the emergence of a potential shift and measuring changing confidence in the evidence for a shift as new data arrive" (Rodionov and Overland, 2005). Also, at the formal point of view, those RSI shifts are statistically reliable. However, it is understandable that in reality those shifts in the last years are meaningless and do not represent any substantial changes. Thus we have ignored shifts that occurred in last 5 years of the analysed time series.

3 Results

3.1 Indices of large-scale atmospheric circulation

As large-scale atmospheric circulation has close relationships with air temperature and precipitation in Estonia (Jaagus, 2006), circulation indices were analysed as the main factors inducing climate variability. 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 of different NAO indices in winter (Figure 2). It means that negative NAO indices have become to occur less and positive anomalies more during the study period indicating the tendency of intensification of westerly circulation over the Atlantic/European sector. Positive trends in the NAO indices were observed in January, February and March while negative trends were found in June and October. 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 and mostly negative trends in single months (Table 2).

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

Figure 2: Time series of NAOPC indexices in winter (DJF) during 1951–2015, itstheir regime shifts since 1989 (wide lines) and linear trends (dashed lines): a) NAOPC in winter; b) NAOL in February and c) NAOG in summer..

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

The AO index and NAO indices for winter demonstrate a statistically significant positive regime shift since the winter 1988/1989 (Table 3, Figure 2a) 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. In the case of the NAOT the shift year was 1988. Return shifts for the NAO indices appeared mostly in February since 2004 (Figure 2b). A negative regime shift was found for summer NAO index since 2007 (Figure 2c). The EA teleconnection index has significant upward regime shifts in many months and in all seasons except autumn (Table 3) corresponding to their positive trends (Table 2) but at different years: from 1970 to 2009. Other teleconnection indices had few regime shifts (not shown in Table 3).

Table 3. Years of statistically significant upward (+) and downward (-) shifts in time series of the circulation indices from different months and seasons.

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 has significantly increased 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 has been detected also for all seasons while the trend values are higher than the annual mean in winter (Figure 3) and spring, and lower in summer and autumn. Among single months, statistically significant trends during the study period were detected in March, April, May, July, August, September and November (Table 43). 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.

Table 34: 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 was detected only in January since 1966 by -2.5 K.

Figure 3: Time series of winter (DJF) mean air temperature (blue) and snow cover duration (red), their regime shifts since the winter 1988/1989 (wide lines) and linear trends (dashed lines).

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 linear trend (dashed line).

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Upward regime shifts are typical for air temperature (Table 34). 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 the western Estonia are weaker than in the inland stations of the eastern Estonia. For example, the changes by trend of annual, winter and spring temperature during the 65 years were in coastal stations – Vilsandi 2.2, 2.4 and 3.0, Ristna 2.0, 2.1 and 2.5, Tallinn 1.9. 2.4. 3.2 – and in inland stations of eastern Estonia – Võru 2.4, 2.4 and 3.4, Tartu 2.5, 2.9 and 3.7, Tiirikoja 2.3, 3.1 and 3.7 K, correspondingly. The values of regime shift in winter mean temperature since 1989 were the following; Vilsandi 1.9, Ristna 1.9, Tallinn 2.2, Võru 2.4, Tartu 2.7, Tiirikoja 2.7 K. Similar upward shift of even higher magnitude was found for monthly mean temperature in February while some stations in the southern Estonia had a downward shift since 2005. Stations in the continental part of Estonia had a downward shift of monthly mean temperature in January by 2.3–2.7 K since 1966 following the 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 revealed since 1966 in the eastern half of the country and by 1.9–2.3 K since 1989 in the coastal region. In April, the shift to the higher temperature by 1.5–2.1 K occurred in 1989 in the southern regions and the western coast while in the northern Estonia it happened since 1999 by 1.7–1.9 K. 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 in the island stations Vilsandi and Kihnu), in August the shift was since 2002 (since 1996 in Vilsandi and Kihnu) by 1.3–1.7 K and in September since 2004 by 1.5–1.7 K. Mean temperature in spring has 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, correlation between winter mean temperature in Tartu and Ristna with the AO index in winter was 0.710 and 0.755, and with NAOPC 0.765 and 0.800, correspondingly~~ (Figure 4)~~. Higher correlation revealed clearly in the coastal zone.

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

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), 3.3 in Võru and 3.0 days per decade in Vilsandi. The change was statistically significant on $p<0.05$ level only in the two first 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~~3). An exception was detected in Vilsandi that 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.

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 correlation coefficients between snow cover duration and indices describing the intensity of westerly circulation (AO, NAO indices) in winter. Their values are between -0.5 and -0.7.

