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Published in:
JOURNAL OF HYDROMETEOROLOGY

DOI:
10.1175/JHM-D-16-0278.1

Published: 01/06/2017

Please cite the original version:
Spatiotemporal Hydroclimate Variability in Finland: Past Trends

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(Manuscript received 1 December 2016, in final form 7 April 2017)

ABSTRACT

Over the past decades, Finland has experienced changes in its climate: temperature and precipitation have increased, resulting in varying runoff patterns. These trends are well studied, but the changes in interannual variability are less known, despite their importance for understanding climate change. This research aims to assess spatiotemporal changes in variability of temperature, precipitation, and runoff for 1962–2014 at the subbasin scale in Finland. Temporal changes in variability were analyzed by constructing moving-window median absolute deviation time series at annual and seasonal scales. Subbasins with similar patterns of temporal variability were identified using principal component analysis and agglomerative hierarchical clustering. Presence of monotonic trends in variability was tested. Distinct areas with similar patterns of statistically significant changes in variability were found. Decreases in annual, winter, and summer temperature variability were discovered across Finland, in southern Finland, and in northern Finland, respectively. Precipitation variability increased in autumn in northern Finland. It also decreased in winter and spring in northern and central parts of Finland. Runoff variability increased in winter in most parts of Finland and in summer in the central parts, but decreased in spring in southern Finland. Comparison with existing studies illustrates that trends in mean climate and its variability do not necessarily match, highlighting the importance of addressing both aspects. The findings of this study provide new information on hydroclimatic variability in Nordic conditions and improve the possibility to adapt and predict the changes in hydroclimatic conditions, including weather extremes.

1. Introduction

Climate change and global warming are unequivocal. According to the Intergovernmental Panel on Climate Change (IPCC), global average temperature has increased 0.85°C (from 0.65°C to 1.06°C) during the period 1880–2012 (IPCC 2015), and during the second half of the period, temperature has increased even more rapidly. Warming is greater at higher northern latitudes, where the study area of this paper is located. Global warming is highly linked to components of the hydrological cycle, for example, precipitation patterns (amount, frequency, and intensity). Warming temperatures as well as changing precipitation causes shifts in runoff regime, and changes in hydroclimate have been projected to continue in the future (IPCC 2015).

Climate change usually refers to changes in climate over time, caused by natural fluctuations or anthropogenic forces, that is, human activities (IPCC 2015). In other words, climate change is a significant change in the average weather conditions for a region over a longer period of time. Measures such as mean state, natural variability, and extreme events can be included when climate is studied. The focus of this study is on climate-induced changes in hydroclimatic variability, rather than trends in hydroclimatic mean conditions. Climate variability refers to variations around the mean state of the climate or other climate statistics, that is, standard deviations or the occurrence of extremes, on different temporal and spatial scales (IPCC 2015). Variability in
hydroclimate can be caused by natural internal processes of the climate system (internal variability) or from variations in natural or anthropogenic external forces (external variability).

The understanding of hydroclimatic variability is important, including for Finland, the specific area of interest in this study. Changes in hydroclimatic variability have impacts on the intensity and frequency of extreme events, for which society and nature can be particularly vulnerable (Thornton et al. 2014). For example, an increase in hydroclimatic variability implies an increase in extremes relative to mean hydroclimate. Different sectors of society and nature are affected differently by possible changes in hydroclimatic variability, both positively and negatively. Some examples of these affected sectors are agriculture and livestock, and consequently also economy and food production; forestry, which is economically important for Finland; natural ecosystems; the tourism industry; and the water sector, for example, water availability, water supply, and hydropower (Maracchi et al. 2005; Marttila et al. 2005; Saarinen and Tervo 2006; Lehtonen and Kujala 2007; Kellomäki et al. 2008; Tervo 2008; Peltonen-Sainio et al. 2009).

In this study, the study area includes the whole of Finland and transboundary watersheds in Norway, Sweden, and Russia. Finland is located at high latitudes in northern Europe, on the edge of the Eurasian continent. Geographical position is the main factor influencing climate within Finland. Latitudinal gradient (55°–70°N), the Atlantic Ocean, the combined continental landmass of Eurasia, the Scandinavian Mountain range, and the Baltic Sea all have their own impacts on climate in Finland (Käyhkö 2004). The climate in Finland is described to be intermediate with characteristics of a maritime (Atlantic Ocean) and a continental (Eurasia) climate.

There are notable differences in hydroclimatic conditions between the seasons. For example, during the winter, the temperature is considerably lower than during the summer and precipitation falls in the form of snow stored in the snowpack, while during the summer, precipitation falls in liquid form with a higher evaporation rate. Snow accumulation and melting are important parts of hydroclimate in Finland and at high latitudes in the Northern Hemisphere (Kuusisto 1984; Irannezhad et al. 2015, 2016). Amount, timing, and duration of snowpack have a significant role in storing water during winter and melting at spring, causing peak river discharge. Furthermore, snow conditions in Finland and high latitudes are projected to change due to climate change (Barnett et al. 2005; Adam et al. 2009). Warming temperature causes less precipitation falling as snow during winter as well as snowmelt occurring earlier in spring.

