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Authors
Matti, Bettina
Dahlke, Helen E
Lyon, Steve W

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On the variability of cold region flooding

Bettina Matti [a,b], Helen E. Dahlke [c], Steve W. Lyon [a,d,*]

[a] Department of Physical Geography, Stockholm University, 106 91 Stockholm, Sweden
[b] Centre for Agroecology, Water and Resilience, Coventry University, Coventry CV1 5FB, UK
[c] Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA
[d] Bolin Centre for Climate Research, Stockholm University, 106 91 Stockholm, Sweden

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SUMMARY

Cold region hydrological systems exhibit complex interactions with both climate and the cryosphere. Improving knowledge on that complexity is essential to determine drivers of extreme events and to predict changes under altered climate conditions. This is particularly true for cold region flooding where independent shifts in both precipitation and temperature can have significant influence on high flows. This study explores changes in the magnitude and the timing of streamflow in 18 Swedish Sub-Arctic catchments over their full record periods available and a common period (1990–2013). The Mann–Kendall trend test was used to estimate changes in several hydrological signatures (e.g. annual maximum daily flow, mean summer flow, snowmelt onset). Further, trends in the flood frequency were determined by fitting an extreme value type I (Gumbel) distribution to test selected flood percentiles for stationarity using a generalized least squares regression approach.

Results highlight shifts from snowmelt-dominated to rainfall-dominated flow regimes with all significant trends (at the 5% significance level) pointing toward (1) lower magnitudes in the spring flood; (2) earlier flood occurrence; (3) earlier snowmelt onset; and (4) decreasing mean summer flows. Decreasing trends in flood magnitude and mean summer flows suggest widespread permafrost thawing and are supported by increasing trends in annual minimum daily flows. Trends in selected flood percentiles showed an increase in extreme events over the full periods of record (significant for only four catchments), while trends were variable over the common period of data among the catchments. An uncertainty analysis emphasizes that the observed trends are highly sensitive to the period of record considered. As such, no clear overall regional hydrological response pattern could be determined suggesting that catchment response to regionally consistent changes in climatic drivers is strongly influenced by their physical characteristics.

1. Introduction

Cold environments are complex in that their hydrological systems interact with both climate variables and the cryosphere. Our understanding of drivers and effects of climate change on these systems is still limited, especially in terms of extreme events related to water resources such as floods and droughts. For flood extremes, this is worrisome as northern landscapes become more densely populated calling for risk mitigation and management strategies that can remain viable under a changing climate. Because there is growing concern about increased frequency and severity of extremes, the understanding of hydrological functioning and responses in cold regions is needed (Kundzewicz et al., 2014).

Recent studies have shown that flood extremes are shifting due to climate change but that changes vary with location (e.g. Burn et al., 2010; Wilson et al., 2010; Hall et al., 2014; Kundzewicz et al., 2014). Across Canada, for example, trends toward decreasing flood magnitudes and earlier flood occurrences have been detected for snowmelt-dominated catchments (Cunderlik and Ouarda, 2009; Burn et al., 2010). An ongoing shift in flow regime from snowmelt-dominated to rainfall-dominated coupled to the development of a bi-modal flow regime with two peaks in the annual hydrograph (one in late spring due to snowmelt and one in late summer due to rainfall events) has been found both in North America and northern Europe (Cunderlik and Ouarda, 2009; Dahlke et al., 2014). With regards to the magnitude and the occurrence of floods, variable spatial and temporal patterns have been

* Corresponding author at: Department of Physical Geography, Stockholm University, SE – 106 91 Stockholm, Sweden. Tel.: +46 (0)8 16 4888.

E-mail addresses: mattib@uni.coventry.ac.uk (B. Matti), hdahlke@ucdavis.edu (H.E. Dahlke), steve.lyon@natgeo.su.se (S.W. Lyon).

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detected for northern Europe (Wilson et al., 2010; Dahlke et al., 2012; Hall et al., 2014). Wilson et al. (2010) and Fleming and Dahlke (2014) showed that trends in annual and seasonal streamflow as well as changes in extreme events can be linked to precipitation and temperature trends, whereas the signal induced by temperature seems to be more clearly reflected in streamflow series. Consistent with this, increasing trends in minimum flows have been observed across much of northern Sweden emphasizing the importance of the cryosphere on hydrological system's response (e.g. Dahlke et al., 2012; Sjöberg et al., 2013).

Concurrent with these changes, climate in northern Sweden has changed over the 19th century. Mean annual air temperature has increased in general and, over the last century, fluctuations have been present (van der Velde et al., 2013). Increasing air temperatures have been measured in northern Sweden at the beginning of the 20th century until the early 1940s, followed by a decrease until the 1970s and an increase ever since to values higher than in the 1930s (Lindström and Alexandersson, 2004; Callaghan et al., 2010). The increase in air temperature is most pronounced in winter, whereas the temperature in summer did not rise significantly (Callaghan et al., 2013). Increasing extreme winter temperatures have been detected leading to enhanced snowmelt during winter and trends toward earlier snowmelt (Callaghan et al., 2010, 2013; Wilson et al., 2010; Hannaford et al., 2013). Mean annual and summer precipitation along with the variability of extreme precipitation events have constantly increased over the last century in northern Sweden (Lindström and Alexandersson, 2004; Callaghan et al., 2010). Enhanced winter precipitation, which mainly falls as snow, has been reported in the late 1980s and 1990s, whereas snow depth increased until the 1980s, but has since then decreased (Lindström and Bergström, 2004; Holmlund et al., 2005; Callaghan et al., 2013). Similarly, snow duration decreased significantly over the last century (Callaghan et al., 2013; Arheimer and Lindström, 2015).

