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Contrasting trends in hydrologic extremes for two sub-arctic catchments in northern Sweden – does glacier melt matter?

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Abstract

It is not clear how climatic change will influence glacial meltwater rates and terrestrial hydrology in the Sub-Arctic and Arctic. This uncertainty is particularly acute for hydrologic extremes (flood events) because understanding the frequency of such unusual events requires long records of observation not often available for the Arctic and Sub-Arctic. This study presents a statistical analysis of trends in the magnitude and timing of hydrologic extremes (flood events) and the mean summer discharge in two sub-arctic catchments, Tarfalajokk and Abiskojokk, in northern Sweden. The catchments have different glacier covers (30 % and 1 %, respectively). Statistically significant trends (at the 5 % level) were identified for both catchments on an annual and on a seasonal scale (3-months averages) using the Mann-Kendall trend test. Stationarity of flood records was tested by analyzing trends in the flood quantiles, using generalized least squares regression. Hydrologic trends were related to observed changes in the precipitation and air temperature, and were correlated with 3-months averaged climate pattern indices (e.g. North Atlantic Oscillation). Both catchments showed a statistically significant increase in the annual mean air temperature over the comparison time period of 1985–2009 (Tarfalajokk and Abiskojokk $p < 0.01$), but lacked significant trends in the total precipitation (Tarfalajokk $p = 0.91$, Abiskojokk $p = 0.44$). Despite the similar climate evolution over the studied time period in the two catchments, data showed contrasting trends in the magnitude and timing of flood peaks and the mean summer discharge. Hydrologic trends indicated an amplification of the hydrologic response in the highly glaciated catchment and a dampening of the response in the nonglaciated catchment. The glaciated mountain catchment showed a statistically significant increasing trend in the flood magnitudes ($p = 0.04$) that is clearly correlated to the occurrence of extreme precipitation events. It also showed a significant increase in mean summer discharge ($p = 0.0002$), which is significantly correlated to the decrease in glacier mass balance and the increase in air temperature ($p = 0.08$). Conversely, the nonglaciated catchment showed a significant decrease in the mean summer discharge

($p = 0.01$), the flood magnitudes ($p = 0.07$) and an insignificant trend towards earlier flood occurrences ($p = 0.53$). These trends are explained by a reduction of the winter snow pack due to higher temperatures in the winter and spring and an increasing soil water storage capacity or catchment storage due to progressively thawing permafrost.

1 Introduction

Recent studies of land-ocean-atmosphere interactions have shown that changes in the global climate are markedly influencing the atmospheric circulation in arctic and sub-arctic regions with direct influences on freshwater terrestrial hydrology (Trenberth et al., 2007; Khaliq et al., 2006; Stewart et al., 2005; Jain and Lall, 2001; Cayan et al., 1999). Regional studies of climate change in northern Europe, for example, have found a general increase in the mean annual temperature and annual precipitation (e.g. Moberg et al., 2005; Jansen et al., 2007; Groisman et al., 2005). There has been a corresponding general increase in winter and spring flows (Peterson et al., 2002; Lindström and Bergström, 2004; Wilson et al., 2010) and a general retreat of glaciers in this region (e.g. Jansson and Pettersson, 2007; Zemp et al., 2009; Koblet et al., 2010). Changes in glacier area and volume likely alter the streamflow dynamics in the catchment in which they are located by changing both the amount and timing of water released during the melt season (e.g. Fountain and Tangborn, 1985; Jansson et al., 2003). Thus, the comparative analysis of trends in streamflow records in catchments with differing glacier cover is considered a good indicator to estimate climate-induced shifts in the hydrological cycle of these regions.

Several studies have examined streamflow variations in glaciated and nonglaciated catchments across the Northern Hemisphere. These trend studies have found both decreasing (Moore and Demuth, 2001; Stahl and Moore, 2006; Pellicociotti et al., 2010) and increasing streamflow trends (Braun and Escher-Vetter, 1996) depending on the percent glacier cover of a catchment. According to Jansson et al. (2003) the retreat of glaciers due to increasing temperatures can affect catchment streamflow in two ways.

While a glacier adjusts its volume to a warmer climate, runoff will first increase. Once the glacier volume is adjusted or approaches an equilibrium volume, flow rates will decrease (e.g. Jansson et al., 2003). However, depending on the glacier coverage, catchment streamflows also exhibit a greater variability (coefficient of variation) that increases both when glacierization percentages increase and decrease, but variability is lowest when glacierization reaches approximately 40 percent (Fountain and Tangborn, 1985; Röthlisberger and Lang, 1987). Regarding recent climate change impact studies in glaciated catchments Birsan et al. (2005) found that most catchments with more than 10 % glacier cover show increasing summer flows, while catchments with less than 10 % glacier cover exhibit negative trends in summer flows. A few studies, such as Fleming and Clarke (2003), Hodgkins (2009), and Pellicciotti et al. (2010), have found similar contrasting trends when comparing glaciated and nonglaciated catchments in sub-arctic Canada, Alaska and the European Alps. Together these studies elucidate the existence of a glacier coverage threshold that determines the hydrologic response of glaciated catchments to climate change. Very few studies have, however, attempted to relate trends in hydrologic extremes to changes in glacier-covered catchment area, perhaps due to scarcity of long streamflow and glacier mass balance records (e.g. Birsan et al., 2005).

Recent studies of the North American and European Arctic and Sub-Arctic regions suggest that the change in the timing and magnitude of climatic and hydrologic extremes may be one of the most significant consequences of climate change in cold regions (Trenberth et al., 2007; Cunderlik and Ouarda, 2009; Callaghan et al., 2010). For the European Arctic and Sub-Arctic region, Busuioc et al. (2001) and Callaghan et al. (2010) reported a general increase in the frequency and magnitude of heavy precipitation ("extremes of extremes") events during the summer melt period. This increase is consistent with the trends documented for the North American Sub-Arctic (Cunderlik and Ouarda, 2009).

Hydrological extremes, however, may not directly reflect these increases in precipitation magnitude. This is because streamflow dynamics and flood events in northern landscapes are typically driven by either snowmelt (thermally driven) in the spring or the occurrence of precipitation events during the late summer and autumn (Kane et al., 2003; Wilson et al., 2010). As a result, trends in hydrologic extremes across the Arctic and Sub-Arctic depend on factors such as the presence of permafrost (subsurface storage and surface storage), topography (energy gradients and surface storage), antecedent moisture (precipitation, evapotranspiration, soil moisture) and precipitation and snowmelt duration and intensity (Kane et al., 1989, 2003). Kane et al. (2003) found for the Upper Kuparuk watershed in Alaska, that both the presence of permafrost (when the active layer is seasonally frozen) and high-gradient topography enhance, the fraction of rainfall and snowmelt that leaves the watershed as runoff. Their results also indicated that a few high-intensity precipitation events appear to generate greater runoff amounts (three times higher) than a large number of low intensity events. They hypothesized that these minor precipitation events may be important in priming the watershed for the high magnitude events by filling water storages. According to McNamara et al. (2008) the shift towards large precipitation events as the principle flood generating mechanism, particularly when they occur late in the summer melt period when the active layer depth is at its greatest, has the potential to cause considerable channel change and orders of magnitude more bed load transport than observed during snowmelt (early) runoff events. Braun et al. (2000), Box et al. (2005) and Knuden and Hasholt (2003) on the other hand reported for different glaciated catchments that streamflow reached large stream discharges during years with low snow accumulation that lead to extreme glacier ice melting. Knuden and Hasholt (2003) observed that glacier ablation reached a record high in 1998 in the Mittivakkat glacier catchment in southeast Greenland, despite the lowest mean temperature recorded. This was attributed to the combination of low summer precipitation and low snow coverage on the glacier surface. Together, the results from these studies indicate the difficulty to predict how glaciated catchments will respond hydrologically and in their extremes to increased climatic variability and change.