~~**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 linear trend (dashed line).~~

3.4 Precipitation

Precipitation has even higher spatial and temporal variability than snow cover duration. Generally, 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~~4, Figure ~~6~~4). Winter season has received significantly more precipitation with the exception in Vilsandi. The majority of stations have experienced also a significant increase in annual precipitation by 15–30 mm per decade. Mostly no changes have been 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) could be found in winter and a negative correlation of the same magnitude appears in May, June and August.

Figure ~~6~~4: Time series of winter precipitation (DJF) in Türi during 1951–2015 (blue line), its regime shift since 1989 (wide black line) and linear trend (dashed line).

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~~4). There have been detected several significant shifts up and down, which express, first of all, multi-annual fluctuations of precipitation and not so much abrupt climatic changes. Upward shifts by more than even 100 mm for annual precipitation were detected in many stations during 1977–1986. They reflect the start of the period of higher precipitation since 1977. Similar shifts for winter precipitation were observed later, starting with 1980/1981 and 1981/1982 in three stations, and ending with 1988/1989 and 1989/1990 in four of 12 stations, for example at Türi (Figure ~~6~~4). Positive regime shifts for monthly precipitation revealed in all stations in the 1980s during the cold season from November to March. In many cases they followed by return shifts in 2003 (February) and 1996 (March). Downward shifts in September precipitation were detected in many stations mostly since 1998. Significant shifts since 1966 in spring (7 stations) and autumn precipitation (2 stations) can be explained by the added wetting correction 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 in five stations (Table ~~4~~5). At the same time, increasing trends revealed at all stations (except Vasknarva that is naturally regulated by Lake Peipsi) in winter season and in three first months of a year (Table ~~5~~6). 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 are obtained from the eastern Estonia ~~(Figure 7)~~ and higher values from the western Estonia. The time series of winter runoff in Emajõgi river measured in Tartu (Figure 5) describes most generally the interannual variations because its catchment area takes 17 per cent of the total territory of Estonia. The highest increase was detected in 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. Vasknarva station is an exception due to its location in the outflow from the Lake Peipsi to Narva River that has a runoff regime very different from other rivers. It has a large area of river basin buffered by the large lake. where 66% of it lies outside of the territory of Estonia. A significant increasing trend revealed there only in February and March.

During the other months few significant trends were detected. In southern Estonia (Õhne, Väike-Emajõgi and Piigaste rivers) runoff has increased also in June and in Võhandu river (Räpina station) in July. They are related to the increase of precipitation in June. Mostly negative changes are typical for spring. In April, which is the most common month for spring flood to occur, the specific runoff has decreased by up to 1 l/s per km^2 per decade but this trend was statistically significant only in Õhne and Kasari rivers. The decrease in May was significant in central and northern Estonia, in 8 stations of 21. It is related to the shift of the spring runoff maximum caused by snow melt to the earlier time, i.e. to March. Annual mean specific runoff has significantly increased in some rivers of southern Estonia (in rivers Emajõgi, Väike-Emajõgi, Õhne and Halliste) by 0.2–0.3 l/s per km^2 per decade, and in Uue-Lõve river in West-Estonian archipelago by 0.47 l/s per km^2 per decade.

Relationship between climatic variables and runoff in Estonia is well exposed particularly in winter. Higher temperature, precipitation and lower snow cover duration in winter are related to higher winter runoff. 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, correlation between snow cover duration and specific runoff in April is strongly positive (r = 0.5–0.6).

Table 45: Trend values, years of regime shifts and corresponding shift values of annual mean specific runoff.

Table 56: 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.

Figure 5: Time series of specific runoff (l/s per km2) in winter at Tartu station on Emajõgi River during 1951–2015, its regime shift since 1987/1988 (wide line) and linear trend (dashed line).

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Figure 6: Regime shifts in winter (DJF) specific runoff of rivers in 14 stations where a statistically significant shift was detected in 1987/1988 and 1988/1989.

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

Time series of annual mean runoff describe long-term alternation of wet and dry periods in Estonia (Table 5). 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.

Regime shifts in winter temperature in Estonia have caused shifts in specific runoff of rivers (Table ~~5~~6). Warmer winters are naturally related to higher runoff in winter and earlier maximum in spring after the snow melt that is typical for Estonia. Usually it has been observed in April but during the last decades it has shifted to March. As a consequence, runoff in March has a positive shift and that causes the negative shift in April. In 14 from 21 stations upward regime shifts in runoff appeared since the winters 1988/1989 or 1987/1988 (Figure 6~~5~~). The same shift was present also in January, February and March. ~~while the increase of runoff in March recorded at all stations has been more than two times.~~ The consistent upward regime shifts in specific runoff appeared in 19 from 21 stations since March 1989, which has been the most prominent change despite the high variability in hydrological and hydrogeological conditions in watersheds analysed in this study. ~~This has been the most significant change at all during the study period.~~ The increase of 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~~7). During the other months there were practically no significant regime shifts in specific runoff.