The existing research of observed changes in hydroclimate has mainly focused on assessing the trends in mean values, showing increasing average temperature and total precipitation at country scale in Finland. Mean annual temperature in Finland has increased by 0.4° ± 0.2°C decade−1 during the period 1961–2011 (Irannezhad et al. 2014a). Other studies also show positive trends in annual mean temperature: 0.14°C decade−1 during the period 1847–2013 (Mikkonen et al. 2015) and 0.7°C century−1 during 1901–2000 (Jylhä et al. 2004). The warming trend after the 1960s has become steeper, between 0.2° and 0.4°C decade−1 (Irannezhad et al. 2014a; Mikkonen et al. 2015). At a seasonal scale, statistically significant positive trends in mean temperature for spring have been found, 0.4° ± 0.2°C decade−1 in 1961–2011 (Irannezhad et al. 2014a) and 1.4°C century−1 in 1901–2000 (Jylhä et al. 2004). Furthermore, both Irannezhad et al. (2014a) and Jylhä et al. (2004) found a statistically significant positive trend in mean temperature for summer (0.3° ± 0.2°C decade−1 and 0.7°C century−1).

In terms of precipitation, a study by Irannezhad et al. (2014b) shows that annual mean precipitation in Finland has increased significantly by 0.92 ± 0.50 mm yr−1 during the period 1911–2011. Moreover, significant increases in mean precipitation were found for winter (0.46 ± 0.19 mm yr−1) and summer (0.32 ± 0.29 mm yr−1). In contrast, Jylhä et al. (2004) did not find any statistically significant trends in precipitation over the period 1901–2000, and neither did Tuomenvirta and Heino (1996) over the period 1910–95.

Trends in runoff are less studied in Finland, but changes in discharge have been studied to some extent and these tend to be quite similar. Previous studies have found positive trends in annual discharge for most of the area of Finland. A study by Hyvärinen (2003) presents an average increase of 0.5 mm yr−1, and in southwestern parts up to 1 mm yr−1, during the twentieth century. A study of the Nordic countries by Wilson et al. (2010) has found positive trends in western parts of Finland during the periods of 1941–2005 and 1961–2000. Clear positive trends have also been found for winter discharge in many regions (Hyvärinen 2003; Korhonen 2007; Korhonen and Kuusisto 2010; Wilson et al. 2010).

While the trends in hydroclimatic conditions in Finland are well studied, much less emphasis is put on understanding climate variability and related aspects. Some regional- and global-scale studies do exist that are relevant to understanding changes in variability in Finland. Schär et al. (2004) and Fischer and Schär (2009) study future variability of summer temperature in Europe compared against past observations. Giorgi et al. (2004b) study future changes in winter and summer
variability of temperature as well as precipitation in Europe (excluding Scandinavia and Baltic states), using a model validated against past observations (Giorgi et al. 2004a). Räisänen (2002) and Giorgi and Bi (2005) study the same variables at the global scale.

Giorgi and Bi (2005) project decreases in winter variability of temperature and precipitation in northern Europe and increases in summer variability on average across an ensemble of general circulation models during the twenty-first century. Change of standard deviation for winter temperature is projected to be $-2.88\,^\circ\text{C}\,\text{decade}^{-1}$, and for summer, $+1.79\,^\circ\text{C}\,\text{decade}^{-1}$. In the case of precipitation, change in coefficient of variation for winter is $-0.08\,\%\,\text{decade}^{-1}$ and for summer is $+3.00\,\%\,\text{decade}^{-1}$. These projected trends in variability are, however, uncertain, with notable differences between circulation models. Intermodel standard deviation of temperature variability for winter is $3.29\,^\circ\text{C}\,\text{decade}^{-1}$ and for summer is $3.74\,^\circ\text{C}\,\text{decade}^{-1}$. For precipitation variability, intermodel standard deviation for winter is $2.75\,\%\,\text{decade}^{-1}$ and for summer is $4.35\,\%\,\text{decade}^{-1}$. These results are in line with the findings of Räisänen (2002) and Fischer and Schär (2009). Both studies were carried out at continental scale (lower resolution) and with an emphasis on the future. Taking into account that there are notable differences in regional climate conditions, and that these studies do not provide adequate observational evidence of changes, there is a need for a consistent, higher-resolution historical analysis of these past trends in hydroclimatic variability within Finland, among other regions.

There are several studies focusing on other aspects related to climate variability, for example, past and future temperature and/or precipitation extremes at the global scale (Tebaldi et al. 2006), in Europe (Frei et al. 2006), and in Nordic countries (Tuomenvirta et al. 1998, 2000); droughts and floods in Nordic countries (Hisdal et al. 2006; Veijalainen et al. 2010; Wilson et al. 2010); role of teleconnections, for example, the North Atlantic Oscillation (Marshall et al. 2001; Wanner et al. 2001; Hurrell et al. 2003; Uvo 2003; Grossmann and Klotzbach 2009; Hurrell and Deser 2010); and millennial-scale climate change and variation in the Northern Hemisphere and Europe (Crowley 2000; Delworth and Mann 2000; Luterbacher et al. 2004; Moberg et al. 2005). These aspects are highly linked to climate variability, though they are more specific and still benefit from a more general understanding of variability itself. Therefore, they are not the focus of this particular study.

As stated, no studies report on past changes in hydroclimate variability in Finland or in Nordic countries. Therefore, the aim of this study is to assess the past spatial and temporal changes in interannual hydroclimatic variability in Finland, in terms of both annual average and seasonal patterns. Spatial and temporal changes in variability of temperature, precipitation, and runoff were analyzed using a subbasin-scale dataset over the years of 1962–2014. Runoff was selected rather than discharge as it focuses on local subcatchment processes, excluding inflows, and therefore emphasizes local spatial variation rather than spatial correlations. These hydroclimatic time series were studied using statistical analyses, moving-window median absolute deviation to quantify hydroclimatic variability; principal component analysis and agglomerative hierarchical clustering to discover areas with similar hydroclimatic variability (Mimmack et al. 2001); and a test for monotonic trends in variances (Noguchi and Gel 2010), to identify the directions of changes and whether changes in hydroclimatic variability are statistically significant.