With the ongoing and expected reduction in global glacier volume, there is a need to better understand how this reduction in glacial volumes affects glacial meltwater runoff and thereby terrestrial hydrology. Assessment of gradual hydrologic change induced by climate and change in the causal mechanism of hydrologic extremes (flood events) in the Arctic and Sub-Arctic is challenging because assessing such events requires long records of observation not often available for these regions. In this current study, we aim to investigate climate induced shifts in the hydrologic response and the runoff generating mechanisms in sub-arctic catchments by analyzing and comparing trends in the magnitude and timing of hydrologic extremes (flood events) in two sub-arctic catchments with differing glacier cover in northern Sweden. For this study the Tarfalajokk catchment, in which Storglaciären is situated with the longest continuous glacier mass balance record currently available worldwide (e.g. Holmlund et al., 2005; Jansson and Pettersson, 2007), and the upper Abiskojokk catchment, which has a continuous 98-yr record of climate observations, were compared. In both catchments the hydrologic trends were related to annual and seasonal trends in the minimum, maximum and mean temperature, the maximum and total precipitation, and the large-scale climatic teleconnection patterns (e.g. Northern Atlantic Oscillation, Atlantic Multidecadal Oscillation). In addition, the flood frequency for each catchment was estimated to test whether streamflow was stationary or impacted by climate variability over the period of record.

2 Methods

2.1 Site descriptions

This study considers two catchments in northern Sweden: the upper Abiskojokk (68°21′36″ N, 18°46′48″ E) and the Tarfalajokk (67°53′56″ N, 18°37′57″ E) (Fig. 1). Both catchments are characterized by relatively pristine land-use conditions and minimal human influences. The drainage areas of the Abiskojokk and Tarfalajokk catchments are 566 km^2 and 21.7 km^2, respectively. The stream gauging stations are located at 340 m (Abiskojokk) and 1091 m (Tarfalajokk) above sea level. The elevation difference (relief) in these mountainous catchments is large and ranges from 340 m to 1800 m in Abiskojokk catchment and from 980 m to 2100 m in the Tarfalajokk catchment. Vegetation is found mainly in the valley bottom of both catchments. A mountain birch forest dominates the valley bottom of Abiskojokk catchment, while alpine heath dominates the Tarfalajokk catchment. Both catchments are located in the discontinuous permafrost zone. The glaciated area in Tarfalajokk catchment is 30 % while only 1 % in Abiskojokk catchment (Fig. 1) is glacierized.

Regional climate in northern Sweden is cold and humid. Annual precipitation amounts are determined by topography and dominant weather patterns. Thus, mean annual precipitation amounts in the Abiskojokk catchment range from approximately 300 mm yr^{-1} as recorded at the Abisko Scientific Research Station (68°21′ N, 18°49′ E, 385 m a.s.l.) to over 900 mm yr^{-1} in the peak areas of the catchment (Josefsson, 1990; Alexandersson et al., 1991). In the Tarfalajokk catchment the mean annual precipitation measured at Tarfala Research Station (67°55′ N, 18°37′ E, 1135 m a.s.l.) has been estimated to 950 mm, of which approximately one third falls between June and August. A mean air temperature of −0.5 °C for the period 1913–2009 has been recorded at Abisko Scientific Research Station and −3.4 °C has been recorded at Tarfala Research Station for the period 1965–2009 (Falkenmark, 1972).

2.2 Data

2.2.1 Hydrometric data

Our analysis is based on long-term daily precipitation and temperature data available for Abiskojokk catchment for the time period 1913–2009, and daily streamflow data from the period 1918–2009. Precipitation and temperature data for Abiskojokk catchment are available from the Abisko Scientific Research Station and streamflow data are available through the Swedish Meteorological and Hydrological Institute (SMHI)

(gage ID 957). Streamflow in Abiskojokk catchment was not monitored for the period 1956–1985. There were, however, no changes in the stream gage location or the stage-discharge relationship between the time period before (1919–1956) and after (1985–2009) this period when monitoring was discontinued. Daily temperature data for Tarfalajokk catchment were available from 1965–2009, daily data of liquid precipitation (available for June through September) were available for the period 1980–2009, and daily streamflow data (available for mid-May through September) were available for the period 1969–2009. Streamflow, precipitation and temperature data are available through the Tarfala Research Station (http://tarfalawiki.natgeo.su.se/tarfalawiki/index.php/Main_Page).

2.2.2 Climate teleconnection pattern data

The climate in Europe and Fennoscandia is largely influenced by the interannual and interdecadal oscillations in the atmospheric circulation over the North Atlantic Ocean. These oscillations are quantitatively described by climate indices, also called teleconnection pattern indices, which are calculated from the 700-hPa geopotential heights (e.g. Climate Diagnostics Bulletin, 2001; Panagiotopolous et al., 2002; Barnston and Livezey, 1987). For the Atlantic-European region, Nesterov (2009) listed several important climate patterns and their indices that control the cyclone trajectories (storm tracks) over the North Atlantic and, thus, the temperature and precipitation anomalies over Europe and Fennoscandia. These indices are the North Atlantic Oscillation (NAO) index (Barnston and Livezey, 1987), the East Atlantic pattern (EA) index, the East Atlantic-Western Russia pattern (EA/WR) index; the Scandinavia pattern (SCA) index, and the Polar-Eurasia pattern (POL) index (Panagiotopoulos et al., 2002; Nesterov, 2009) (Table 1). These climate pattern indices were selected to evaluate the influence of climate on the hydrology in the Tarfalajokk and Abiskojokk catchments. In addition to these teleconnection pattern indices, the Atlantic Multidecadal Oscillation (AMO) index (Enfield et al., 2001) was included in the analysis, which is a principal expression of the sea surface temperature of the Atlantic Ocean that influences the heat fluxes from the ocean to the atmosphere and thus the transport of moist air masses to high-latitude regions (Enfield et al., 2001).

2.3 Statistical methods

2.3.1 Trend statistics and correlations

The nonparametric Mann-Kendall (MK) trend test (Kendall, 1975; Helsel and Hirsch, 1992; Douglas et al., 2000) was used to investigate trends in the time series data available for both catchments. The test is based on the assumption that time series data are independent and identically distributed and not auto-correlated (Helsel and Hirsch, 1992; Douglas et al., 2000). The MK trend test determines whether a time series exhibits a trend without specifying whether the trend is linear or nonlinear.

For each catchment the MK trend test was performed to assess the degree of non-stationarity in the annual series and series for 3-month seasons (i.e. December through February defines winter; March through May defines spring; June through August defines summer; September through November defines autumn) temperature and precipitation data. For the annual and 3-months groupings the length of each time series corresponded to the number of years of data available. For all groupings, trends in the minimum, mean, and maximum temperature values, and the total and maximum precipitation values were determined. In addition, for both catchments, trends in the maximum daily flow (flood magnitude), the date of maximum daily flow (flood occurrence), and the mean summer flows were assessed using the MK trend test. The date of flood occurrence is denoted by the day of the year (Julian Day [DoY]). For each data set the MK trend test was performed with a significance level of 5 % (2-sided). In addition, linear regressions were fit to the time series data to determine approximate rates of change. In this study trends were estimated for the maximum record period available for each catchment as well as for overlapping time windows to allow direct comparison of the observed trends between the two catchments. Trends were also estimated for the common time windows for which observations from both catchments

were available covering the period 1965–2009 for temperature records, 1980–2009 for precipitation records and 1985–2009 for discharge records. In addition, trends were estimated for the 1985–2009 period representing the longest record period possible for which temperature, precipitation and discharge data from both catchments were available.

To identify whether flood events in each catchment were predominantly associated with precipitation events or warm temperature periods (and subsequent snowmelt), flood occurrences were compared to the day of occurrence of the annual 1-day maximum and the median day of occurrence of the annual maximum total precipitation of three consecutive days (3-day maximum) and the 1-day and 3-day maximum mean air temperature for each record year.

For each catchment a joint analysis of climate pattern indices (Table 1) and the hydrologic extremes and the mean summer (JJA) discharge was performed. Pairwise correlations between the logarithms of the maximum annual discharge, the day of the flood peaks, the mean summer discharge and seasonally (3-months averages over the winter, spring and summer season) and annually (12-months) averaged climate pattern indices were calculated. In addition, for Tarfalajokk catchment hydrologic extremes and the mean summer discharge were correlated to the winter (b_w), summer (b_s) and net mass balance (b_n) of Storglaciären, the largest glacier in the catchment covering 2.9 km^2. This analysis sought to assess both the response of the catchment hydrology to climate and the effect of glaciers on long-term streamflow variations in each catchment.