Due to the complexity of cold region hydrological systems, however, a catchment's response can vary depending not only on climate forcing but also on catchment properties. As shown by previous studies, a region with a uniform climatic input can develop different streamflow responses depending on the state and the distribution of permafrost, storage capacity, glacial coverage, soil properties and a catchment's geomorphology and elevation (e.g. Birsan et al., 2005; Carey et al., 2010; Lyon et al., 2010; Walvoord et al., 2012; Tetzlaff et al., 2015). The cryosphere in general and permafrost in particular have significant impact on streamflow in cold environments by buffering the hydrograph through enhanced subsurface flow causing an increase in winter base flow and a decrease in spring flood magnitude (Dahlke et al., 2012; Walvoord et al., 2012; Sjöberg et al., 2013). The discontinuous permafrost zone is particularly important for a catchment's streamflow response due to the significant ice content in the ground, which influences infiltration and transit times (Lyon et al., 2010; Tetzlaff et al., 2015). Furthermore, snow is a significant feature of cold regions, where snow depth as well as snow duration play a crucial role for different hydrological signatures such as timing and magnitude of the spring flood, but also onset of snowmelt (e.g. Burn et al., 2010). Since these characteristics can differ on a local scale, variable streamflow responses on catchment scales can develop (e.g. Dahlke et al., 2012; Fleming and Dahlke, 2014).

Owing to the complexity of cold environments, a better understanding of the hydrology in sub-arctic catchments is needed. Decadal scale variability caused by atmospheric circulation such as the North Atlantic Oscillation brings about the need for long-term trend analysis to detect actual trends instead of natural variability in the system (Hannaford et al., 2013). This study focuses on examining trends and responsible mechanisms in the generation of high flow extremes (floods) in cold environments and their interactions with climate. Following the methodology in Dahlke et al. (2012) an emphasis is placed on changes in high flow extremes with consideration of trends and patterns across a range of flow characteristics. The goal of this study is to determine whether there are consistent regional patterns of change in streamflow records across the Swedish Sub-Arctic. This is accomplished by investigating 18 sub-arctic catchments in northern Sweden for changes in their hydrology. The consistency (or lack thereof) in spatial patterns of flooding has the potential to yield information about the evolution of hydrological responses across cold regions in general and northern Sweden specifically.

2. Methods

2.1. Study area

This study explored changes in 18 unregulated catchments located in the Swedish Sub-Arctic at latitudes ranging from 65 to 69°N (Fig. 1). The catchments considered have an area ranging from 100 to 10,000 km^2 and a mean elevation of 720 m a.s.l. (Table 1). Northern Sweden is characterized by the Scandinavian mountain range in the west and the Baltic Sea in the east. The Scandinavian mountain range denotes the border to Norway and has elevations up to about 2100 m a.s.l. in Sweden. The catchments considered all drain toward the Baltic Sea with the Scandinavian mountain range functioning as the regional water divide.

The glacial coverage in each of the catchments was estimated to be less than 2% of the catchments area (SMHI, 2013) and therefore not considered further in this study. The catchments are located in the continuous, discontinuous, sporadic or isolated permafrost zone, depending on latitude and elevation (Christiansen et al., 2010). The vegetation in the Swedish Sub-Arctic is mainly characterized by birch forests, tall shrubs, meadow, heath, and wetlands (Callaghan et al., 2013). These vegetation compositions are changing due to increasing air and soil temperatures and the thawing of permafrost resulting in an increase in tall shrubs and wetland graminoid vegetation (Callaghan et al., 2010). Northern Sweden is characterized by a cold and humid climate. The catchments considered have a mean annual air temperature between 0 and −8 °C with the lower values at higher elevations and latitudes. Above-average mean annual air temperatures have been reported in northern Sweden over the last decade (0.2–2.8 °C higher than multi-annual average 1961–1990) (SMHI, 2014a). Precipitation varies on an east–west gradient with annual values up to 2000 mm/year in the west (mountainous areas) and 500 to 700 mm/year in the east. Over the last decade, mean annual precipitation values varied year to year with ranges from 80% to 170% compared to the multi-annual average 1961–1990 depending on year and location (SMHI, 2014b). Years with above-average mean annual precipitation were in the majority.

Streamflow in northern Sweden is mainly snowmelt-dominated, with peak streamflow occurring in late spring and summer (May to July) when about half the annual streamflow occurs (Lindström and Bergström, 2004). The spring flood is approximately double the volume of the autumn flood caused by rainfall events (Arheimer and Lindström, 2015). Streamflow in northern Sweden can vary substantially at decadal scales as indicated by both the dry period in the 1970s and the wet period starting in the mid-1990s. Further, a higher than average increase in extreme values was reported over the entire 20th century starting in the 1990s with large floods both in 1995 and 2000 (Lindström and Bergström, 2004). Especially the flood in 1995 caused by enhanced winter precipitation was remarkable in northern Sweden, since it occurred in most catchments across the region (Lindström and Bergström, 2004; Holmlund et al., 2005). A loss in lake ice and a decrease in ice duration were reported over the