2. Data and methodology

Analyses in the present study used annual and monthly subbasin-scale data of mean temperature, total precipitation, and total runoff for the period of 1962–2014, provided by the Finnish Environmental Institute [Suomen ympäristökeskus (SYKE)]. The areal temperature and precipitation data were interpolated and corrected based on observed daily temperatures as well as precipitations, and then runoff data were simulated using SYKE’s Watershed Simulation and Forecasting System (WSFS).

To begin with, time series for the whole study area were analyzed, namely, averaged annual and seasonal mean temperature, total precipitation, and total runoff. The Mann–Kendall trend test was used to detect trends in mean. This was carried out to understand and show the context of changes in hydroclimatic variability with climate change in Finland.

Temporal changes in hydroclimatic variability were then studied by constructing moving-window median absolute deviation (MAD) time series of mean temperature, total precipitation, and total runoff. These were calculated both for the whole study area and for each subbasin separately. Spatial patterns in changing hydroclimatic variability were studied using principal component analysis and agglomerative hierarchical clustering of the subbasin MAD time series. By doing so, areas with similar changes in temporal hydroclimatic variability were identified and grouped together. Finally, areas with statistically significant changes in variability and direction of trend were determined using the test for monotonic trend variances.
More detailed descriptions of the data and each analysis follow below.

**a. Data**

The source data used in the present study consisted of annual and monthly values of mean temperature, total precipitation, and total runoff for 6172 subbasins in Finland, including transboundary watersheds in Norway, Sweden, and Russia (Finland’s Environmental Administration 2015). Subbasins were defined on a grid with a resolution of about 1 km. The data covered the time period from January 1962 to December 2014. The subbasin-scale areal temperature and precipitation data were calculated using temperature and precipitation observations from the Finnish Meteorological Institute from approximately 190 and 250 observation stations, respectively, in 2010, though the number of stations and precipitation gauge type varied in time (Veijalainen 2012). In addition to that, observations for transboundary watersheds from 11 temperature and 16 precipitation observation stations were provided by Norwegian Meteorological Institute, Swedish Meteorological and Hydrological Institute, and Hydrometeorological Center of Russia.

To obtain a stable precipitation observation network during the whole time period, missing observation values were calculated from the three closest observation stations. The method was not used for the temperature data because the temperature observation network was considered to be dense enough to cover the spatial variation for the whole time period. The precipitation observations were corrected with elevation and aerodynamic corrections (Taskinen and Söderholm 2016). The aerodynamic corrections using temperatures and wind observations were made separately for different gauge types (Wild, Tretjakov, H&H-90, and automatic precipitation gauge types), which were in use in different decades.

The subbasin-scale areal meteorological values were then calculated from the three closest observation stations by inverse distance weighting, taking into account elevation differences. The subbasin-scale temperature and precipitation data were then used as an input in the HBV-type conceptual hydrological model WSFS, to calculate the runoff data (Vehviläinen et al. 2005; Veijalainen 2012; Olsson et al. 2015). The study area size is 390,000 km$^2$ in total, and the sizes of subbasins varied mostly between 1 and 6197 km$^2$, with a median of 42 km$^2$. The WSFS has been calibrated with observations of discharges, water levels, and snow water equivalents over the period of 1981–2013. For more detailed descriptions of the source data, see Vehviläinen et al. (2005) and Veijalainen (2012).

Seasonal values were calculated from these source data. Seasons were formed by 3-month periods: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). The data used in the present study thus contained time series of annual and seasonal subbasin-scale mean temperature, total precipitation, and total runoff for the time period from January 1962 to December 2014.

**b. Detecting hydroclimatic trends**

The Mann–Kendall trend test (Mann 1945; Kendall 1975) was used to detect possible trends at study area scale for annual and seasonal mean temperature, total precipitation, and total runoff time series. The Mann–Kendall trend test is a nonparametric test, which is commonly used to detect monotonic trends in climate and hydrological datasets. The test detects if a trend exists in the time series, whether the trend is positive or negative, and whether this trend is statistically significant. A bootstrap version (Santander Meteorology Group 2012) of the Mann–Kendall trend test was used to take into account the possible autocorrelation of the data. A 95% significance level was used for detecting trends.

**c. Quantifying hydroclimatic variability**

MAD was used to examine the variability of hydroclimatic variables, that is, how hydroclimate deviates from the median. Moving-window MAD time series were used to discover temporal changes in variability in hydroclimatic variables. Data are not symmetric but skewed, so instead of the mean, the median was used to measure central tendency of the data. The median is less sensitive to individual extreme values or outliers. MAD was calculated as the median of the absolute deviations from the median. Moving-window MAD time series involved calculating MAD on smaller data subsets (series of data with a chosen width of a window). The window was moved forward one step at a time from the first year until the last year of the time period. Each step had a length of one year, and after each step, the MAD for a particular window was calculated. The width of the window had to be long enough to reduce noise from the data so that the constructed moving-window MAD time series exposed a clear signal and trends were visible. At the same time, the width of the window had to be short enough to catch interannual hydroclimate variability. Multiple widths of the window were tested, and widths
of 11 and 21 years were chosen to be used for the analysis, as they capture interannual variability at two different time scales. A wider window captures longer-term variability, and by increasing the averaging period (the width of the window) from 11 to 21 years, change in variability was considerably reduced.