2.3.2 Flood frequency analysis

The Extreme Value type I distribution, also known as the Gumbel distribution, was fit to all flood peaks for both Tarfalajokk and Abiskojokk catchments using the maximum likelihood method (Gumbel, 1958; Jenkinson, 1969). This was done to estimate the exceedance probability of a certain flood event based on the full flood record. Model adequacy of the fitted distribution was tested with a probability plot correlation test

(Vogel, 1987). In order to test whether both flood records satisfy the stationarity assumption, and to examine trends in the flood percentiles over the full record period, a trend analysis on the quantiles, estimated from the consecutive windows of 10 yr, was performed using a generalized least squares (GLS) regression model (Fox and Hartnagel, 1979). Significance of the trend was estimated at a significance level of 5 %. This allowed assessment of shifts in the period of record and identification of periods with the most prominent changes in the flood distribution while accounting for the autocorrelation in the residuals of the regression model at the same time. The trend analysis was performed on quantiles equal to exceedance probabilities of 0.5, 0.1, 0.05 and 0.01, which correspond to floods with return periods of 2, 10, 20, and 100 yr, respectively.

3 Results

3.1 Temperature and precipitation trends

The most prevalent trends in the Abiskojokk and Tarfalajokk catchment comprise a significant increase in the mean annual air temperature over their 98-yr and 45-yr study periods, respectively (Fig. 2). The mean annual temperature increased at a rate of 0.09 °C decade^{-1} and 0.54 °C decade^{-1} in the Abiskojokk and Tarfalajokk catchments, respectively, over each record period (Tables 2 and 3). The seasonal temperatures in the Abiskojokk catchment show significant ($p < 0.05$) increasing trends in the mean and maximum spring (March–May) temperature, and a significant decrease in the temperature range observed during summer (June–August) over the 98-yr record, which can be attributed to a significant increase in the minimum summer temperature and a significant decrease in the maximum summer temperature (Table 3). During this period, spring saw the largest (0.15 °C decade^{-1}) and summer the smallest (0.03 °C decade^{-1}) mean temperature rise in Abiskojokk catchment. During the past 45 yr, widespread trends towards higher mean annual and seasonal air temperatures

were observed in both catchments (Tables 2 and 3). These trends were also significant for the common time period of 1985–2009 (Table 4). Comparison of temperature trends for the past 45 yr (1965–2009) in both catchments shows that the annual mean air temperature in Abiskojokk and Tarfalajokk catchments increased at a similar rate of 0.46 °C decade^{-1} and 0.54 °C decade^{-1} respectively (Tables 2 and 3). Temperature increase in the Abiskojokk and Tarfalajokk catchments was even higher during the 1985–2009 period with rates of 0.67 °C decade^{-1} and 0.96 °C decade^{-1} respectively (Table 4). In both catchments, winter (DJF) saw the largest while summer (JJA) saw the smallest mean temperature rise during that period (Tables 2 and 3). During the 1965–2009 and 1985–2009 period in both catchments, spring warming has accelerated at a similar rate. However, in the Tarfalajokk catchment the mean autumn (SON) temperature is increasing at a higher rate (0.56 °C decade^{-1}) than the spring temperature (0.45 °C decade^{-1}) (Tables 2, 3 and 4).

The annual precipitation in Abiskojokk catchment showed a significant ($p = 0.01$) increasing trend over the 1913–2009 period (Fig. 3, Table 3). The largest contributor to the increase in the total annual precipitation was the winter (DJF) precipitation, which increased since 1913 at a rate of 1.7 mm decade^{-1} ($p = 0.06$). In contrast, the maximum and total precipitation of the spring, summer and autumn season remained relatively constant over the 98-yr record period (Table 3). Comparison of precipitation trends since 1980 in both catchments shows that there are no clear trends in the annual or seasonal maximum and total precipitation amounts during the past 30 yr, with exception of the maximum winter (DJF) precipitation in Abiskojokk catchment, which decreased significantly at a rate of 10.4 mm decade^{-1} since 1980 ($p = 0.02$) (Table 3). Similarly, there was no significant trend in the annual and seasonal, maximum and total precipitation records in both catchments during the 1985–2009 period (Table 4). However, variability in extreme precipitation and the magnitude of outliers (“extremes of extremes”) has increased in both catchments over each record period. An extreme precipitation event in 1915 equaled 39.7 mm day^{-1}. Since that time, the number of years per decade with precipitation amounts exceeding 25 mm day^{-1} has doubled in Abiskojokk catchment. Similarly, precipitation extremes in the Tarfalajokk catchment have risen from 42 mm day^{-1} in 1980 to 81 mm day^{-1} in 2004. In contrast to the changes in precipitation magnitude in both catchments, the summer precipitation frequency (i.e. number of precipitation days in JJA) remained unchanged in both catchments (Fig. 3).

3.2 Mean discharge and hydrologic extremes

3.2.1 Trends

Tarfalajokk showed a significant ($p = 0.0002$) increasing trend in the mean summer (JJA) discharge corresponding to an increase of approximately 0.5 m^3 s^{-1} decade^{-1} over the long-term record period (1969–2009) (Fig. 4a). In addition, the maximum annual discharge events of Tarfalajokk have shown a significant ($p = 0.03$) increasing trend over this period at a rate of approximately 1.75 m^3 s^{-1} decade^{-1} (Fig. 4b). Both trends were also significant for the common time period of 1985–2009. The median flood recorded for the long-term period was 11.3 m^3 s^{-1} and the maximum and minimum floods were 23.4 m^3 s^{-1} and 6.5 m^3 s^{-1}, respectively. The majority of flood peaks occurred in mid-to-late summer (Fig. 4c) after the beginning of July (DOY = 190) with a median date of the annual flood of 24 July (DOY = 205). The occurrences of the annual floods showed an increasing albeit not significant trend for the long-term period and a decreasing (not significant) trend over the 1985–2009 period (Fig. 4c).

Both the long-term trends of the mean summer discharge and the maximum annual discharge (flood) events of Abiskojokk show a decreasing but not statistically significant ($p > 0.05$) trend over the long-term record period from 1919 to 2009 (Fig. 4d and e). The rates of decrease in mean summer discharge and flood magnitudes are approximately 0.14 m^3 s^{-1} decade^{-1} and 2.1 m^3 s^{-1} decade^{-1} respectively. Both the decreasing trend in mean summer discharge and the maximum annual flood event were significant at the 10 % level during the common time period of 1985–2009 with p-values of $p = 0.01$ and $p = 0.07$ respectively. The median flood recorded for Abiskojokk for

the period 1919–2009 is 124 m^3 s^{-1} and the maximum and minimum recorded floods are 62.6 m^3 s^{-1} and 277 m^3 s^{-1} respectively. The median date of the annual flood in Abiskojokk is 24 June (DOY = 175), with early March to early August as the range of dates for the 93-yr record period (Fig. 4f). However, as indicated in Fig. 4f, in Abiskojokk the majority of flood peaks occur in the first half of the summer snowmelt season before mid July (Julian Day = 195). Over the long-term period of 1919–2009 the flood timing of Abiskojokk is significantly ($p = 0.01$) shifting towards earlier flood occurrences in the spring and summer melt period at an average rate of 2 days in 12 yr. The flood events showed a similar shift towards earlier occurrences at an average rate of 2 days in 11 yr during the common time period of 1985–2009 (Fig. 4f).

3.2.2 Flood frequency analysis

The Gumbel distribution provided a good fit for both catchments based on a probability plot correlation test (Tarfalajokk: $r = 0.98$, Abiskojokk: $r = 0.99$) (Vogel, 1987). A trend analysis on the moving window results revealed that the Tarfalajokk catchment exhibits a significant increasing trend ($p < 0.01$) in the 2-yr, 10-yr, 20-yr, and 100-yr flood quantile. The estimated 100-yr flood for Tarfalajokk is 26.8 m^3 s^{-1} based on the 41-yr record. However, during the past 10 yr the frequency of exceedance of the entire flood distribution moved towards lower exceedance probabilities (Fig. 5a). Five of the seven flood peaks with exceedance probabilities of 20 % or less occurred during the last decade.