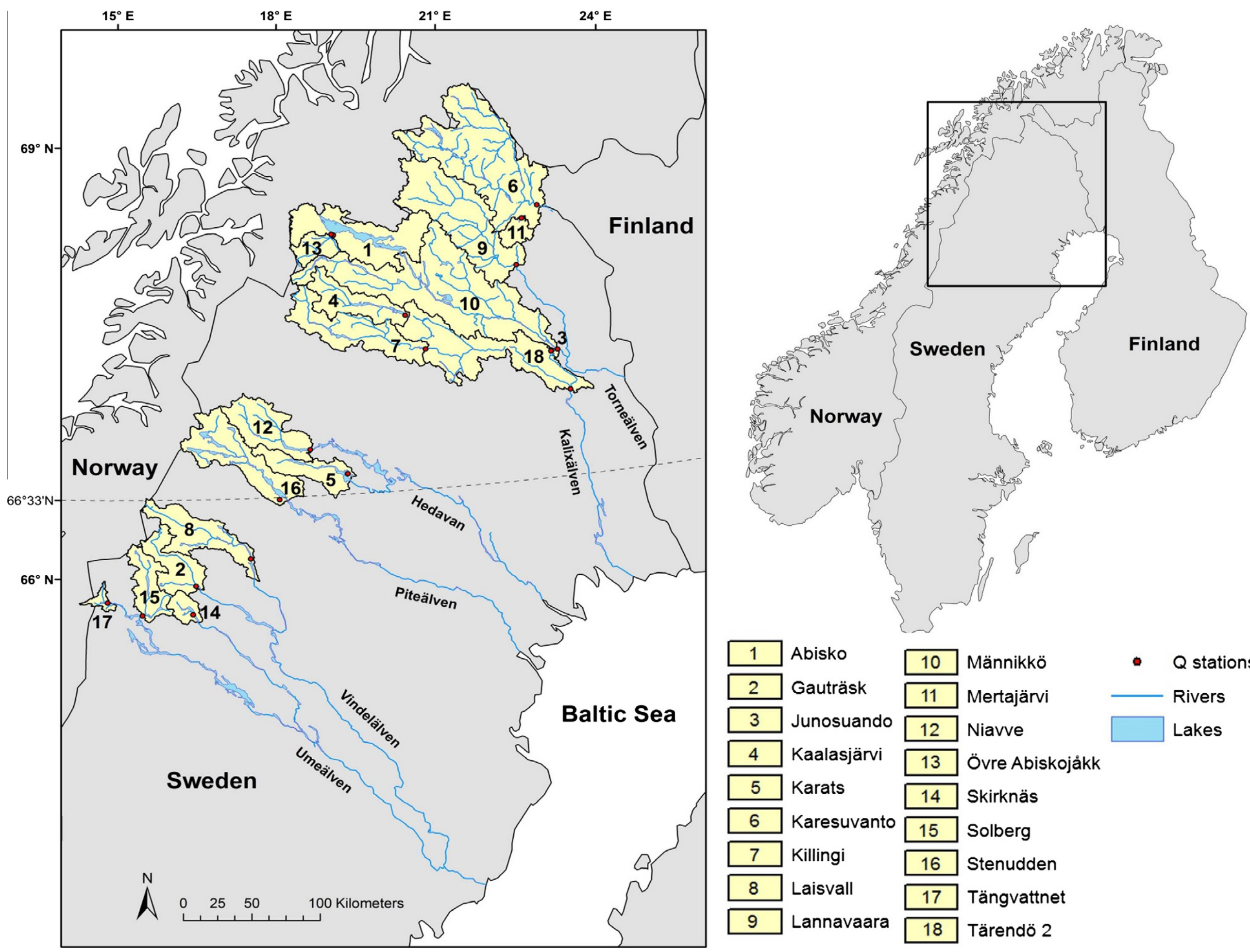

Fig. 1. Map over northern Sweden showing the location of the catchments considered.

last century, which affects air temperature, vegetation and streamflow (Lindström and Bergström, 2004; Callaghan et al., 2013). Lake ice and especially ice jamming have an influence on the snowmelt flood in spring (Lindström and Bergström, 2004).

2.2. Data and trend statistics

Daily streamflow time series of at least 24 years (1990–2013) of continuous measurements were acquired from the Swedish Meteorological and Hydrological Institute (SMHI, 2013). The total length of record available for all catchments varies between 24 and 103 years (Table 1) and corresponds to the full period of record of the time series considered. Time series were tested for trends using the non-parametric, rank-based Mann–Kendall trend test (Douglas et al., 2000; Helsel and Hirsch, 2002; Yue et al., 2002). Based on the assumption that the time series does not show serial correlation this test determines whether a time series shows a significant trend without specifying whether this trend is monotonic or linear (Helsel and Hirsch, 2002; Clarke, 2013). Time series were tested for serial correlation by applying the Durbin–Watson test prior to the Mann–Kendall trend test to avoid false detections of trends (Durbin and Watson, 1950, 1951; Burn and Hag Elnur, 2002; Helsel and Hirsch, 2002).

Similar to Dahlke et al. (2012) we considered the following hydrological parameters: annual maximum daily streamflow, which represents the flood magnitude, and the date of the annual maximum daily streamflow, which represents the flood occurrence. Further, annual minimum daily flow, mean summer flow (June to August), date of the snowmelt onset and date of the center of mass were assessed. Parameters associated with a date are referred to by the day of the year (DOY). Snowmelt onset was determined using the algorithm for "spring pulse" onset of streamflow developed by Cayan et al. (2001), which is a characterization of the shape of the hydrograph. The flow regime of a catchment can be determined and shifts therein can be detected using snowmelt onset (Stewart et al., 2005). The center of mass indicates the day of the year, when the cumulative streamflow reached 50% of the total annual streamflow and is an indicator for the shape of the hydrograph and thus the timing of when the majority of flows occur within the year (Stewart et al., 2005). A shift in the flow regime can be detected calculating the center of mass, which made it a widely used indicator to relate snowmelt to climate variability and change (e.g. Stewart et al., 2005; Whitfield, 2013). Whitfield (2013) pointed out that the center of mass as indicator for changes in the timing of the snowmelt caused by a change in temperature is only useful for pronounced hydrological regimes such as those associated with snowmelt-dominated regimes. To detect evident changes in the actual melting both the approaches for snowmelt onset and center of mass should be addressed (Stewart et al., 2005). This highlights that a change only in spring pulse onset or center of mass does not compulsory show a change in the flow regime caused by a change in temperature. Because the center of mass approach is sensitive to minimum flows and precipitation during winter it is more likely to indicate variations in the annual streamflow instead of a change in the timing of streamflow (Whitfield, 2013).

Table 1
Properties for the catchments considered in this study. The length of the record period represents the full period of record available for each catchment; whereas the numbers in brackets represent the number of years with actual data (years with missing data are subtracted). The last year considered for all catchments is 2013.