Figure ~~8~~7: Time series of specific runoff (l/s per km2) in March (blue) and April (red) at Riisa station on Halliste River during 1951–2015 and their regime shifts of opposite sign since 1989 and 2009 (wide lines).

~~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. Such kind of local-scale integrated analysis of trends and regime shifts in time series of many inter-related and indicative variables of the climate system starting is innovative enabling to detect general regularities of a long-term environmental change. We suppose that our findings are relevant for 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 of the study region. The Atlantic Ocean is virtually 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 weather is formed under the influence of a cold and dry continental air mass.

The 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 in winter. Snow cover duration is directly dependent on temperature while precipitation has more indirect relationships. Higher temperature in winter is caused by 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 abruptly occurred since the winter 1988/1989.

Changes in large-scale atmospheric circulation, trends as well as regime shifts, naturally have caused changes in other parameters. For example, the intensification of westerly circulation in winter during 1951–2015 has induced a significant increase of winter and spring temperature, 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. The shift year 1989 was found 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; Soomere et al., 2015).

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 comparison with the previous analysis (Jaagus, 2006) the warming trend has intensified during the last 15 years annually as well as monthly and seasonally. The only exception is spring. The trend in March and spring mean temperature in Estonia during 1951–2015 is much lower than in 1951–2000. At the same time, mean temperature in summer and autumn had no trend in 1951–2000 (Jaagus, 2006) but a statistically significant trend appeared when we used updated time series (Table 4).

In the majority of cases with significant trends, there was also detected a regime shift. It allows to assume that the climate change is not a monotone process but consists of abrupt changesregime 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 continent 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 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. The trend in snow cover duration in Estonia has not changed in comparison with the results of the previous study (Jaagus, 2006). Snow cover duration has continued to decrease using the updated time series.

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 case of winter months. It is natural because higher winter temperature in Estonia is related to cyclonic weather conditions that are also illustrated with higher cloudiness, wind speed and precipitation. The results of the trend analysis are in line with the previous study. Only exception is November when precipitation has significantly increased during the longer period (Table 4). Regime shifts in precipitation are not ~~similar~~ coherent in the 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 1980s is characterised by an upward shift in annual precipitation detected in many stations. Similar regime shifts were found also for the three Baltic countries (Jaagus et al., 2016).

~~The response of river runoff to changes in climate parameters is more complicated.~~ Annual mean runoff has not revealed any strong trends or shifts in spite of 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. As the most important change in the hydrological regime of rivers, ~~Due to the milder winter and earlier snowmelt~~ the maximum spring runoff has moved from May and April to March due to milder winter and earlier snowmelt. It could be considered as a logical consequence of climate warming that is projected for the end of this century (Jaagus et al., 1998; Jaagus and Mändla, 2014).

Despite the comparatively small territory, ~~T~~there ~~a~~were found quite obvious spatial differences in regime shifts in Estonia. The Vasknarva station on Narva River reflects runoff fluctuations on much wider area than the territory of Estonia buffered by Lake Peipsi. Therefore, they are not well comparable with shifts in other stations. There were detected much less statistically significant regime shifts in specific runoff in the northern Estonia (Jägala, Valgejõgi, Kunda and Purtse rivers) than in the other parts of Estonia. Upward shifts revealed there 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 Vihterpalu, Leivajõgi and Keila Rivers in north-western Estonia where shifts were detected also in January, February and winter as a whole. Rivers in western Estonia (Kasari, Pärnu, Lõve) have the strongest regime shifts. 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 revealed also in annual runoff. Two other groups of rivers were distinguished in central Estonia (Pedja, Põltsamaa, Navesti) and southern Estonia (Võhandu, Piigaste, Väike-Emajõgi, Õhne, Halliste). Both groups can be characterised by positive regime shifts in January and March and negative shift in April since the end of the 1980s, but in southern Estonia there are shifts also in February and June.

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 the AO and NAO indices, which has brought bigger amount of warm air from the North Atlantic to the Baltic Sea region. As a consequence, winter air temperature has increased significantly and the duration of snow cover has 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 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 shift years since 1977 at some stations and winter precipitation since the end of 1980s.