The values of the 2-yr, 10-yr, 20-yr, and 100-yr flood quantiles for the Abiskojokk show significant decreasing trends ($p < 0.01$) over the full record period (Fig. 5b, Table 5). The estimated 100-yr flood for Abiskojokk based on the entire 93-yr (1918–2009) record is 246.5 m^3 s^{-1}. The results of the moving window analysis indicate that during the 1919–1955 period the estimated 100-yr flood showed a higher variability and moved towards lower exceedance probabilities compared to the long-term estimate of 246.5 m^3 s^{-1} (Fig. 5b). Since 1985, however, the entire flood distribution moved towards higher exceedance probabilities as confirmed by the significant decreasing trend ($p < 0.01$) (Table 5). This means that flood events with a return period of approximately 20–30 yr (values exceeded with a probability of 4–5 %) over the entire record were essentially a 100-yr flood (flow values exceeded with a probability of 1 %) during the past decade.

3.3 Climatological controls on flood events

3.3.1 Temperature and precipitation

Table 6 summarizes the percentage of years when the annual 1-day maximum and/or annual 3-day maximum for the total precipitation and mean temperature coincided with the observed flood peak for the year. From the 27 flood events considered for Tarfalajokk, 59 % of the flood events coincided with the annual 1-day maximum precipitation and only 19 % coincided with the annual 1-day maximum temperature (Table 6). It should be noted that for three events, the annual 1-day maximum precipitation coincided with the annual 1-day maximum temperature. Similar results were observed when considering the annual 3-day maximum for precipitation and temperature. The majority of the flood events coincided with the median day of occurrence of the maximum annual total precipitation observed over three consecutive days.

For Abiskojokk, the occurrence of floods coincided with the annual 1-day maximum precipitation in 18 % and with the annual 1-day maximum temperature in 25 % of the 61 flood events considered (Table 6). Thus, flood events in Abiskojokk catchment showed a greater coincidence with the maximum annual temperature events than with the maximum annual precipitation events, though neither explained the majority of the annual maximum floods. Again, three flood events occurred on the same day as the annual 1-day maximum precipitation and temperature. This changes, however, when considering the annual 3-day maxima runoff. The flood occurrences coincided with the annual 3-day maximum precipitation in 21 % and with the annual 3-day average maximum

temperature in 20 % of the 61 flood events considered. Again, neither explained the majority of the annual maximum floods.

3.3.2 Climate teleconnections

The logarithm of the magnitude of the annual maximum discharge for the Tarfalajokk catchment was positively correlated with the AMO index throughout all seasons; and negatively correlated with the SCAND index for spring (MAM), summer (JJA) and annual average of the (Table 7). These correlations suggest that (in a linear response sense) one should expect larger floods in years with higher sea surface temperatures over the North Atlantic and the SCAND index in a negative phase. The negative phase of the SCAND index causes negative height pressure anomalies over northern Europe and Fennoscandia that lead to lower temperatures and above normal precipitation (Table 1). This likely predicts higher snow accumulation, precipitation amounts and runoff in these areas.

The timing of flood occurrences in Tarfalajokk catchment was not significantly correlated with any of the climate indices considered (Table 7). Mean summer (JJA) discharge in Tarfalajokk catchment, however, had a significant positive correlation with the AMO index throughout the winter, spring and summer season (Table 7). The mean summer (JJA) discharge in Tarfalajokk catchment had a significant positive correlation with the summer (JJA) and annual average of the EA index (Table 7). The positive phase of the EA index causes negative height anomalies east of Newfoundland that lead to above normal temperatures in European Russia but above normal precipitation across northern Fennoscandia (Table 1).

For the Abiskojokk catchment, the logarithms of the maximum annual flood events were negatively correlated with the winter (DJF) and summer (JJA) EA and SCAND pattern indices (Table 7). Thus, one should expect larger floods in the Abiskojokk catchment when both the SCAND and EA index are in their negative phase during the flood season. The negative phase of both the SCAND index and the EA index causes an intensification of the meridional circulation that leads to a negative temperature anomaly or below average temperatures and above normal precipitation over northern Europe (Table 1). The timing of flood occurrences in Abiskojokk catchment had a significant negative correlation with the spring (MAM) average of the EA and the EA/WR pattern index and annual average of the EA index (Table 7). In contrast to Tarfalajokk catchment the mean summer (JJA) discharge in Abiskojokk catchment had a significant negative correlation with the winter (DJF) and annual average of the AMO index (Table 7). The AMO index is a principal expression of the sea surface temperature of the Atlantic Ocean that influences the heat fluxes from the ocean to the atmosphere and thus the transport of moist air masses to high-latitude regions (Enfield et al., 2001). The mean summer (JJA) discharge in Abiskojokk catchment had a significant positive correlated with the winter (DJF) and annual average of the NAO index which is characterized by above normal precipitation and above normal winter and spring temperatures in Fennoscandia.

4 Discussion

4.1 Regional precipitation and temperature trends

Figure 6 provides a visual summary of the critical hydrometeorologic and hydrologic processes in these two basins. Characteristics of the two catchments and the results of critical statistical trend tests are summarized in Table 8. The data show that there is a clear increase in the annual mean temperature in both catchments over the respective long-term and common time periods associated largely to a statistically significant increase in spring temperatures in the Abiskojokk catchment and winter temperatures in the Tarfalajokk catchment (Figs. 2 and 3, Tables 2, 3 and 4). With the exception of the winter period, trends in the annual and seasonal minimum temperature were not statistically significant in either catchment. The slope of the mean annual temperature rise in the Abiskojokk catchment over the past 98 yr agrees with evidence that Arctic air temperature has been rising at an average rate of 0.09 decade^{-1} since 1875

(Table 3) (Polyakov et al., 2003; Trenberth et al., 2007). The long-term (1913–2009) seasonal temperature trends observed at Abisko Scientific Research Station are in general agreement with the results of Jones et al. (1999), Serreze et al. (2000) and Polyakov et al. (2003) who observed the smallest warming trend in summer (JJA) (0.05 °C decade^{-1}) and the largest warming trend during the winter and spring (DJF, MAM) (0.13 and 0.12 °C decade^{-1} respectively) within the 55–85 N zonal band. The rise in mean annual temperature that was recorded in both catchments since 1965 (0.46 and 0.54 °C decade^{-1} for Abiskojokk and Tarfalajokk respectively) is consistent with mean annual temperature trends reported for Scandinavia and the Baltic Sea area by Callghan et al. (2010) and Lehman et al. (2011). In addition, there is a diurnal asymmetry in the warming in Tarfalajokk catchment comprised of a rise in minimum temperature at a rate three times the rate of the increase in the maximum temperature. This trend is consistent with observations from Karl et al. (1993) and Rusticucci and Barrucand (2004) for large parts of the Northern and Southern Hemisphere landmass. In contrast there was an increase in minimum temperature (for all seasons) and a decrease in the maximum summer temperature in the Abiskojokk catchment (Tables 3 and 4).

Precipitation is another critical parameter. Despite the significant increase in annual precipitation in the Abiskojokk catchment over the past century (1913–2009), Abiskojokk as well as Tarfalajokk lack a significant increasing or decreasing trend in the seasonal or annual totals or maximum precipitation during the past three decades (1985–2009). Although the frequency of precipitation events remained unchanged in both catchments over the long-term period (Fig. 3), the variability and magnitude of extreme precipitation events was increasing. These trends are consistent with findings reported by Busuioc et al. (2001), Callaghan et al. (2010) and Birsan et al. (2005), who hypothesize changes in the large-scale circulation patterns, increased moisture transport to arctic regions and the lack of adequate rain gage coverage to capture the large spatial variability of precipitation as potential reasons for the inconsistent trends.

4.2 Shifting hydrology and hydrological extremes

Although both catchments demonstrated similar precipitation and temperature trends over the common time periods, we found contrasting trends in the mean summer discharge, as well as the flood magnitude and flood timing between the Abiskojokk and Tarfalajokk catchments. Analysis of hydrological trends in the Tarfalajokk catchment showed a statistically significant increase in the mean summer discharge and the magnitude of flood peaks; and an insignificant decrease in the flood occurrences over the comparison time period of 1985–2009 (Fig. 3). Mean summer discharge in the Tarfalajokk catchment had a significant negative correlation with the winter mass balance (b_w) of Storglaciären (in terms of snow water equivalent) (Table S1, Supplement) suggesting an increasing contribution of glacier melt to total discharge. Fleming and Clarke (2003), Hodgkins (2009), and Pellicciotti et al. (2010) observed a similar increase in summer discharge in catchments with high (>10 %) glacier cover. The observed increase in mean summer discharge in the Tarfalajokk catchment coincides with the observed gradual decrease in the mass balance of Storglaciären, whose retreat has been related to increased air temperatures and variability in the NAO (Linderholm and Jansson, 2007), and AMO indices during the last six decades (Table S2, Supplement). Our results show that the mean summer discharge is likewise significantly correlated to the AMO index (Table S2, Supplement), which suggests that the climatic forcing on the glacier mass balance in Tarfalajokk catchment subsequently affects the mean discharge during the summer melt season.