The moving-window MAD time series were standardized by dividing each MAD value by the mean of the constructed moving-window MAD time series. This standardizing method was used instead of the usual method of subtracting the mean and dividing by the standard deviation, because that method can be inappropriate for zero-bound data (Mimmack et al. 2001), such as precipitation. Standardized time series capture relative rather than absolute changes in variability. Standardization was performed so that variables measured at different scales contribute equally to the subsequent analyses and are therefore comparable. Each variable for each time series has an equal mean value of one. The reported coefficient of MAD therefore measures variability in relative terms, defined as the ratio of each MAD value to the mean of the MAD time series. It is a dimensionless measurement, similar to the coefficient of variation, so variability of the source data with different units is comparable.

d. Identifying areas with similar hydroclimatic variability

Principal component analysis (PCA; Jolliffe 2002) and agglomerative hierarchical clustering (Gong and Richman 1995) were used to identify spatial patterns in changing variability of hydroclimatic variables in annual and seasonal scales, that is, to discover areas where temporal hydroclimate variability changes similarly. The analysis follows the method of Mimmack et al. (2001).

PCA was used to reduce dimensionality and amount of the data, while retaining most of the variability of the source data. PCA for standardized moving-window MAD time series of each subbasin were carried out in T mode (Richman 1986) by using singular value decomposition of the data matrix. In T mode, the time series is simplified using a data matrix formed so that it had time as columns and subbasins as rows. This identifies spatial patterns, rather than using S mode to simplify spatial variation and identify temporal patterns. The number of retained principal components was determined using the criterion of cumulative percentage of total variation. The cutoff level was chosen such that the retained principal components account for 90% of total variation, which was deemed to be sufficient for the purpose of identifying clusters of similar MAD time series.

In agglomerative hierarchical clustering, each data point was initially treated as an individual cluster. Then at each step of clustering, the two most similar clusters were combined as a new cluster, until finally there was only a single cluster, including all data points. Clustering was carried out based on Ward’s minimum variance method (Ward 1963), which minimizes the total within-cluster variance. At each step, a merged pair of clusters leads to minimum increase in variance of combined clusters (Murtagh and Legendre 2014).

The optimal number of clusters was determined using several different methods together: the R package called NbClust (Charad et al. 2014, 2015), cluster dendrograms (treelike hierarchical diagrams; Krumbein and Graybill 1965), and time series for each cluster. NbClust provides 30 indices, which use different methods to determine the optimal number of clusters in the data. The package has been developed to compare these indices and to suggest the best clustering scheme. In cluster dendrograms, distance between clusters (dissimilarity) was presented on a vertical axis and different data points (subbasins) were listed on the horizontal axis. Clusters were chosen such that the (visual) distance between clusters was maximized and the distance within clusters was minimized. In most of the cases, results from NbClust and dendrograms were similar, and the optimal number of clusters was chosen based on those. As a last step in choosing the number of clusters, time series for that certain number of clusters were produced and examined to make sure the chosen clustering scheme describes as clearly as possible the characteristics of changing variability in those areas. Selecting too few clusters proved to oversimplify phenomena by grouping areas that were still substantially different, and choosing too many clusters made it difficult to draw any insight from the cluster maps as well as perceive differences in time series.

e. Detecting direction and statistical significance of changes in hydroclimatic variability

The direction and statistical significance of changes in hydroclimatic variability for each subbasin were studied using the test for a monotonic trend in variances (Noguchi and Gel 2010; Gastwirth et al. 2015), which is based on the finite-intersection approach, the Brown–Forsythe transformation, and Kendall’s tau coefficient. The finite-intersection approach (Mudholkar et al. 1993, 1995) combines p values of the component test statistics, which correspond to a finite number of nested hypotheses. Fisher’s p value combination method (Fisher 1934) is used in this study. The idea of nested hypotheses, breaking down the original hypothesis into a number of more manageable components, was originally suggested by Hogg (1961). In this case, the test of each hypothesis involves determining the statistical significance of the difference between variability in nested subgroups. The
subgroups are defined by splitting the data into subsets of equal length, corresponding to a chosen window width. The first subgroup is compared to the second subgroup, and then these subgroups are combined and compared to the next subgroup, until finally all except the last subgroup is compared to the final one. The Brown–Forsythe transformation (Brown and Forsythe 1974), which is a robust modification of Levene’s transformation, was used in this study, meaning that variability is effectively measured using MAD rather than standard deviation. Roughly speaking, the presence and significance of a trend is given by correlation between the absolute deviations of the nested groups. If the correlation is positive, the MAD increases between the groups. The nonparametric, distribution-free Kendall’s tau coefficient (Kendall 1975) was used to allow identification of possible nonlinear trends. Because of the small number of data points, the bootstrap version of the test is used, as recommended by Lim and Loh (1996).

Two widths of the analysis window were used to study the statistical significance of changes in variability. Windows of 11 and 21 years were used so that they match with window widths used in construction of moving-window MAD time series; however, in this case, the windows are nonoverlapping. Tests were performed using a 95% significance level and one-sided tests, determined by the direction of the trend indicated by the Kendall correlation across all subgroups, consistent with the approach used by the trend test itself.