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

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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 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. Years of statistically significant upward (+) and downward (-) shifts in time series of the circulation indices from different months and seasons..

	AO		NAOL		NAOG		NAOPC		NAOT		EA	
	+	-	+	-	+	-	+	-	+	-	+	-
Jan			1983						1983	1963	1970	
Feb	1989		1989	2004			1989	2004	1988	2004		
Mar							1989		1982			
Apr					1990	1971					1983	
May	1961											
Jun		2009				2007		2007	1964	2007		
Jul				1962						2008	1998	
Aug	1991	2002									2009	
Sep	2003				2003	1993						
Oct				1965							1980	
Nov												
Dec											1977	
Year	1989						1989				1977	
Spring							1989		1986	2007	2001	
Summer		2009				2007		2007		2007	1998	
Autumn				1965								1988
Winter	1989				1989		1989		1988		1987	

Table ~~3~~4: 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 was detected only in January since 1966 by -2.5 K.

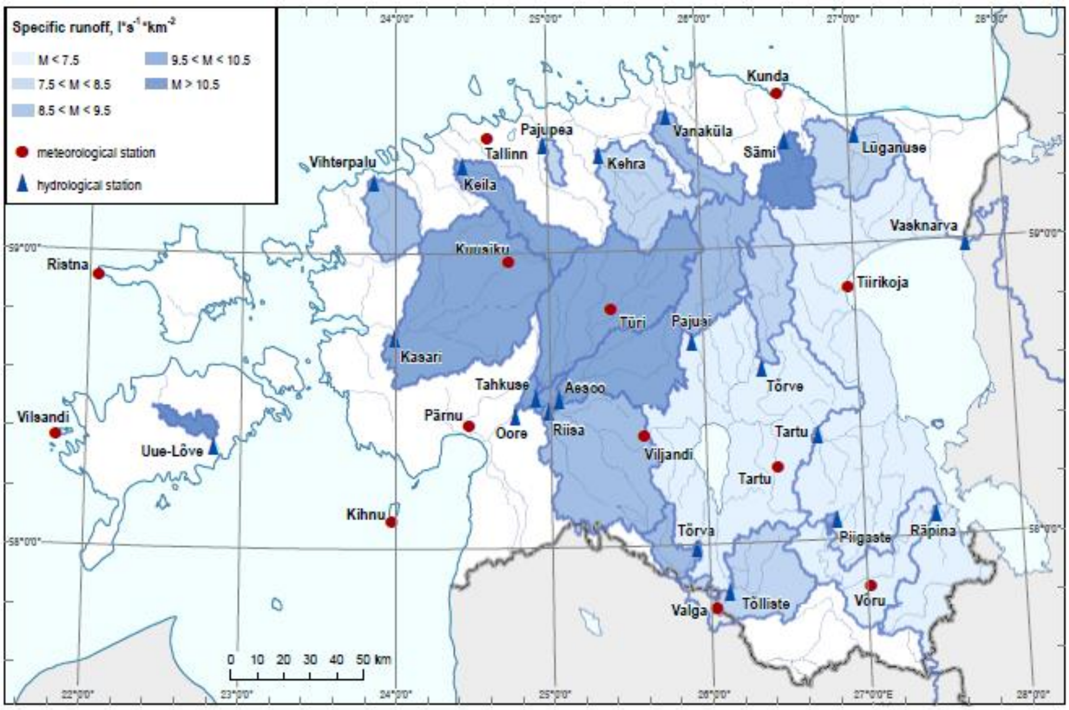
	Temperature			Precipitation				
	Trend (K per decade)	Upward shift year	Shift value (K)	Trend (mm per decade)	Upward shift year	Shift value (mm)	Downward shift year	Shift value (mm)
Jan	0.37	1988	4.0	**2.0**				
Feb	0.54	1989	2.3	1.0	1995	24.0	2003	-21.7
Mar	**0.62**	1966	3.4	**1.3**	1988	23.4	1996	-18.6
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~~5: 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		