Trends in air temperature cannot explain the observed trends in the magnitude and timing of flood peaks in the Tarfalajokk catchment, because 59 % of the flood events coincided with the annual 1-day maximum precipitation and only 19 % coincided with the annual 1-day maximum temperature (Table 5). In the Arctic and Sub-Arctic, the majority of the annual floods are traditionally snowmelt-generated, thus, thermally driven events (Lindström and Bergström, 2004). Kane et al. (2003) showed in the Upper Kuparuk River, Alaska that, rainfall-generated runoff events produce flood magnitudes that

can exceed by a factor of three those generated by snowmelt. They concluded that the likelihood of major rainfall-generated floods is especially prevalent in catchments with limited soil storage; catchment size and the orientation of the catchment are also important factors. Similarly, Cunderlik and Ouarda (2009) reported that the importance of rainfall floods has been increasing across continental arctic and sub-arctic Canada during the past three decades, while snowmelt floods showed significant negative trends in the magnitude.

For the common time period (1985–2009) Abiskojokk showed significant decreasing trends in the mean summer discharge and in the magnitude of flood peaks (significant at 10 % level) suggesting changes in the catchment hydrology that diminish flood intensities. In addition, Abiskojokk catchment showed a negative trend in the timing of flood peaks, which is significant for the long-term record period, implying that the occurrence of floods is shifting toward the earlier part of the year. Both the mean summer discharge and flood magnitudes showed significant correlations to the NAO index and the AMO index of the previous winter season (Table 7). Because both the NAO index and the AMO index are reliable indicators of large-scale moisture and energy flow into northern Europe, it is possible that winter precipitation and the build-up of the winter snow pack subsequently affect streamflow dynamics in the spring and summer melt season. These results agree with results of previous studies from nonglaciated, permafrost dominated catchments in Fennoscandia (Korhonen and Kuusisto, 2010; Wilson et al., 2010), Sub-Arctic Canada (Carey and Woo, 2001; Dery and Wood, 2005; Abdul-Aziz and Burn, 2006; Cunderlik and Ouarda, 2009; Khaliq et al., 2009; Burn et al., 2010), and Alaska (Woo and Thorne, 2008; Brabets and Walvoord, 2009; Hodgkins, 2009) who discuss a similar range of explanations for the observed trends. Burn et al. (2010) hypothesized that the decreasing trend in flood magnitudes and occurrences is the results of increased winter and spring temperatures that lead to greater losses of the snowpack before the onset of spring melt. Climate records from the Abiskojokk catchment indicate a significant increase in the winter and spring air temperature and a negative, albeit insignificant ($p = 0.35$), trend in winter precipitation, which could result in similar reductions in the spring snow pack and an extension of the snow-free summer melt period (Table 4).

On the other hand, higher temperatures can result in increased permafrost thawing; that can lead to increased catchment permeability and increased subsurface flow through the active layer that could potentially have a dampening effect on peak flows (Lyon et al., 2009, 2010). Indeed, several studies across sub-arctic Sweden have documented accelerated permafrost thawing. Malmer et al. (2005) reported that areas of ponds have increased while areas with dry palsa tops have decreased. For the Abiskojokk catchment Åkerman and Johansson (2008) documented increases in active layer thickness in nine lowland mires with discontinuous permafrost between 1978 and 2006, and estimated an average permafrost thawing rate of 0.7–1.3 $\mathrm{cm\,yr^{-1}}$ based on those data. This progressive increase in active layer thickness is likely to cause increased water flow via subsurface flow pathways as indicated by the negative trend in mean summer discharge in the Abiskojokk catchment. Similar indicators of a progressive increase in catchment storage have been documented by means of a greater annual discharge (Lindström and Bergström, 2004), increased total organic carbon (TOC) export rates to lakes (Kokfelt et al., 2009), and increased dissolved inorganic carbon (DIC) exports to streams (Lyon et al., 2010).

Altogether our results suggest that the effect of climate warming on the arctic and sub-arctic hydrologic system can fundamentally change the hydrologic responses exhibited by those systems (Fig. 6 and Table 9). Our observations indicate that sub-arctic mountain catchments experience an amplified response to climate forcing relative to that found for lower altitudes. In the glaciated Tarfala catchment, trends in hydrological extremes (floods) indicate that this catchment is becoming more efficient in transmitting water to its outlet which can be attiributed in large parts to the decreased size of the glacier and the more rapid melting of catchment snow cover. Conversely, in the Abisko catchment, research has shown that the mean soil depth and soil water storage capacity is increasing with the melting of permafrost; as a result hydrologic extremes (floods) and streamflow exhibit a generally decreasing trend likely due to the dampening effect

of increased sub-surface catchment storage. In addition, the decreases in mean summer discharge and flood magnitudes in the Abiskojokk catchment are likely the result of earlier snowmelt, as indicated by the decreasing trend in flood occurrences associate with warming climate and thawing permafrost. We suggest that the increase in mean summer discharge in the glaciated Tarfala catchment is due to higher temperatures, more summer precipitation (positive but insignificant trend) and more ice melt. On the other hand, increase in flood magnitudes of Tarfalajokk is likely due to the increase in extreme precipitation events in conjunction with catchment properties that promote fast runoff such as high-gradient topography, limited soil storage and increased mean streamflow due to increased glacier melt. For extreme flows it appears that glacier presence plays a key role in runoff production in mountain catchments. However, the potential role of changes in the snow cover characteristics should to be examined in more depth. A reduction in the seasonal snow cover in nonglaciated catchments would potentially lead to a decrease in streamflow from these catchments due to the reduced precipitation input, while the same reduction in a glaciated catchment would potentially leave the glacier ice exposed for a longer time, thus resulting in a short term increase in streamflow until depletion of the glacier mass reaches the critical stage after which streamflow will decrease (Jansson et al., 2003).

5 Conclusions

This study presents a statistical analysis of trends in the magnitude and timing of hydrologic extremes (flood events) and the mean summer discharge in the sub-arctic Tarfalajokk and Abiskojokk catchments in northern Sweden with a glacier cover of 30 % and 1 %, respectively. Statistically significant annual trends were identified for both catchments for annual and seasonal volumes using the Mann-Kendall trend test. Trends in flood quantiles from a flood frequency analysis with a 10-yr moving window were also considered. Hydrologic trends were related to observed changes in precipitation and air temperature, and correlated with 3-months averaged climate teleconnection pattern indices (e.g. North Atlantic Oscillation). In both catchments a statistically significant increase in the mean annual air temperature has been observed, mostly reflecting a significant increase in winter and spring temperatures. The main rise in temperature has occurred in the winter and spring season in both catchments during the past three decades. Seasonal precipitation depths (total and maximum) showed neither significant increasing nor decreasing trends in the same period.

Despite the similarity in precipitation and temperature trends, the catchments exhibited fundamentally different trends in the mean summer discharge, and in the flood magnitude and timing. The glaciated Tarfalajokk catchment showed a statistically significant increase in the mean summer discharge and the magnitude of flood peaks, and progressively earlier flood occurrences (not significant); the nonglaciated Abiskojokk catchment showed a significant decrease in the mean summer discharge and in the flood magnitudes (at the 10 % level) and a insignificant trend towards earlier flood occurrences during the past three decades. Correlation analyses of hydrologic trends in the Tarfalajokk catchment with glacier mass balance data and climate pattern indices show statistically significant relationships for both the flood peaks and the mean summer discharge with the winter mass balance of Storglaciären and the Atlantic Multidecadal Oscillation. These relationships suggest that climatic forcing (e.g. reduction in snow cover) on the glacier mass balance in Tarfalajokk catchment affect the streamflow dynamics in the summer melt season. The increase in flood magnitudes, however, is clearly correlated to an increase in extreme precipitation events in conjunction with catchment properties that promote fast runoff such as high-gradient topography, limited soil storage and increased mean streamflow due to increased glacier melt. Conversely, the decreasing trends observed in the nonglaciated Abiskojokk catchment in combination with the precipitation and temperature trends point towards a reduction of the winter snow pack due to warmer temperatures and an increasing sub-surface storage capacity or catchment storage due to progressively thawing permafrost. Together these results show that similar climate forcing can cause fundamentally different responses of hydrologic systems in the Arctic and Sub-Arctic.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/9/1041/2012/ hessd-9-1041-2012-supplement.pdf.