For the statistical test for a monotonic trend in variances, different nonoverlapping windows can be defined within the overall 53-yr time period, and the choice of window affects the result. How the time series is split into groups affects the variability of each group, and therefore the evaluation of homogeneity. To overcome this issue, repeated tests were used, with the nonoverlapping windows starting in different years. In each individual test, windows are nonoverlapping, though repeated tests overlap so that the whole time period is covered. The test was repeated until the ending point of the last window of the last test is set to the last year of the study period. With the 11-yr window, 10 repeated tests were done, and 12 repeated tests were done in the case of the 21-yr window. For example, the first test with four 11-yr windows is for the period 1962–2005, the next is for the period 1963–2006, and so on.

In addition to the direction of the trend, the results report both areas where all tests show statistical significance and areas where at least one of the tests shows statistical significance. The former indicates that the assessment of statistical significance is robust. The latter indicates that a statistically significant change in variability may exist, but that further investigation is needed regarding how the time series is divided.

3. Results

This section presents the results of the analysis with some interpretation. First, in section 3a, trends in hydroclimate at the study area scale are presented as a background for hydroclimatic variability, which is the focus of present study. Section 3b shows temporal changes in hydroclimatic variability for the study area as a whole. A more detailed view of changing variability is given in section 3c, where spatial patterns in changing variability are shown. All the results are provided in tab-delimited text files and as a georeferenced tagged image file format (TIFF) in the PANGAEA data repository (Lindgren et al. 2017).

a. Hydroclimatic trends in study area scale

Time series of annual and seasonal mean temperature, total precipitation, and total runoff are shown in Fig. 1. In the case of temperature, statistically significant positive trends were found using the Mann–Kendall test at the annual and seasonal scale for all seasons. Statistically significant positive trends were also found for annual, winter, and summer precipitation, as well as winter runoff.

b. Temporal changes in hydroclimatic variability in study area scale

Study area scale–averaged moving-window MAD time series show the temporal changes in variability of temperature, precipitation, and runoff (Fig. 2). The test for a monotonic trend in variances was used to study statistical significance of changes in hydroclimate variability.

The moving-window MAD time series of mean temperature (Figs. 2a,d) show decreases in annual and winter variability with both widths of window. In both cases, some analysis windows identify the trend as statistically significant. In the case of spring and summer, there is neither a clear increase nor a decrease in changing variability. For autumn variability, an increase is identified with a 21-yr window, but a decrease is identified with the shorter 11-yr window. These changes are not statistically significant. Given that the longer window reacts more slowly to changes in hydroclimate than the shorter window, a possible interpretation is that the trend in autumn variability is changing direction, from the long-term increase indicated by the 21-yr window to the emerging decrease indicated by the 11-yr window.

In terms of precipitation totals (Figs. 2b,e), both window widths show an increase in variability of annual total precipitation, but changes are not statistically significant. Variability in winter and spring precipitation is decreasing, and in the case of spring, most of the analysis windows
show statistically significant trends. In summer, variability is increasing but the trend is not statistically significant, and in autumn, there are no clear increases or decreases in total precipitation variability at the study area scale.

Moving-window MAD time series of runoff totals (Figs. 2c,f) show an increase in winter and summer variability, but the changes are not statistically significant. For annual, spring, and autumn, no long-term changes were found regarding variability of runoff totals at the study area scale.

c. Spatial patterns in changing variability and statistical significance of changes

PCA and agglomerative hierarchical clustering revealed spatial patterns in changing variability. Results are presented as maps showing areas (clusters of subbasins) where variability of each hydroclimatic variable is changing similarly. Furthermore, moving-window MAD time series of these areas with similar changes are presented to describe characteristics of the hydroclimatic variability. These maps and time series for mean temperature (Fig. 3), total precipitation (Fig. 4), and total runoff (Fig. 5) are presented in this section. Moreover, the test for a monotonic trend in variances identified statistical significance of changes in hydroclimate variability. Table 1 presents total areas and number of subbasins with statistically significant changes in variability. The areas are mapped in Fig. 6.

These results suggest a negative trend in variability for the whole study area for annual and winter mean
These changes in variability are statistically significant in many parts of the study area (Figs. 6a,b,f,g; Table 1). For summer mean temperature variability, a statistically significant decrease was found in northern Finland (Figs. 3g,h and 6d,i).

With regards to annual precipitation variability, statistically significant decreases were found in southern parts of Finland (Figs. 4a,b and 6k,p), even though at study area scale, variability was found to increase (Figs. 2b,e). Statistically significant decreases were also found in spring precipitation variability in the central part of the study area (Figs. 4e,f and 6m,r). In the case of autumn precipitation variability, a statistically significant increase in northern Finland and a decrease in southeastern Finland was found (Figs. 4i,j and 6o,t).

For runoff variability in many parts of the study area, a statistically significant increase was found in winter runoff (Figs. 5c,d and 6v,aa; Table 1) and a statistically significant decrease in spring runoff (Figs. 5e,f and 6w,ab; Table 1). Moreover, in summer variability, statistically significant increases were found in the central part of the study area (Figs. 5g,h and 6x,ac).