Name	SMHI gauge ID	Area (km^2)	Mean elevation (m a.s.l.)	Elevation range (m a.s.l.)	Start year of the record	Length of the record period (years)
Abisko	2357	3384	702	332–1782	1985	29
Gauträsk	1630	1177	842	391–1499	1954	60 (50)
Junosuando	4	10,248	580	205–1975	1968	46
Kaalasjärvi	1456	1426	871	446–2081	1947	67 (56)
Karats	1403	978	650	404–1538	1942	72
Karesuvanto	10,006	3082	560	316–1505	1972	42
Killingi	2159	2351	795	473–2074	1976	38
Laisvall	2414	1534	825	429–1595	1990	24
Lannavaara	5	3865	584	336–1346	1923	90 (60)
Männikkö	11	10,038	551	207–1975	1915	98 (78)
Mertajärvi	1780	349	415	342–703	1960	54
Niavve	591	1577	866	300–1991	1925	89
Övre Abiskojåkk	957	969	969	340–1782	1986	28
Skirknäs	2275	317	777	483–1243	1981	33
Solberg	436	1079	783	455–1746	1911	103
Stenudden	37	2423	792	433–1862	1916	98
Tängvattnet	1673	100	774	472–1365	1958	56
Tärendö 2	2358	7452	609	148–2086	1985	29

The Mann–Kendall trend test was performed for all catchments for (i) a common period ranging from 1990 to 2013 and (ii) the full period of record available for each catchment using a 95% confidence interval (2-sided). To allow for direct comparison between the catchments, approximate rates of change per decade were assessed by fitting linear regressions to the data series.

2.3. Flood frequency analysis

To assess flood frequency, an extreme value type I distribution (Gumbel distribution) was fit to all annual flood peaks for the catchments using the method of moments (Vogel, 1986; Stedinger et al., 1993; Loucks et al., 2005). The Gumbel distribution has the cumulative distribution function

$$F_X(x) = \exp\left\{-\exp\left[-\frac{(x-\xi)}{\alpha}\right]\right\} \tag{1}$$

where X is a random variable, x is a possible value of X, ξ is the location parameter calculated using $\mu_X = \xi + 0.5772\alpha$ and α is the scale parameter calculated using $\sigma_X^2 = \pi^2\alpha^2/6$, where μ_X is the mean and σ_X^2 the variance of the data set (Gumbel, 1941, 1954; Loucks et al., 2005). The Gumbel distribution fitting to all annual flood peaks was done for each catchment over the full periods of record available. Model adequacy of the fitted Gumbel distribution was tested applying the Kolmogorov–Smirnov test for goodness-of-fit at the 95% confidence interval, which provides bounds within all observations should fall (Smirnov, 1948; Chowdhury et al., 1991). The goodness-of-fit was further tested by applying Filliben's Probability Plot Correlation Coefficient (PPCC) test at a significance level of 5%, which assesses the correlation between the ordered observations and the corresponding fitted quantiles of the distribution, a measure of the linearity of the probability plot (Filliben, 1975; Chowdhury et al., 1991).

To explore changes in the flood percentiles over the full record periods, selected flood percentiles were tested for stationarity using 10-yr moving windows. The 50th, 90th, 95th, 98th and 99th percentiles were selected, which correspond to a flood with a return period of 2, 10, 20, 50 and 100 years, respectively. For each window, a Gumbel distribution was fit to all flood peaks within the 10-yr window and the goodness-of-fit of the fitted distribution was likewise tested using the PPCC test. Trends in each flood percentiles over time were estimated by fitting a generalized least squares (GLS) regression model using a maximum likelihood estimator (Fox and Hartnagel, 1979). Serial autocorrelation in the time series was determined applying the Durbin–Watson test (Table 2), which quantifies the serial autocorrelation based on the residuals of the regression model (Fox, 2002). An autoregressive moving average model (ARMA(2,0) structure) was fit to the errors in the residuals of the GLS model to account for autocorrelation in the residuals of the moving windows. The ARMA(2,0) structure specifies that only a second order autoregression process was fit to the data. The order of the AR process was determined using the autocorrelation function (ACF) and the partial autocorrelation function. A sinusoidal decay in the partial ACF with a positive first and a negative second spike, as detected for the time series, is indicative for an AR(2) process (Fox, 2002). Likewise, a 95% confidence interval was applied.

3. Results

3.1. Trends in hydrological signatures

Linear rates of change per decade were determined for selected hydrological parameters (Table 3). For the flood magnitudes only one catchment (Stenudden, $p = 0.02$, Fig. 2a) showed a significant (decreasing) trend over its full record period. Across all catchments, linear rates of change ranged from −7.4% to +4.3% per decade over the full periods of record, and −10.4% to +12.4% over the common data period of 1990 to 2013, whereby no significant trends were detected. It is interesting that most of the catchments showed one or more of their largest magnitude floods in the recent two decades (years 1995, 2004, 2005, 2012), which is consistent with previous work (e.g. Lindström and Bergström, 2004). The Stenudden and Gauträsk catchments (Fig. 2) demonstrated signs of the large flood in 1995 which was experienced by nine of the catchments. These catchments are all located in the south of the study area or characterized by an above-average mean elevation. The long record period of the Stenudden catchment further showed high flows in the 1920s, whereas the Gauträsk catchment showed an increasing but not significant trend ($p = 0.32$) with remarkable high flows in the years 1995, 2005, 2010 and 2013.

Over the full periods of record, the flood occurrence showed a significant decreasing trend representing an earlier occurrence for two catchments (Laisvall, $p = 0.03$ and Solberg, $p = 0.04$). The median date of the annual flood was June 12 (DOY = 163) and June 5 (DOY = 156) for the Laisvall and the Solberg catchments, respectively. For almost all catchments non-significant decreasing trends were detected. Note, this excludes Abisko, $p = 0.96$ and Mertajärvi,

Table 2
Durbin-Watson test results (*d*-values) determining autocorrelation in the errors of the generalized least squares regression model.