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Table 1. Summary of climate pattern indices considered in this study and their relationship to temperature and precipitation anomalies in Northern Europe exemplified for the positive phase of the climate pattern indices. The monthly averaged climate index data were acquired for the period 1950–2009 from the sources specified below.

Climate index	Temperature (positive phase)	Precipitation (positive phase)	Data source and references
Atlantic Multidecadal Oscillation (AMO)	above-average temperatures across Scandinavia especially during the summer	above-average precipitation across northern Europe and Fennoscandia	http://www.esrl.noaa.gov/psd/data/correlation/amon.us.data Enfield et al. (2001), Arguez et al. (2009), Sutton and Hodson (2005)
East Atlantic/Western Russia (EA/WR)	below-average temperatures across northeastern Fennoscandia	above-average precipitation across northern Fennoscandia	http://www.cpc.ncep.noaa.gov/data/teledoc/eawruss.shtml Barnston and Livezey et al. (1987), Arguez et al. (2009)
East Atlantic (EA)	no clear effect	above-average precipitation across northern Europe and Fennoscandia	http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml Panagiotopoulos et al. (2002), Nesterov (2009)
North Atlantic Oscillation (NAO)	above-average temperatures across Fennoscandia	above-average winter precipitation and below-average summer precipitation across Fennoscandia	http://www.cpc.ncep.noaa.gov/data/teledoc/nao.shtml Panagiotopoulos et al. (2002), Nesterov (2009)
Polar/Eurasia (POL)	no clear effect	above-average precipitation across polar regions north of Fennoscandia	http://www.cpc.ncep.noaa.gov/data/teledoc/poleur.shtml Panagiotopoulos et al. (2002)
Scandinavia pattern (SCAND)	above-average temperatures across Fennoscandia across Fennoscandia	below-average precipitation	http://www.cpc.ncep.noaa.gov/data/teledoc/scand.shtml Panagiotopoulos et al. (2002)

Table 2. Summary for Tarfalajokk catchment of the Mann-Kendall (MK) trend test statistics for the annual and seasonal precipitation (1980–2009) and temperature (1965–2009) data. Trend significance of the MK trend test is indicated by the 2-sided p-value and trends significant at the 5 % level are highlighted in bold. Linear change rates and the type of change (i.e. increasing, positive values; decreasing, negative values) were estimated from the slope of a linear regression fitted to the data.

	Temperature (1965–2009)						Precipitation (1980–2009)			
Time period	MK trend test (p-value)			Linear change rate (°C decade^{-1})			MK trend test (p-value)		Linear change rate (mm decade^{-1})	
	min	mean	max	min	mean	max	max	total	max	total
Annual	**0.04**	<**0.01**	**0.04**	0.93	0.54	0.31	0.32	0.56	4.31	21.03
MAM	0.61	**0.01**	0.06	0.17	0.45	0.56				
JJA	0.52	**0.01**	**0.03**	0.13	0.28	0.31				
SON	**0.04**	<**0.01**	**0.02**	0.82	0.56	0.47				
DJF	<**0.01**	<**0.01**	**0.02**	1.74	0.82	0.43				

Table 3. Summary for Abiskojokk catchment of the Mann-Kendall (MK) trend test statistics for the 1913–2009 annual and seasonal precipitation and temperature data (upper table) and the 1965–2009 temperature and 1980–2009 precipitation data (lower table) to allow direct comparison to records from Tarfalajokk catchment. Trend significance of the MK trend test is indicated by the 2-sided p-value and trends significant at the 5 % level are highlighted in bold. Linear change rates and the type of change (i.e. increasing, positive values; decreasing, negative values) were estimated from the slope of a linear regression fitted to the data.

	Temperature Long-term trend (1913–2009)						Precipitation Long-term trend (1913–2009)			
Analysis period	MK trend test (2-sided p-value)			Linear change rate (°C decade^{-1})			MK trend test (2-sided p-value)		Linear change rate (mm decade^{-1})	
	min	mean	max	min	mean	max	max	total	max	total
Annual	0.87	**0.01**	**0.02**	0.02	0.09	−0.14	0.64	**0.01**	0.35	4.70
MAM	0.11	**0.01**	**0.02**	0.08	0.15	0.23	0.13	0.67	−0.17	0.07
JJA	<**0.01**	0.40	**0.02**	0.20	0.03	−0.13	0.38	0.21	0.49	1.80
SON	0.74	0.10	0.14	0.05	0.08	0.07	0.81	0.52	−0.02	0.94
DJF	0.27	0.37	0.36	0.19	0.08	0.04	0.15	0.06	0.22	1.70
	Longest overlapping time period (1965–2009)						Longest overlapping time period (1980–2009)			
Annual	0.13	<**0.01**	0.38	0.63	0.46	−0.16	0.87	0.95	0.16	−5.59
MAM	0.59	**0.01**	0.08	−0.16	0.47	0.55	0.63	0.45	0.46	3.22
JJA	**0.04**	**0.04**	0.38	−0.34	0.26	−0.16	0.83	0.94	0.25	−2.14
SON	0.23	<**0.01**	0.16	0.42	0.34	0.25	0.91	0.89	−0.91	0.36
DJF	**0.03**	**0.02**	0.28	1.18	0.76	0.24	**0.02**	0.15	−2.73	−10.37

Table 4. Summary of the Mann-Kendall (MK) trend test statistics of annual and seasonal temperature and precipitation trends for the common time period of 1985–2009 for the Tarfalajokk and Abiskojokk catchments. Trend significance of the MK trend test is indicated by the 2-sided p-value and trends significant at the 5 % level are highlighted in bold. Linear change rates and the type of change (i.e. increasing, positive values; decreasing, negative values) were estimated from the slope of a linear regression fitted to the data.

	Temperature						Precipitation			
	Tarfalajokk						Tarfalajokk			
Analysis period	MK trend test (2-sided p-value)			Linear change rate (°C decade^{-1})			MK trend test (2-sided p-value)		Linear change rate (mm decade^{-1})	
	min	mean	max	min	mean	max	max	total	max	total
Annual	0.18	<**0.01**	<**0.01**	1.60	0.96	1.16	0.29	0.91	5.76	4.72
MAM	0.16	0.28	0.43	1.34	0.63	0.57				
JJA	0.32	<**0.01**	<**0.01**	−0.42	0.72	1.16				
SON	0.82	0.15	<**0.01**	0.43	0.68	1.48				
DJF	0.06	<**0.01**	0.12	2.65	1.41	0.80				
	Abiskojokk						Abiskojokk			
Annual	0.47	<**0.01**	0.91	0.95	0.67	0.10	0.09	0.44	3.55	9.18
MAM	0.98	0.20	0.07	−0.94	0.65	0.99	0.70	0.76	0.56	1.65
JJA	0.10	**0.05**	0.90	0.61	0.52	0.10	0.15	0.09	4.02	18.75
SON	0.37	0.39	0.19	0.77	0.36	0.56	0.56	0.98	0.33	−1.37
DJF	0.48	0.69	0.09	1.34	0.52	0.83	0.35	0.47	−1.61	−13.51

Table 5. Results of nonstationarity test on selected percentiles (50th, 90th, 95th, 98th, and 99th) of the annual maximum discharge data of Tarfalajokk and Abiskojokk catchments. The percentiles were estimated by performing a moving window analysis with a 10-yr window. Nonstationarity was estimated at a significance level of 5 % by performing a trend analysis on the quantiles using a generalized least squares regression model. 2-sided p-values smaller than 0.05 and highlighted in bold indicate that the selected quantiles exhibited nonstationarity.