Table ~~5~~6: 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			


Specific runoff, l*s-1*km-2
M < 7.5
7.5 < M < 8.5
8.5 < M < 9.5
9.5 < M < 10.5
M > 10.5
meteorological station
hydrological station
Kunda
Pajupea
Vanaküla
Tallinn
Sämi
Lüganuse
Kehra
Vihterpalu
Keila
Vasknarva
Kuusiku
Ristna
Tiirikoja
Türi
Pajusi
Kasari
Tõrve
Tahkuse
Aesoo
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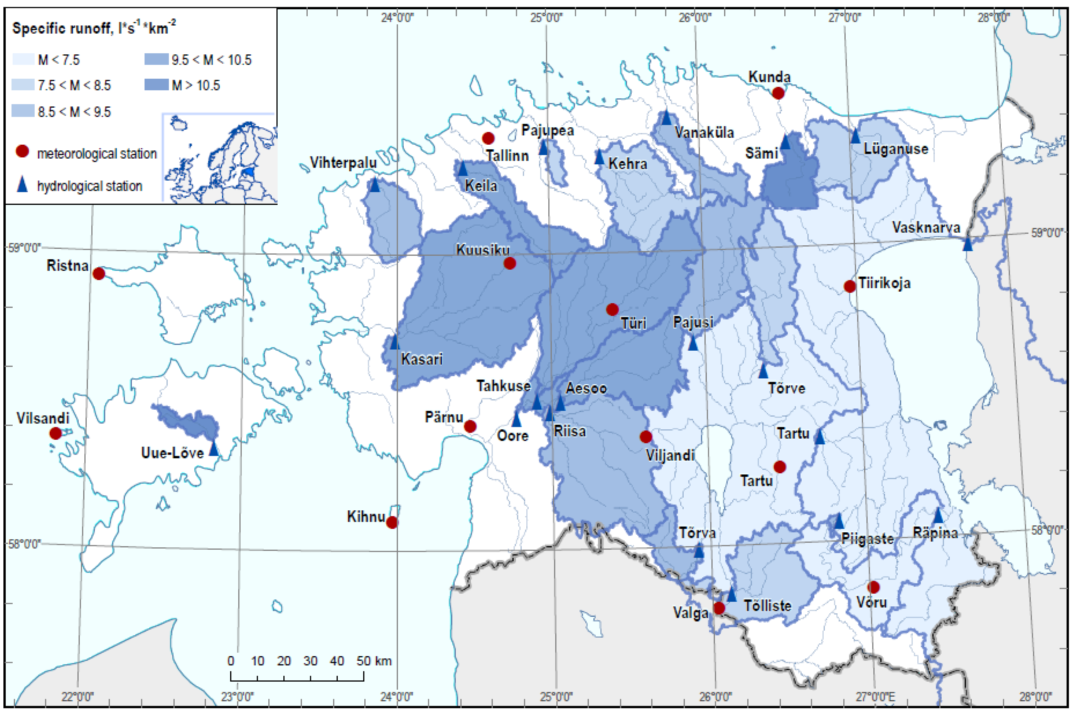
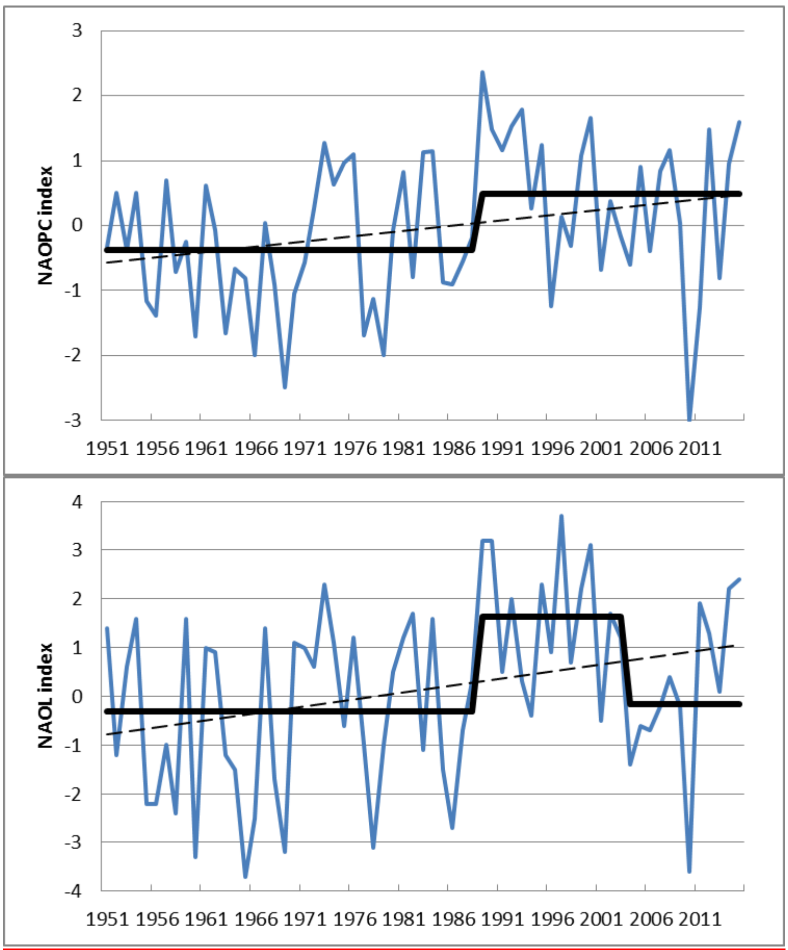


Figure 1: Location map of Estonia with meteorological and hydrological stations, and annual mean specific runoff of studied river basins.