	Full record periods available					Common period 1990–2013				
Return period (years)	2	10	20	50	100	2	10	20	50	100
Exceedance probability	0.5	0.1	0.05	0.02	0.01	0.5	0.1	0.05	0.02	0.01
Abisko	0.46	0.63	0.72	0.81	0.87	1.14	2.08	2.19	2.22	2.20
Gauträsk	1.06	0.56	0.50	0.46	0.44	1.39	2.04	2.02	1.98	1.95
Junosuando	0.44	0.46	0.46	0.47	0.47	1.52	1.47	1.30	1.16	1.10
Kaalasjärvi	0.81	0.52	0.47	0.43	0.41	1.69	2.13	2.08	2.01	1.97
Karats	0.27	0.31	0.32	0.32	0.32	1.97	1.34	1.29	1.25	1.24
Karesuvanto	0.36	0.64	0.76	0.87	0.93	1.03	0.91	0.85	0.80	0.77
Killingi	0.49	0.54	0.54	0.54	0.54	1.00	1.40	1.44	1.46	1.48
Laisvall	0.74	1.39	1.49	1.56	1.60	0.74	1.39	1.49	1.56	1.60
Lannavaara	0.24	0.50	0.58	0.65	0.68	0.96	0.73	0.67	0.63	0.60
Männikkö	0.30	0.28	0.30	0.33	0.34	1.38	1.46	1.24	1.07	0.99
Mertajärvi	0.62	0.77	0.76	0.74	0.73	0.66	1.25	1.51	1.78	1.94
Niavve	0.40	0.18	0.16	0.14	0.13	1.48	1.33	1.10	0.94	0.86
Övre Abiskojåkk	0.71	1.39	1.57	1.74	1.83	0.75	1.34	1.50	1.66	1.75
Skirknäs	0.55	0.34	0.33	0.33	0.33	1.36	1.23	1.19	1.16	1.14
Solberg	0.35	0.44	0.40	0.36	0.35	1.20	1.49	1.49	1.49	1.49
Stenudden	0.21	0.21	0.22	0.23	0.24	1.76	1.72	1.68	1.65	1.63
Tängvattnet	0.53	0.86	0.90	0.91	0.91	0.76	1.54	1.68	1.78	1.82
Tärendö 2	0.63	0.82	0.88	0.95	0.98	1.52	1.69	1.70	1.71	1.72

Table 3
Linear change rates of trends identified with the Mann–Kendall trend test over the full periods of record (left side) and the common period among the data (right side). Linear rates of change were determined by fitting a linear regression line to the data. Relative changes (%) are shown for flood magnitude (MAG), mean summer flows (SUF) and annual minimum flows (MIN). Changes in flood occurrence (OCC), snowmelt onset (SNO) and center of mass (COM) are in days. Trends computed with the Mann–Kendall trend test significant at a level of 5% are highlighted in bold. A negative linear rate of change corresponds to a decreasing trend and a positive rate of change corresponds to an increasing trend.

	Full record periods available						Common period 1990–2013					
	MAG (%)	OCC (days)	SUF (%)	SNO (days)	COM (days)	MIN (%)	MAG (%)	OCC (days)	SUF (%)	SNO (days)	COM (days)	MIN (%)
Abisko	−0.9	0.5	−1.5	−3.2	−0.7	−1.6	−8.5	−1.6	−9.9	**−5.5**	−0.3	0.1
Gauträsk	0.7	−1.2	0.3	**−1.4**	−0.6	**3.5**	3.1	−2.9	**−23.9**	−2.3	0.4	−6.1
Junosuando	1.7	−0.5	3.1	**−2.2**	1.3	3.2	7.3	−3.4	−8.4	−2.4	1.3	−15.2
Kaalasjärvi	0.8	−1.3	1.1	−0.8	0.1	**3.8**	−1.7	−4.3	−8.6	−1.3	1.9	6.7
Karats	−1.0	−0.5	−1.2	**−1.1**	0.2	0.5	−7.6	6.7	−6.6	−1.1	5.3	−2.0
Karesuvanto	−5.3	−1.8	−0.6	−0.2	1.4	−1.3	8.0	**−9.4**	**−18.3**	−0.8	1.5	−20.5
Killingi	−1.8	−0.3	0.3	−0.9	1.3	13.0	−0.8	−7.2	**−14.6**	−0.4	2.6	−15.4
Laisvall	−7.4	**−7.7**	**−22.5**	−1.6	<−0.1	−6.4	−7.4	**−7.7**	**−22.5**	−1.6	<−0.1	−6.4
Lannavaara	−2.0	−1.4	−1.8	−0.9	−0.3	**6.7**	12.4	−2.9	−13.2	−1.1	−0.3	6.9
Männikkö	−0.8	−1.7	0.2	**−0.9**	−0.5	**1.9**	4.0	−10.7	−10.0	0.8	1.5	0.4
Mertajärvi	−1.6	2.6	3.8	**−1.5**	−0.1	**10.0**	2.7	14.0	−6.7	−1.0	1.3	7.1
Niavve	−0.1	−1.1	−1.2	**−1.0**	−0.7	−1.8	−3.8	−7.2	**−14.7**	−0.9	1.3	2.1
Övre Abiskojåkk	0.5	−4.9	**−14.6**	**−4.8**	1.4	7.3	1.8	−7.6	**−20.8**	**−7.4**	0.5	−1.4
Skirknäs	−4.1	−0.4	−6.4	−2.2	−1.5	2.3	−9.5	−5.7	**−23.2**	−1.7	1.6	−11.1
Solberg	1.0	**−1.5**	−0.9	−0.6	−0.6	**5.9**	−3.5	−6.5	**−26.3**	−0.4	0.2	−25.1
Stenudden	**−2.5**	−0.4	−0.7	**−1.0**	**−0.8**	**7.7**	−10.4	**−9.8**	**−12.8**	−1.4	0.9	**−13.9**
Tängvattnet	1.5	−1.5	1.0	−1.4	−0.9	5.6	3.5	−4.2	**−23.7**	−2.3	1.3	−6.0
Tärendö 2	4.3	−0.4	−3.7	1.6	1.9	4.6	1.5	−7.4	−11.0	2.3	2.8	1.9

$p = 0.75$, where increasing trends were found. Catchments with a decreasing trend in flood occurrence showed rates of change varying from 0.3 to 7.7 days per decade, and 0.5 and 2.6 days per decade for the Abisko and Mertajärvi catchments, respectively. Considering all catchments, the median date of the annual flood was in June (DOY = 143–180) with ranges from the beginning of May (DOY = 120) to the beginning of October (DOY = 283). Over the common period, a significant (decreasing) trend in flood occurrence was detected for three catchments (Karesuvanto, $p = 0.03$, Laisvall, $p = 0.03$ and Stenudden, $p = 0.01$). Almost all catchments showed decreasing trends in flood occurrence (exceptions are the Karats, $p = 0.49$ and Mertajärvi catchments, $p = 0.84$), where linear rates of change were 1.6–10.6 days per decade. Linear rates of change of 6.7 and 14.0 days per decade were detected for the Karats and Mertajärvi catchments, respectively, which showed increasing trends in flood occurrence. The corresponding median flood occurrence dates were June 8 (DOY = 159) and May 25 (DOY = 145) for the Karats and the Mertajärvi catchments, respectively. Among all catchments the median annual flood occurrence date was in June (DOY = 145–182) and ranged from the beginning of May (DOY = 120) to the beginning of October (DOY = 283).