Annual Exceedance probability	Return period of flood (years)	Tarfalajokk		Abiskojokk	
		Long-term (1969–2009)	Common time period (1985–2009)	Long-term (1918–2009)	Common time period (1985–2009)
0.5	2	<**0.01**	<**0.01**	**0.02**	<**0.01**
0.1	10	<**0.01**	<**0.01**	**0.02**	<**0.01**
0.05	20	<**0.01**	<**0.01**	**0.01**	<**0.01**
0.02	50	<**0.01**	<**0.01**	<**0.01**	<**0.01**
0.01	100	<**0.01**	<**0.01**	<**0.01**	<**0.01**

Table 6. Frequency that occurrences of the annual 1-day maximum precipitation (MAP), the annual 3-day maximum total precipitation (3 day-MP), the 1-day mean air temperature (MAT), and the annual 3-day mean air temperature (3 day-MT) were coincident with the maximum annual flood event. *N* – number of years considered in the statistic.

	MAP	3 day-MP	MAT	3 day-MT	*N*
Tarfalajokk	59 %	56 %	19 %	19 %	27
Abiskojokk	18 %	21 %	25 %	20 %	61

Table 7. Correlations between seasonal (3-months averaged) and annual (12-months averaged) anomalies of climate teleconnection patterns and annual maximum flood peaks [log(flood)], flood occurrence day (DOY), and mean summer (JJA) discharge for Tarfalajokk and Abiskojokk catchments. Correlations that are significant at the 5 % significance level for a 2-sided test are highlighted in bold.

		TARFALAJOKK			ABISKOJOKK		
		log(Flood)	DOY	Mean JJA discharge	log(Flood)	DOY	Mean JJA discharge
DJF	NAO	−0.21	−0.05	−0.07	0.17	0.03	0.30
	EA	−0.23	−0.17	0.17	**−0.44**	−0.27	0.00
	EA/WR	−0.04	0.02	−0.18	−0.08	0.02	**0.39**
	SCAND	−0.04	0.18	−0.01	−0.31	0.08	**−0.49**
	POL	−0.07	0.19	−0.20	0.20	0.30	0.11
	AMO	0.37	−0.17	**0.58**	0.00	0.16	−0.32
MAM	NAO	−0.33	−0.26	−0.15	0.01	−0.10	0.24
	EA	0.22	0.05	0.21	−0.24	**−0.38**	−0.23
	EA/WR	0.25	−0.11	0.18	−0.04	−0.32	0.05
	SCAND	−0.37	−0.07	−0.21	−0.17	−0.05	−0.09
	POL	−0.09	0.13	−0.24	−0.14	−0.24	0.22
	AMO	0.39	0.16	**0.50**	0.08	0.13	−0.19
JJA	NAO	−0.15	0.05	−0.25	0.01	−0.24	0.08
	EA	0.16	−0.18	0.34	−0.34	−0.21	**−0.38**
	EA/WR	−0.23	−0.17	−0.29	−0.23	−0.23	−0.20
	SCAND	−0.38	0.12	−0.14	−0.04	−0.18	−0.08
	POL	−0.07	−0.29	−0.18	0.13	−0.19	0.04
	AMO	**0.54**	0.15	**0.59**	0.17	0.09	−0.22
Annual	NAO	−0.02	0.26	−0.05	0.15	0.17	**0.42**
	EA	0.22	−0.09	**0.41**	−0.18	−0.33	−0.19
	EA/WR	−0.30	−0.09	−0.20	−0.08	0.07	0.27
	SCAND	−0.29	−0.04	−0.18	−0.17	0.04	−0.18
	POL	−0.17	0.06	0.02	0.28	0.18	**0.35**
	AMO	**0.44**	−0.04	**0.66**	−0.09	0.06	−0.33

Table 8. Summary of trends observed in the two Swedish catchments: Tarfalajokk and Abiskojokk. Streamflow dynamics and flood events in northern landscapes are typically driven by either snowmelt (thermally driven) in the spring or the occurrence of precipitation events during the late summer and autumn. n.s. means the process did not exhibit a statistically significant trend at the 5 % level, although the trend was negative (decrease) for the Abiskojokk catchment (–).

Basin	Basin area	Glacier cover	Mean annual air temperature	Annual precipitation	Hydrologic extreme magnitude	Hydrologic extreme timing	Summer discharge	Hydrologic effect
Tarfalajokk	21.7 km^2	30 %	Increase	n.s.	Increase	n.s.	Increase	Amplified[c]
Abiskojokk	566 km^2	1 %	Increase	Increase[a], n.s.[b]	– n.s.	Decrease[a], –n.s.[b]	Decrease	Dampened[d]

[a] – for period 1913–2009.

[b] – for period 1985–2009.

[c] Increasing trend in the flood magnitudes and summer discharge.

[d] Decrease in the mean summer discharge and flood magnitudes and trend towards earlier flood occurrences.

Table 9. Implications of hydrometeorologic and hydrologic trends observed in the glaciated (30 %) Tarfalajokk and the nonglaciated (1 %) Abiskojokk catchment for the long-term hydrologic response of glaciated and nonglaciated catchments to climate warming.

	Tarfalajokk (30 % glacier cover)	Abiskojokk (1 % glacier cover)
Climatic trends	– Significant increase in mean air temperature – No significant trend in the precipitation depths	– Significant increase in mean air temperature – No significant trend in the precipitation depths
Hydrologic trends	– Significant increase in the annual maximum discharge (floods) – Significant increase in the mean summer (JJA) discharge – Decrease (insignificant) in the day of flood occurrences	– Significant decrease in the mean summer discharge – Decrease (insignificant) in the annual maximum discharge (floods) and the day of occurrence of the annual maximum discharge event (floods)
Implications	– Amplified hydrologic response – Catchment is more efficient in transmitting water to outlet – Increase in mean summer discharge and glacial melt water contributions due to increase in mean air temperature – Increase in flood magnitudes due to increase in glacier melt and extreme precipitation (depths) in conjunction with high-gradient topography and limited soil storage – Reduction in snow cover (amount and duration) will potentially lead to greater glacier melt if glacier ice is exposed for longer periods	– Dampened hydrologic response – Increase in mean soil depth, soil water storage capacity and permafrost thaw due to increase in air temperature – Decrease/dampening of mean summer discharge and hydrologic extremes (floods) due to increased soil storage capacity – Earlier occurrence of flood events and spring snowmelt peaks due to increase in air temperature – Reduction in snow cover (amount and duration) will potentially lead to smaller spring snowmelt peaks and longer dry-flow periods during summer period

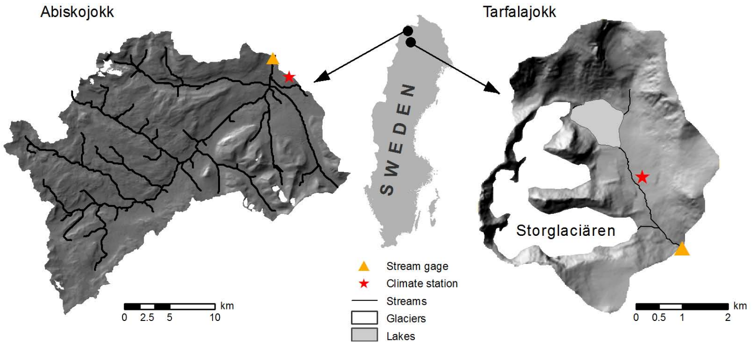

Fig. 1. Site map showing the Abiskojokk and Tarfalajokk catchments in northern Sweden. Triangles and stars indicate locations of stream gages and rain gages respectively.