4. Discussion

Analyses in this study were carried out using a subbasin-scale annual and seasonal mean temperature,
FIG. 3. Changes in variability of annual and seasonal mean temperature in the study area over the period of 1962–2014. Maps and time series are showing (a),(b) annual; (c),(d) winter; (e),(f) spring; (g),(h) summer; and (i),(j) autumn variability for window widths of 11 and 21 years. Maps show areas with similarly changing variability using different colors. Accompanying time series show the time series of variability for the corresponding areas. In time series, the x axis shows the start and end years of analysis windows, and the y axis shows relative MAD values.
FIG. 4. As in Fig. 3, but for precipitation.
FIG. 5. As in Fig. 3, but for runoff totals.
total precipitation, and total runoff dataset in Finland for the period of 1962–2014. Results from the analysis give a very mixed picture, with trends and patterns of variability differentiated spatially and by season. However, some distinct areas were found where hydroclimatic variability follows similar patterns of change on annual and/or seasonal scale. This section discusses results of the study in relation to previous studies, as well as their general implications. In addition, limitations of the present study and how they were treated, as well as suggestions for future research directions, are discussed.

### a. Comparison to previous studies

In this study, subbasin-scale data were used instead of grid-scale data (Irannezhad et al. 2014a,b) or data from just few observation stations (Korhonen and Kuusisto 2010; Wilson et al. 2010), as done in previous studies. Results of this study are, however, well in line with previous studies, in terms of trends in mean hydroclimate during the time period of 1962–2014 (section 3a). Statistically significant positive trends were found for annual, winter, and summer precipitation totals, similar to the study by Irannezhad et al. (2014b). Also in the case of annual, spring, and summer mean temperature, statistically significant positive trends were found in the present study as well as previous studies by Jylhä et al. (2004), Irannezhad et al. (2014a), and Mikkonen et al. (2015). Furthermore, the current study found statistically significant positive trends in winter and autumn mean temperatures. Results about trends in runoff totals showed a statistically significant increase in winter, which is comparable to studies about discharge by Hyvärinen (2003), Korhonen and Kuusisto (2010), and Wilson et al. (2010).

Previous studies focus mainly on trends in the mean state of climate and not on changes in variability. Consistent with expectation (IPCC 2001), results of present and previous studies show that changes in mean state of climate do not necessarily mean parallel changes in climate variability. For example, whereas mean annual temperature is increasing according to presented results (Fig. 1) and previous studies (Jylhä et al. 2004; Irannezhad et al. 2014a; Mikkonen et al. 2015), this study shows interannual variability in mean temperature to be decreasing (Figs. 2a,d). On the other hand, results from the present study on changes in annual total precipitation variability (Figs. 2b,e) and previously studied mean precipitation sum trends (Irannezhad et al. 2014b) both show increases at study area scale. Furthermore, previous studies have found significant increases in winter and summer mean total precipitation; however, the variability does not show clear changes in the present study. These examples illustrate the importance of assessing variability as well as mean hydroclimate, as was the aim of this study.

There are similarities between the current study and those by Räisänen (2002) and Giorgi and Bi (2005) regarding continental-scale temperature and precipitation variability. This study found decreasing trends for winter temperature and precipitation variability in Finland, which agrees with the projections for northern Europe. For the summer, both articles project an increasing trend for both precipitation and temperature variability, while this study found increases in precipitation variability in some areas and decreases in temperature variability in northern Finland. Giorgi and Bi (2005) used an ensemble of general circulation models and reported an average value across models as a result. The

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<th>Runoff variability</th>
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<td></td>
<td>11-yr window</td>
<td>21-yr window</td>
</tr>
<tr>
<td>Annual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease</td>
<td>167.40 (2577)</td>
<td>232.17 (3646)</td>
</tr>
<tr>
<td>Increase</td>
<td>0.00 (0)</td>
<td>1.16 (25)</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease</td>
<td>85.17 (1269)</td>
<td>195.80 (2806)</td>
</tr>
<tr>
<td>Increase</td>
<td>0.00 (0)</td>
<td>0.00 (0)</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease</td>
<td>0.00 (0)</td>
<td>6.69 (176)</td>
</tr>
<tr>
<td>Increase</td>
<td>0.16 (3)</td>
<td>3.03 (63)</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease</td>
<td>97.50 (1446)</td>
<td>137.48 (2195)</td>
</tr>
<tr>
<td>Increase</td>
<td>0.00 (0)</td>
<td>8.13 (142)</td>
</tr>
<tr>
<td>Autumn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decrease</td>
<td>0.11 (2)</td>
<td>0.00 (0)</td>
</tr>
<tr>
<td>Increase</td>
<td>0.00 (0)</td>
<td>26.16 (495)</td>
</tr>
</tbody>
</table>
FIG. 6. Areas where changes in hydroclimatic variability are statistically significant ($p < 0.05$) over the period of 1962–2014: (a)–(j) mean temperature, (k)–(t) total precipitation, and (u)–(ad) total runoff variability in annual and seasonal scales. Maps (a)–(e), (k)–(o), and (u)–(y) show results from 10 repeated tests with different start years for a monotonic trend in variances with 11-yr width nonoverlapping window, and maps (f)–(j), (p)–(t), and (z)–(ad) show results from 12 repeated tests with 21-yr width window. Red and blue colors indicate areas where trend is statistically significant. Orange and purple colors indicate areas where at least one of the repeated tests shows statistically significant positive or negative trend in variability.
models include notable intermodel variation, which leads to uncertainty in estimating changes in variability. Our results also provide a more localized analysis with higher spatial resolution, revealing more diversity in changing variability and deeper understanding of variability at regional scale.

b. General implications

Given that results of this study for Finland in many regards matched those of Giorgi and Bi (2005) for northern Europe, this potentially provides support regarding their other estimates. For instance, decreases in winter temperature variability are expected not just in northern Europe (consistent with our study), but also in other Northern Hemisphere midlatitude regions (Mediterranean and eastern North America). Similarly, winter precipitation variability is expected to decrease in both northern Europe and eastern Africa. Summer temperature and precipitation variability show increases in most parts of the globe, including northern Europe (Giorgi and Bi 2005). The support of this study for each variable is, however, spatially inconsistent. The observed trend is not statistically significant in all of our study subbasins, and some areas even show trends in the opposite direction. The former may simply indicate that the signal is not sufficiently strong, but the latter suggests that there may be substantial spatial variation within regions for some variables, even in direction of trend. In light of the large uncertainty across models reported by Giorgi and Bi (2005), results of this study may help to evaluate existing climate models and identify areas for improvement. The ensemble average variability, however, already seems to agree with results of this study in general, and analysis of the ensemble on smaller regions would be needed to evaluate the climate models against some of the trends we observe.