NAOPC index
3
2
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0
-1
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1951 1956 1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011
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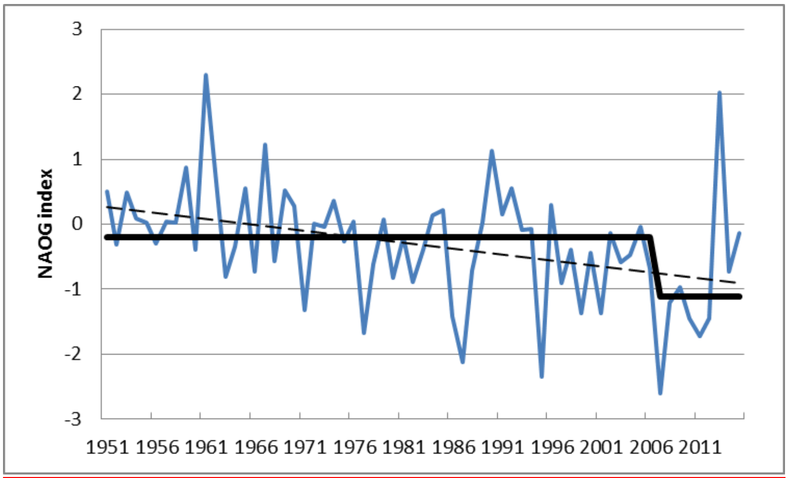
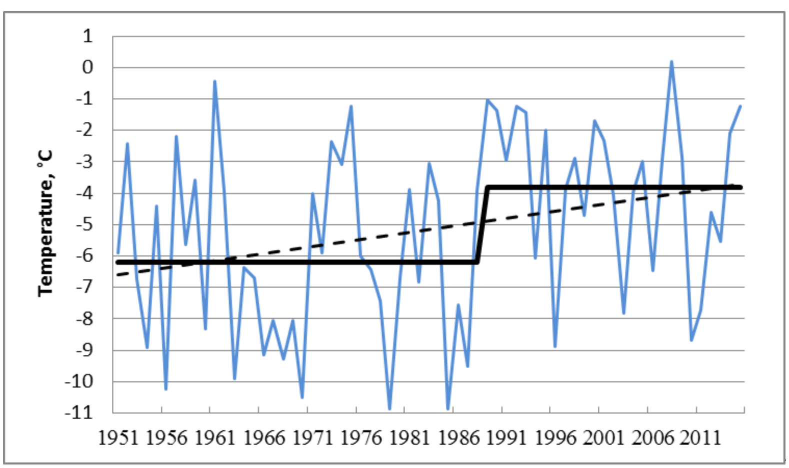


Figure 2: Time series of NAO~~PC~~ ind~~ex~~ices ~~in winter (DJF)~~ during 1951–2015, ~~its~~their regime shift~~s~~ ~~since 1989~~ (wide lines) and linear trends (dashed lines): a) NAOPC in winter; b) NAOL in February and c) NAOG in summer..



~~**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 linear trend (dashed line).~~

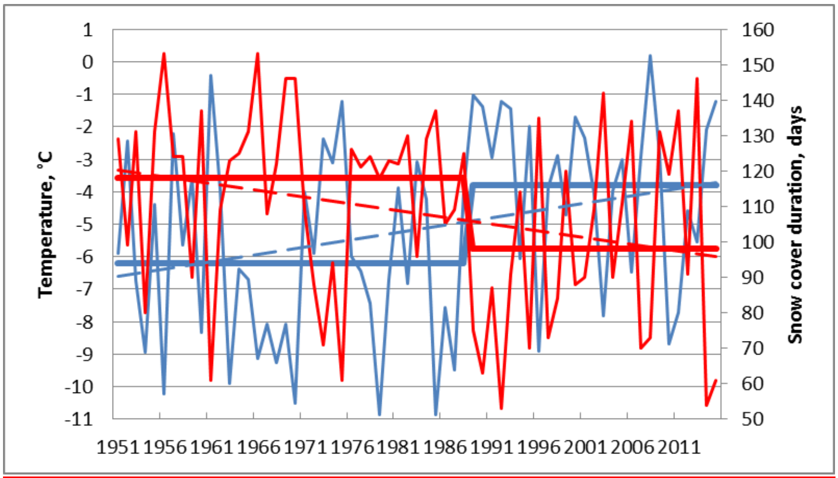


Figure 3: Time series of winter (DJF) mean air temperature (blue) and snow cover duration (red), their regime shifts since the winter 1988/1989 (wide lines) and linear trends (dashed lines).