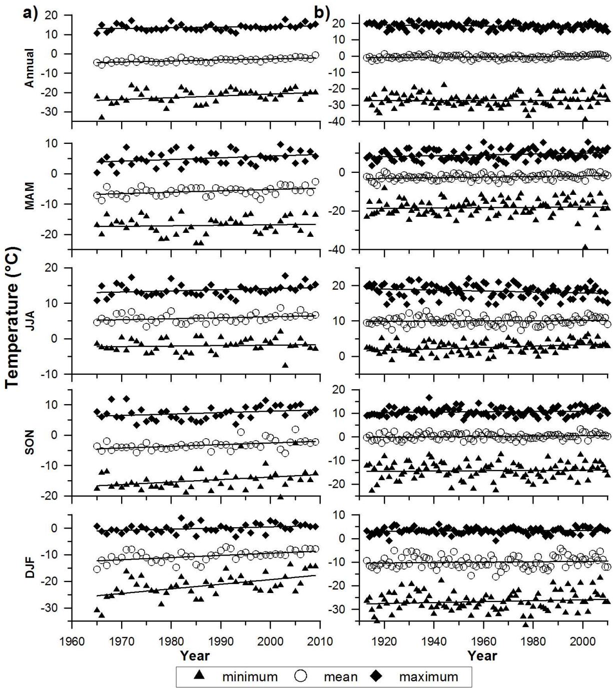

Fig. 2. Time series of annual and seasonal air temperatures (˚C) for **(a)** Tarfalajokk and **(b)** Abiskojokk catchments. The maximum, mean and minimum annual and seasonal temperatures are indicated by a filled diamond, open circle and filled triangle respectively. Black lines indicate linear regressions versus time. Linear change rates and MK trend statistics are presented in Tables 2 and 3.

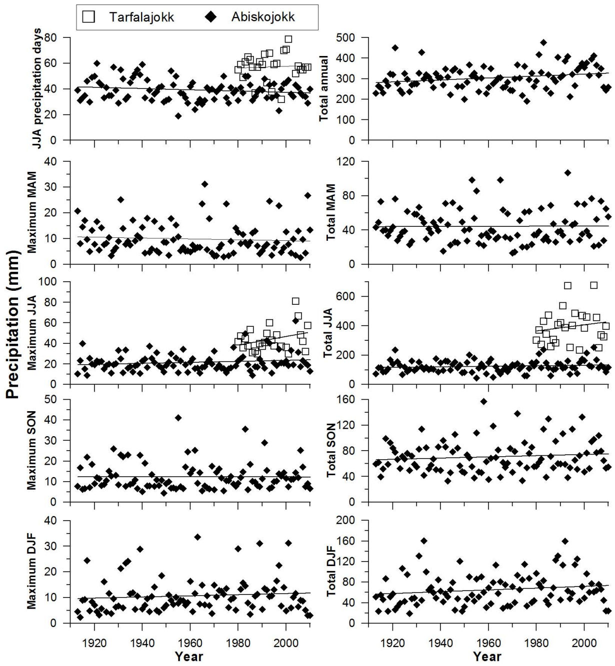

Fig. 3. Time series of annual and seasonal maximum and total precipitation amounts (mm) for Tarfalajokk (open squares) and Abiskojokk (filled diamonds) catchment. The top left graph shows the number of days with precipitation for the summer (JJA) season. Black lines indicate linear regressions versus time. Linear change rates and MK trend statistics for the long-term record periods and common time windows are presented in Tables 2 and 3.

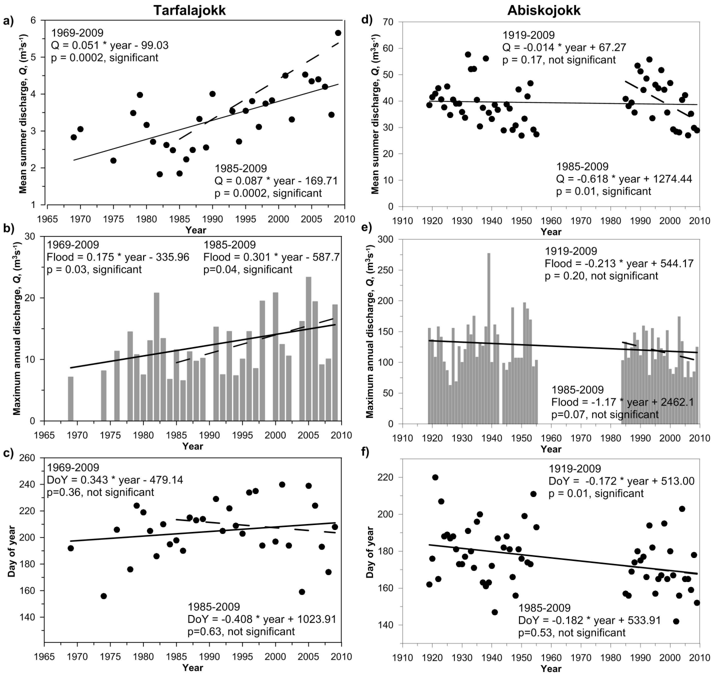

Fig. 4. Statistical characteristics of the Tarfalajokk and Abiskojokk discharge. (**a**, **d**) Time series of mean summer (JJA) discharge; (**b**, **e**) time series of the annual maximum discharge (floods); and (**c**, **f**) time series of the flood occurrence date of annual maximum flood events in Tarfalajokk and Abiskojokk catchment respectively. The solid lines represent linear trends over the full record period in each catchment. The dashed lines represent linear trends for the common time period 1985–2009 for which discharge records were available in both catchments.

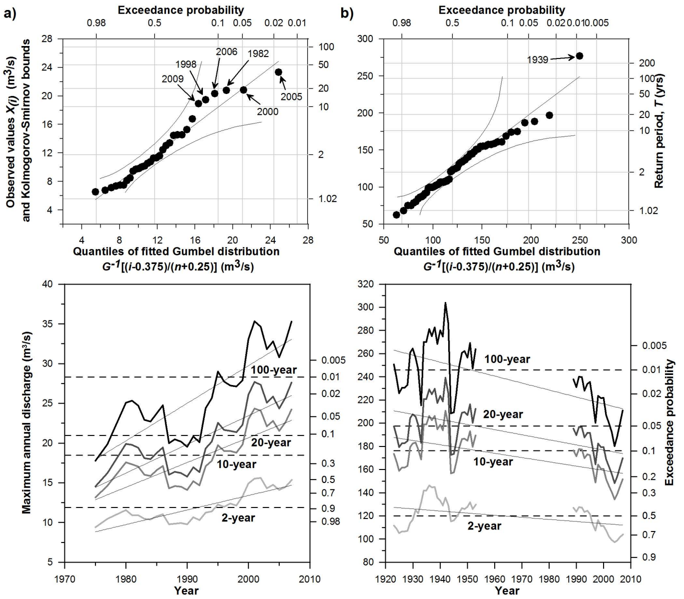

Fig. 5. Top graphs: plots of annual maximum discharge for **(a)** Tarfalajokk and **(b)** Abiskojokk catchments versus quantiles of fitted Gumbel distribution. Bottom graphs: trends in the 2-yr, 10-yr, 20-yr, and 100-yr return periods (50th, 90th, 95th, and 99th percentile) of the annual maximum flood for the **(a)** Tarfalajokk and **(b)** Abiskojokk catchments. Flood records were tested for stationarity by performing a moving window analysis with a 10-yr moving window and the Mann-Kendall trend test with a significance level of 5 %. The solid lines indicate linear trends in the flood records. Dashed lines represent the percentiles estimated from the full record. Trends and variability in the flood percentiles reflect changes in the underlying probability distribution as a response to decadal and interannual climate forcings (i.e. NAO) and changes in the hydrological system properties.

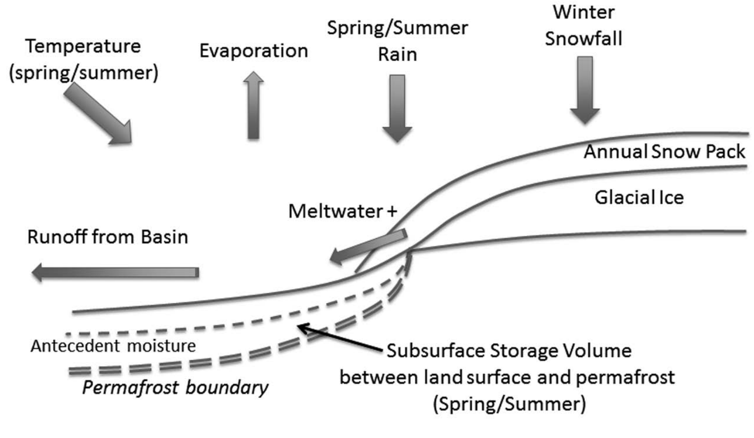

Fig. 6. Dominant hydrometeorologic and hydrologic processes affecting the annual discharge and generation of extreme flood peaks in the Tarfalajokk and Abiskojokk catchments.