A second major implication of this work is methodological. The reporting of changes in variability over time raises questions about interpretation. In this study, variability was measured as standardized MAD from the data’s median. Standardization was carried out by dividing MAD values with a constant mean MAD so variability was measured in relative terms, enabling comparison of different variables measured at different scales.

Variability itself is a common, widely used measure to complement the mean, and it is intrinsically useful to understand the range of variation to be coped with. Higher variability in hydroclimatic conditions may increase the uncertainties in planning, as one needs to be prepared for and take into account a wider range of hydroclimatic conditions. High variability notably favors more adaptive solutions, for example, in fields of agriculture and engineering (Brown and Lall 2006; Howden et al. 2007; Kummu et al. 2014; Oikarinen 2014; Thornton et al. 2014). In contrast, lower variability allows concentration on more efficient static solutions. However, if variability increases, static solutions may become inadequate and require adaptive action. We therefore argue that it is useful to examine variability in broad terms in addition to narrower studies of extreme events.

When studying extreme events, mean and variability cannot be separated, because they interact in determining intensity and frequency of extreme events. It is also reported, however, that the frequency of extreme events is relatively more dependent on any changes in the variability than in the mean of climate (Katz and Brown 1992). This suggests that more focus should be placed on changing climate variability as it is highly linked to extremes. Examining extreme events themselves also introduces new difficulties. It requires one to define what is extreme in terms of a physical threshold (e.g., exceedance of an event above preexisting threshold) or frequency of recurrence (e.g., probability of occurrence of an event). What is considered “extreme” is itself subjective, which necessarily means that analyses of extreme events are tied to narrower, well-defined application areas.

c. Limitations of the present study

Key assumptions of the study include the selection of width of moving windows, definition of clusters, and selection of the source data to be analyzed. Moving windows and clustering are commonly used methods in time series analysis, and the way they are used in present study is considered to provide robust scientific results.

First, in analysis of the statistical significance of changes in hydroclimate variability with the test for a monotonic trend in variances, the chosen width of the window and starting year of the analysis had notable effects on results. To overcome this issue and to cover the whole time period, repeated tests were conducted with different starting years. Only a few areas were found where all the repeated tests showed statistical significance (e.g., Figs. 6r,aa), but there were more areas where at least one of repeated tests identified statistical significance. These latter areas were interpreted to indicate possible statistically significant changes in variability. This was seen to be an informative and robust way to present areas where interesting changes in hydroclimatic variability may be occurring. Second, choosing the width of the window, or in other words the length of period, for moving-window MAD time series proved to be an important part in analysis of temporal changes in hydroclimatic variability. The decision to use two widths of analysis windows, 11 and 21 years, was considered suitable to detect interannual variability and
to show variability with different timeframes but with similar patterns.

Third, the ease of identification of spatial patterns is influenced by the number of clusters used. The strength of clustering is in condensing large volumes of information. There is therefore a trade-off involved. Selecting too few clusters risks oversimplifying phenomena and grouping areas that are still substantially different. On the other hand, selecting too many clusters makes it difficult to draw any insight from the maps and diminishes the noticeable difference between clusters. The choice of number of clusters was informed by different methods (the R package called NbClust, cluster dendrograms, and cluster time series), allowing for up to 15 clusters to emerge. NbClust provided and compared 30 indices for the optimization of number of clusters and suggested the best clustering scheme. Another method, a cluster dendrogram, was used to check the clustering scheme visually in terms of maximizing distance between clusters and minimizing distance within clusters. Then time series were produced and examined to verify that the chosen clustering scheme described the characteristics of changing variability within each cluster. However, some subjectivity necessarily remains in the clusters identified.

This study used interpolated and corrected areal temperature and precipitation data as well as simulated runoff data, all based on observed daily temperatures and precipitations. While results are likely to be different than those obtained from raw observed climate data, the data used were considered to have advantages. First, the original data are known to have missing values and discontinuities in observation techniques used in addition to measurement noise. The raw precipitation data required aerodynamic, wetting, and evaporation corrections. The overall correction varies from 1% to 40% depending on precipitation type (drizzle, rain, or snow) and gauges, and this affects the trends (Taskinen and Söderholm 2016) as well as spatial and temporal variation. Second, compared to data using a limited number of climate observations, these interpolated and simulated data have higher spatial coverage. With the use of suitable methods, this yields more—and more easily interpretable—information about spatial patterns, which is beneficial for regional studies with complex and variable terrains. If interpolation and model structure assumptions are acceptable, simulated values have the advantage of providing a coherent dataset (partially) addressing these issues. The resulting data are temporally continuous, which makes it comparable over time, facilitating the analysis presented here.