The results of the mean summer flow statistics showed the most consistent pattern with all catchments exhibiting decreasing trends (significant for ten catchments) over the common period. Linear rates of change ranged from 6.6% to 26.3% less mean summer flow per decade, whereas six catchments experienced a decrease in mean summer flow of more than 20% per decade. All these catchments are located in the south of the study area or a combination of small area (<1500 km^2) and above-average mean elevation. Two catchments (Laisvall, $p = 0.01$ and Övre Abiskojåkk, $p = 0.01$) further showed a significant decreasing trend in mean summer flow over the full periods of record. Linear rates of change over the full periods among all catchments ranged from a decrease in mean summer flow of 22.5% to an increase of 3.8%, whereas bigger changes in mean summer flow were detected for the catchments showing a decreasing trend.

The analysis on snowmelt onset dates resulted in decreasing trends for most of the catchments over the full record periods

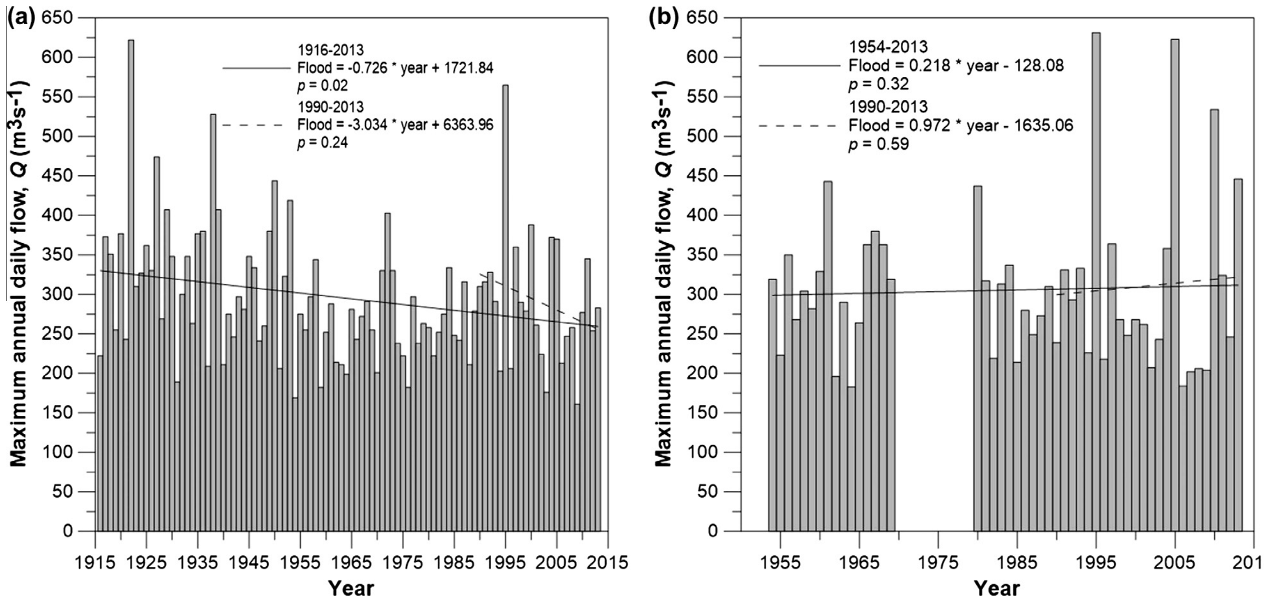

Fig. 2. Trend analysis on the annual maximum daily streamflow (m^3/s) for the (a) Stenudden and (b) Gauträsk catchments. The solid line represents the linear trend over the full periods of record, whereas the dashed line represents the linear trend over the common period 1990–2013. The *p*-value represents the 2-sided *p*-value computed with the Mann–Kendall trend test.

(exception Tärendö 2, $p = 0.56$), with significant trends for eight catchments. Linear rates of change per decade were 0.2–4.8 days for catchments with earlier onset of snowmelt (1.6 days later for Tärendö 2). Two catchments (Abisko, $p = 0.03$ and Övre Abiskojåkk, $p = 0.02$) showed a significant decreasing trend in the date of snowmelt onset over the common period. Decreasing trends were detected for almost all catchments (exceptions Männikkö, $p = 0.80$ and Tärendö 2, $p = 0.43$, which are located most eastwards). Linear rates of change varied from 0.4 to 7.4 days per decade for catchments with earlier snowmelt onset and 0.8 to 2.3 days per decade for positive trends.

For the hydrograph center of mass over the full periods of record, only one catchment (Stenudden, $p = 0.02$) showed a significant change toward an earlier center of mass. Linear rates of change varied from 0.005 to 1.5 days for catchments with negative trends and 0.1 to 1.9 days for catchments with positive trends. Over the common period of record, no significant trends were detected for the change in date of the center of mass. Linear rates of change were less than one day per decade for an earlier and 0.2–5.3 days per decade for a later center of mass.

Trends in annual minimum daily flows resulted in significant increasing trends for seven catchments over their full record periods, whereas no catchment showed a decreasing trend. At non-significant levels, both increasing and decreasing trends were detected. Linear rates of change ranged from −6.4% to +13.0% per decade. Over the common period of record, only the Stenudden catchment showed a significant (decreasing) trend in annual minimum daily flow with a linear rate of change of −13.9% per decade. Non-significant trends were ranging from −25.1% to +7.1% per decade.