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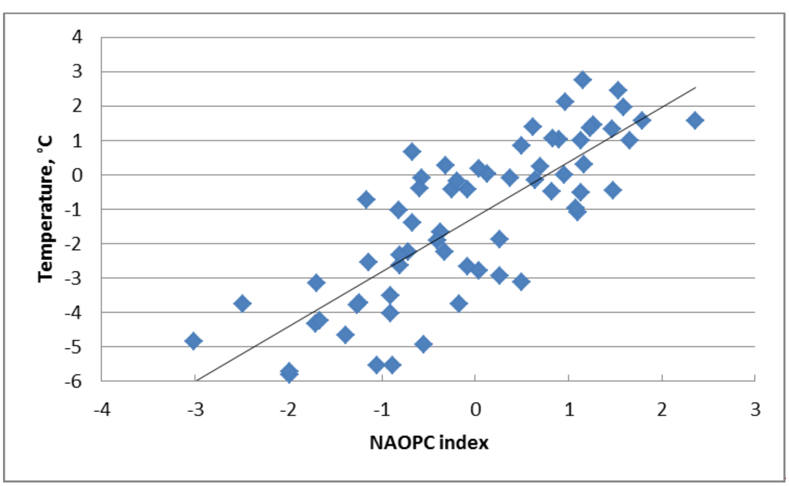
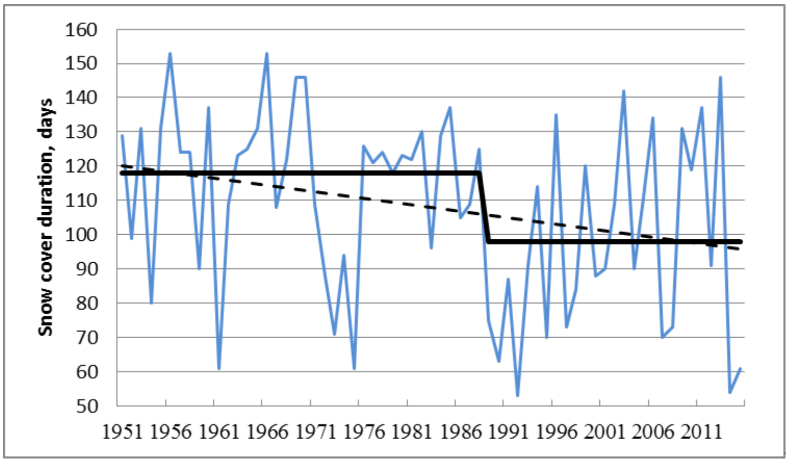


~~**Figure 4:** Scatter plot of winter mean NAOPC index and winter mean temperature in Ristna (r = 0.800).~~



~~**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 linear trend (dashed line).~~

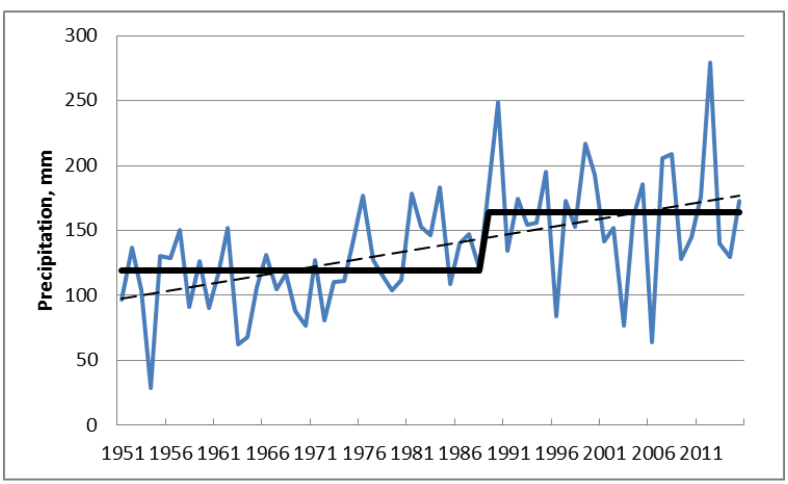


Figure ~~6~~4: Time series of winter precipitation (DJF) in Türi during 1951–2015 (blue line), its regime shift since 1989 (wide black line) and linear trend (dashed line).