Possible uncertainties and limitations that the source data may contain were not considered in this study. Factors that can cause these uncertainties can be, for example, changes in number of gauge stations in the network, missing observation values, changes in precipitation measurement methods (especially changes in gauge types), and correction methods for gauge precipitation observations (especially different aerodynamic corrections). The runoff data are simulated with the WSFS hydrological model and not observed and thus may contain uncertainties linked with model structure and parameters. The results are therefore interpreted to represent climate variability as captured by the reference source data produced by the WSFS model. By providing an overview for the whole of Finland, this study identifies hotspots that may be of interest for further, more detailed, study.

d. Future research directions

The present study analyzed changes in variability and thus provides a basis for more in-depth analysis of extreme events and changes in their frequency and intensity. At a global scale, frequency and intensity of the extremes have been projected to change (IPCC 2015), but this change has not yet been documented in Finland. An increase in variability implies an increase in the probability as well as the absolute values of the extremes (IPCC 2001). However, it should be noticed that the effect of change in variability on extremes depends on change in mean state. Future studies could focus on floods, droughts, heavy rains, and heat waves specifically.

Moreover, it would be interesting to study more specific hydroclimatic variables and how their variability has changed, for example, the start and end date of thermal seasons, snow water equivalent, and snow accumulation and melt.

Future studies may also focus on causes behind the identified changes in hydroclimatic variability. In climate change studies, correlation between trends of climatic variables and different teleconnections, for example, North Atlantic Oscillation (NAO), has been widely studied, and the studies show that teleconnections are highly linked to global and regional climate change (Wanner et al. 2001; Hurrell et al. 2003; Hurrell and Deser 2010). Teleconnections themselves are varying and changing phenomena, and their effects on hydroclimate can therefore also change in time. In the case of Finland, interesting teleconnections to study, among others, would be the NAO and the Arctic Oscillation (AO), which have already been studied in Finland to some extent, but their linkage to the changes discovered in this study are not known. Furthermore, recent studies have already linked changes in mean temperature (Irannezhad et al. 2014a) and precipitation (Irannezhad et al. 2014b) in Finland to several teleconnections, including east Atlantic/west North Atlantic Oscillation.
Russia (EA/WR), Scandinavia (SCA), and polar/Eurasia (POL). However, the effect of these teleconnections on variability has not been addressed.

Finally, another possible future research direction could be to predict how climate variability will change in the coming years and decades in Finland, using different climate change scenarios, as well as a historical analysis of information dating further back in time, if reliable data are available. Based on the present study, changes in hydroclimatic variability are clearly significant enough, as well as spatially and temporally complex enough, to warrant additional research. Moreover, hydroclimatic variability and extreme events related to it affect various sectors of society, as discussed in section 1. Further and more detailed research is needed to improve understanding of spatial and temporal changes in hydroclimatic variability in Finland, as well as identifying the sectors of society affected. This would improve the possibility to adapt to and predict the changing hydroclimatic conditions.

5. Conclusions

This study aimed to assess the spatial and temporal interannual changes in hydroclimatic variability in Finland. Specifically, changes in variability of temperature, precipitation, and runoff were analyzed using a subbasin-scale dataset at both annual and seasonal scales over the period of 1962–2014. To achieve the aims, statistical analyses, MAD, PCA, agglomerative hierarchical clustering, and the test for a monotonic trend in variances were used.

Results show that trends and patterns of hydroclimatic variability varied a lot both spatially and temporally. However, some areas with similar patterns in changing hydroclimatic variability were found. In terms of temperature, the present study found statistically significant decreases in annual and winter mean temperature variability for most parts of Finland and for summer in northern Finland, respectively. For total precipitation variability, the present study found an increase in annual variability at the study area scale.

In addition, this study suggests a statistically significant decrease in annual precipitation variability in southern parts of Finland, which indicates that there are substantial spatial differences within the study area. Furthermore, statistically significant decreases are suggested for spring and autumn precipitation variability in the central parts of Finland and increases for autumn in northern Finland. With regard to runoff variability, winter and summer variability showed increases in study area scale, and for winter, this increase was statistically significant in central parts of Finland.

Previous and present studies together show that changes in mean state of hydroclimate does not necessarily mean parallel changes in hydroclimatic variability. This demonstrates the importance of this study’s focus on climate-induced changes in hydroclimatic variability rather than only trends in hydroclimatic mean conditions. The presented findings thus provide new information on hydroclimatic variability in Finland, particularly as it relates to observed rather than predicted climate change.

This study also argues that it is useful to examine variability of hydroclimatic conditions in addition to extreme events. Understanding the range of variation and its changes helps planning and decision-making choose between flexible adaptive and efficient static solutions in different sectors of society in anticipation of high- and low-variability conditions.

Altogether, this study points to a future research direction that recognizes changes in hydroclimatic variability, identifies sectors and functions of society that are affected by it, and would thus seek appropriate adaptation strategies. This line of research has the potential to better prepare people and infrastructure to improve the ability to adapt and predict the changes in hydroclimatic conditions, including weather extremes.

Acknowledgments. Ville Lindgren received funding from Maan-ja vesiteknii tuku ry., Joseph H. A. Guillaume received funding from Emil Aaltonen Foundation (‘eat-less-water’ project), Timo A. Räsänen received funding from Maan-ja vesiteknii tuku ry. (Grant 29049), and Matti Kummu received funding from Academy of Finland project SCART (Grant 267463) and Academy of Finland SRC project Winland. We thank the Finnish Meteorological Institute for providing the temperature and precipitation observations of 1962–2014 used in this study.

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