3.2. Flood frequency analysis

The Gumbel distribution provided a good fit for all catchments (Fig. 3). The lowest value resulting from the PPCC test was $r = 0.959$ for the Skirknäs catchment, which is above the critical value assuming a significance level of 5% (Loucks et al., 2005). The test for stationarity of the selected flood percentiles using 10-yr moving windows also matched the Gumbel distributions fitted to each window well. The probability plot correlation coefficients estimated for each catchment and the 10-yr window were all above the critical value except for the Skirknäs catchment for which $r = 0.735$ in one occasion was considered as acceptable since the mean *r*-value over all 10-yr windows was $r = 0.914$ for this catchment.

When analyzing the stationarity of selected flood percentiles, four catchments showed a significant trend over the full periods of record (Table 4, Fig. 4). A significant increasing trend in the 10, 20, 50 and 100-yr flood percentiles was detected for the Gauträsk ($p < 0.01$), Kaalasjärvi ($p = 0.04$), Övre Abiskojåkk ($p < 0.04$) and Tängvattnet ($p < 0.01$) catchments (Fig. 4a and e). All these catchments are characterized by an area of less than 1500 km^2 and an above-average mean elevation. The Solberg catchment showed a significant increasing trend in the percentiles of the 10 and 20-yr floods ($p = 0.03$ and $p = 0.05$, respectively). There was a significant decreasing trend in the 2-yr flood percentile, which represents the median flow, for two catchments (Männikkö, $p = 0.05$ and Stenudden, $p = 0.02$). Among all catchments, there were both increasing and decreasing trends at non-significant levels in the flood percentiles.

For the common period 1990–2013, increasing trends for at least the 50-yr and the 100-yr flood percentiles were detected for three catchments (Gauträsk, $p < 0.04$, Övre Abiskojåkk, $p < 0.03$ and Tängvattnet, $p < 0.03$) (Fig. 4b and f). The Männikkö catchment showed a significant increasing trend for the 10 and the 20-yr flood percentiles ($p = 0.03$ and $p = 0.05$, respectively), whereas a significant increase only in the 10-yr flood percentile was detected for the Junosuando catchment ($p = 0.02$). Over the common period, three catchments showed a significant decreasing trend in the 10, 20, 50 and 100-yr flood percentiles (Abisko, $p < 0.01$, Kaalasjärvi, $p < 0.01$ and Stenudden, $p < 0.01$). A significant increasing trend in the 2, 10 and 20-yr flood percentiles was detected for the Karats catchment ($p = 0.01$, $p = 0.04$ and $p = 0.05$, respectively). Additionally, the Skirknäs catchment showed a significant decreasing trend in the 2-yr flood percentile ($p = 0.01$).

Considering the median flow, which is represented by the 2-yr flood, the results of the flood frequency analysis agree with the results of the trend analysis on the flood magnitude. The median flow showed both increasing and decreasing trends at non-significant levels, whereas all significant trends were decreasing,

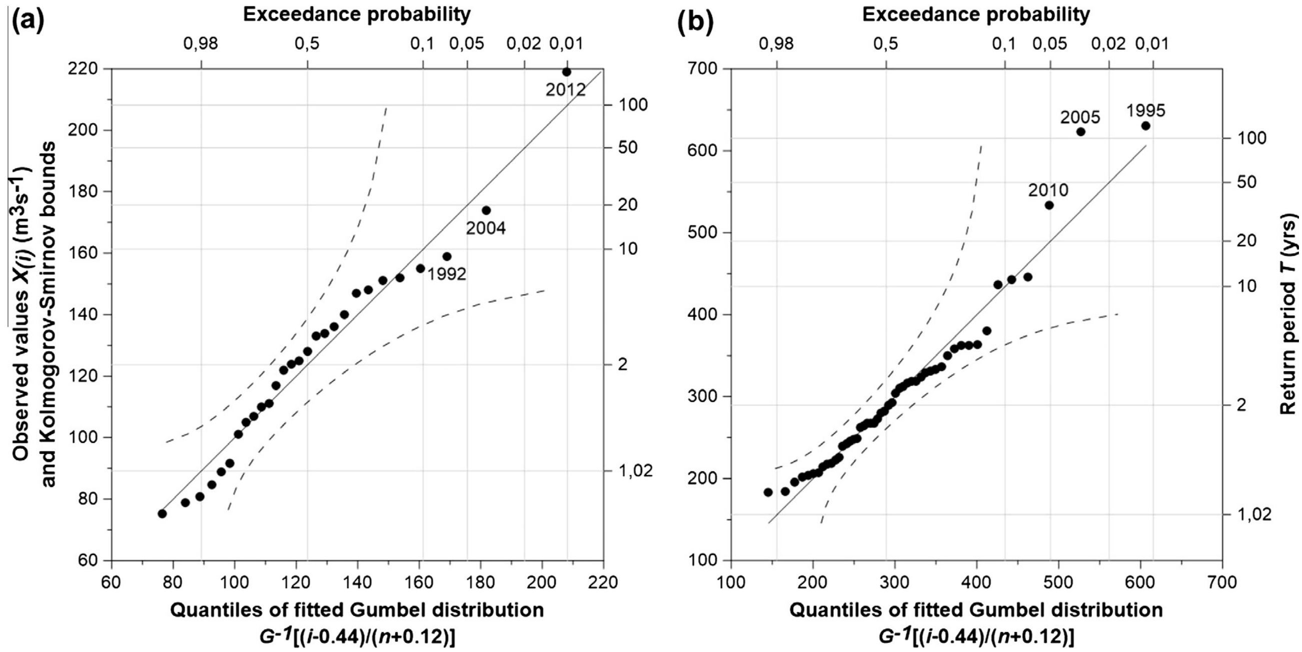

Fig. 3. Probability plots for (a) the Övre Abiskojåkk and (b) the Gauträsk catchments. Quantiles of the fitted Gumbel distribution using Gringorten's plotting position are plotted against the observed values $X_{(i)}$ (m^3/s) (Gringorten, 1963). The solid line represents the idealized Gumbel distribution and the dashed lines represent the Kolmogorov–Smirnov bounds at the 95% confidence level. Exceedance probabilities and return periods are plotted on the secondary *x* and *y*-axis, respectively. The three floods with the highest return periods are labeled.

indicating changes toward lower flows. The Stenudden catchment, the only catchment with a significant trend for the flood magnitude ($p = 0.02$, Fig. 2a), showed a significant decrease in the 2-yr flood over both the full record period and the common period ($p = 0.02$ and $p < 0.01$, respectively).