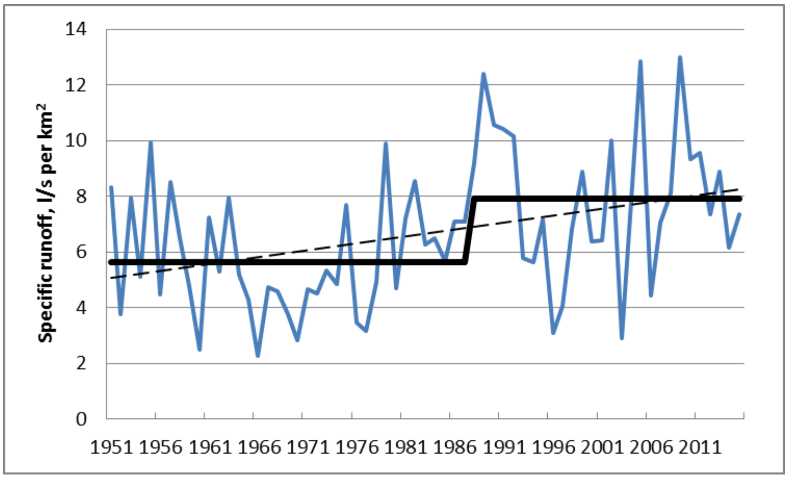


Figure ~~7~~5: Time series of specific runoff (l/s per km2) in winter at Tartu station on Emajõgi River during 1951–2015, its regime shift since 1987/1988 (wide line) and linear trend (dashed line).

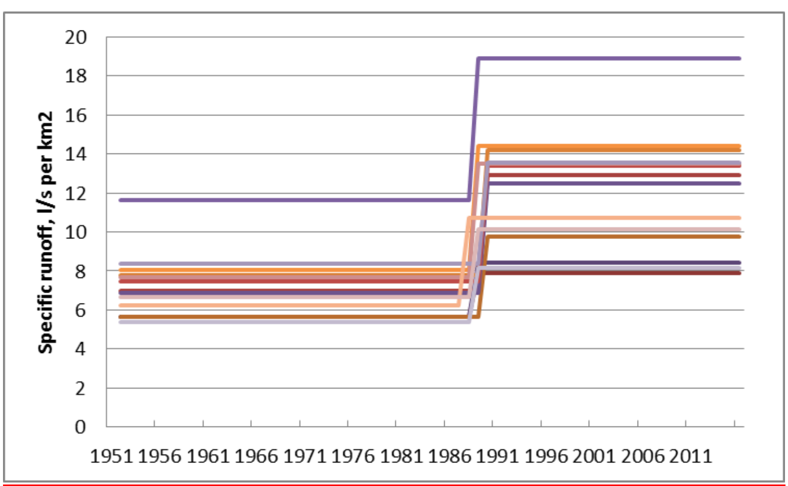


Figure 6: Regime shifts in winter (DJF) specific runoff of rivers in 14 stations where a statistically significant shift was detected in 1987/1988 and 1988/1989.

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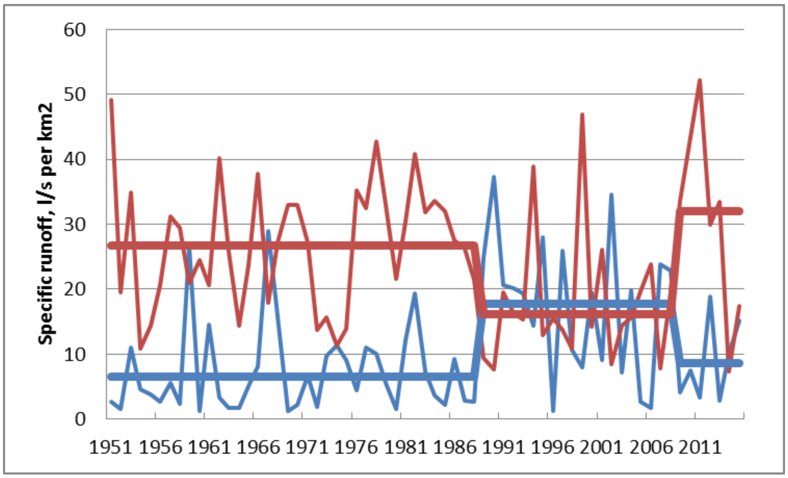

Figure 87: Time series of specific runoff (l/s per km^2) in March (blue) and April (red) at Riisa station on Halliste River during 1951–2015 and their regime shifts of opposite sign since 1989 and 2009 (wide lines).