4. Discussion

4.1. Long-term changes in catchment hydrology

Our results reflect the complexity of the hydrological system and interactions with climate variables and the cryosphere. Previous studies have shown that catchments located within a region of similar climate forcing can exhibit heterogeneous streamflow responses suggesting that climate is not the only driver influencing a catchment's streamflow (e.g. Birsan et al., 2005; Carey et al., 2010; Dahlke et al., 2012; Fleming and Dahlke, 2014). This difference in streamflow variability or catchment response to uniform climate forcing can be caused by multiple variables such as snow duration, snow cover, and the state of permafrost affecting the processes that translate rainfall into runoff in these hydrological systems (e.g. Cayan et al., 2001; Stewart et al., 2005; Cunderlik and Ouarda, 2009; Walvoord et al., 2012). Whereas only a few catchments showed significant trends in the

Table 4
Test for stationarity of selected flood percentiles over both the full record periods (left side) and the common period (right side). A moving window analysis with 10-yr windows was computed and stationarity was tested by fitting a least squares regression model to selected flood percentiles. 2-sided *p*-values indicating stationarity are shown. Values significant at a 5% significance level are highlighted in bold. Increasing trends are indicated with a (+), whereas (−) represents decreasing trends. The selected flood percentiles are the 50th, 90th, 95th, 98th and 99th percentiles, which correspond to a flood with a return period of 2, 10, 20, 50 and 100 years respectively and an annual exceedance probability of 0.5, 0.1, 0.05, 0.02 and 0.01 respectively.

	Full record periods available					Common period 1990–2013				
Return period (years)	2	10	20	50	100	2	10	20	50	100
Exceedance probability	0.5	0.1	0.05	0.02	0.01	0.5	0.1	0.05	0.02	0.01
Abisko	0.90 (−)	0.85 (−)	0.81 (−)	0.76 (−)	0.74 (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)
Gauträsk	0.87 (−)	**0.01** (+)	**<0.01** (+)	**<0.01** (+)	**<0.01** (+)	0.95 (−)	0.09 (+)	**0.04** (+)	**0.02** (+)	**0.01** (+)
Junosuando	0.29 (+)	0.94 (+)	0.95 (+)	0.88 (+)	0.84 (+)	0.15 (+)	**0.02** (+)	0.06 (+)	0.10 (+)	0.12 (+)
Kaalasjärvi	0.44 (+)	**0.04** (+)	**0.04** (+)	**0.04** (+)	**0.04** (+)	0.07 (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)
Karats	0.23 (−)	0.98 (+)	0.91 (+)	0.82 (+)	0.78 (+)	**0.01** (−)	**0.04** (−)	**0.05** (−)	0.06 (−)	0.06 (−)
Karesuvanto	0.14 (−)	0.22 (−)	0.23 (−)	0.27 (−)	0.31 (−)	0.46 (+)	0.64 (+)	0.69 (+)	0.75 (+)	0.78 (+)
Killingi	0.18 (−)	0.33 (+)	0.19 (+)	0.12 (+)	0.12 (+)	0.58 (−)	0.65 (−)	0.65 (−)	0.66 (−)	0.67 (−)
Laisvall	0.60 (−)	0.15 (−)	0.13 (−)	0.12 (−)	0.12 (−)	0.55 (−)	0.15 (−)	0.13 (−)	0.12 (−)	0.12 (−)
Lannavaara	0.45 (+)	0.73 (+)	0.99 (−)	0.63 (−)	0.44 (−)	0.13 (+)	0.07 (+)	0.08 (+)	0.08 (+)	0.08 (+)
Männikkö	**0.05** (−)	0.48 (−)	0.63 (−)	0.71 (−)	0.74 (−)	0.75 (+)	**0.03** (+)	**0.05** (+)	0.07 (+)	0.08 (+)
Mertajärvi	0.33 (−)	0.08 (−)	0.10 (−)	0.14 (−)	0.16 (−)	0.54 (−)	0.58 (−)	0.73 (−)	0.97 (+)	0.69 (+)
Niavve	0.96 (−)	0.99 (+)	0.99 (+)	0.99 (−)	0.99 (−)	0.07 (−)	0.21 (−)	0.39 (−)	0.52 (−)	0.58 (−)
Övre Abiskojåkk	0.91 (+)	**0.04** (+)	**0.01** (+)	**<0.01** (+)	**<0.01** (+)	0.59 (+)	0.16 (+)	0.08 (+)	**0.03** (+)	**0.01** (+)
Skirknäs	0.13 (−)	0.62 (+)	0.52 (+)	0.44 (+)	0.41 (+)	**0.01** (−)	0.20 (−)	0.31 (−)	0.41 (−)	0.48 (−)
Solberg	0.19 (+)	**0.03** (+)	**0.05** (+)	0.06 (+)	0.08 (+)	0.20 (−)	0.10 (−)	0.11 (−)	0.11 (−)	0.12 (−)
Stenudden	**0.02** (−)	0.14 (−)	0.18 (−)	0.21 (−)	0.23 (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)	**<0.01** (−)
Tängvattnet	0.31 (+)	**<0.01** (+)	**<0.01** (+)	**<0.01** (+)	**<0.01** (+)	0.40 (+)	0.08 (+)	**0.03** (+)	**0.01** (+)	**<0.01** (+)
Tärendö 2	0.21 (+)	0.92 (+)	0.83 (−)	0.61 (−)	0.50 (−)	0.60 (−)	0.14 (−)	0.10 (−)	0.08 (−)	0.08 (−)

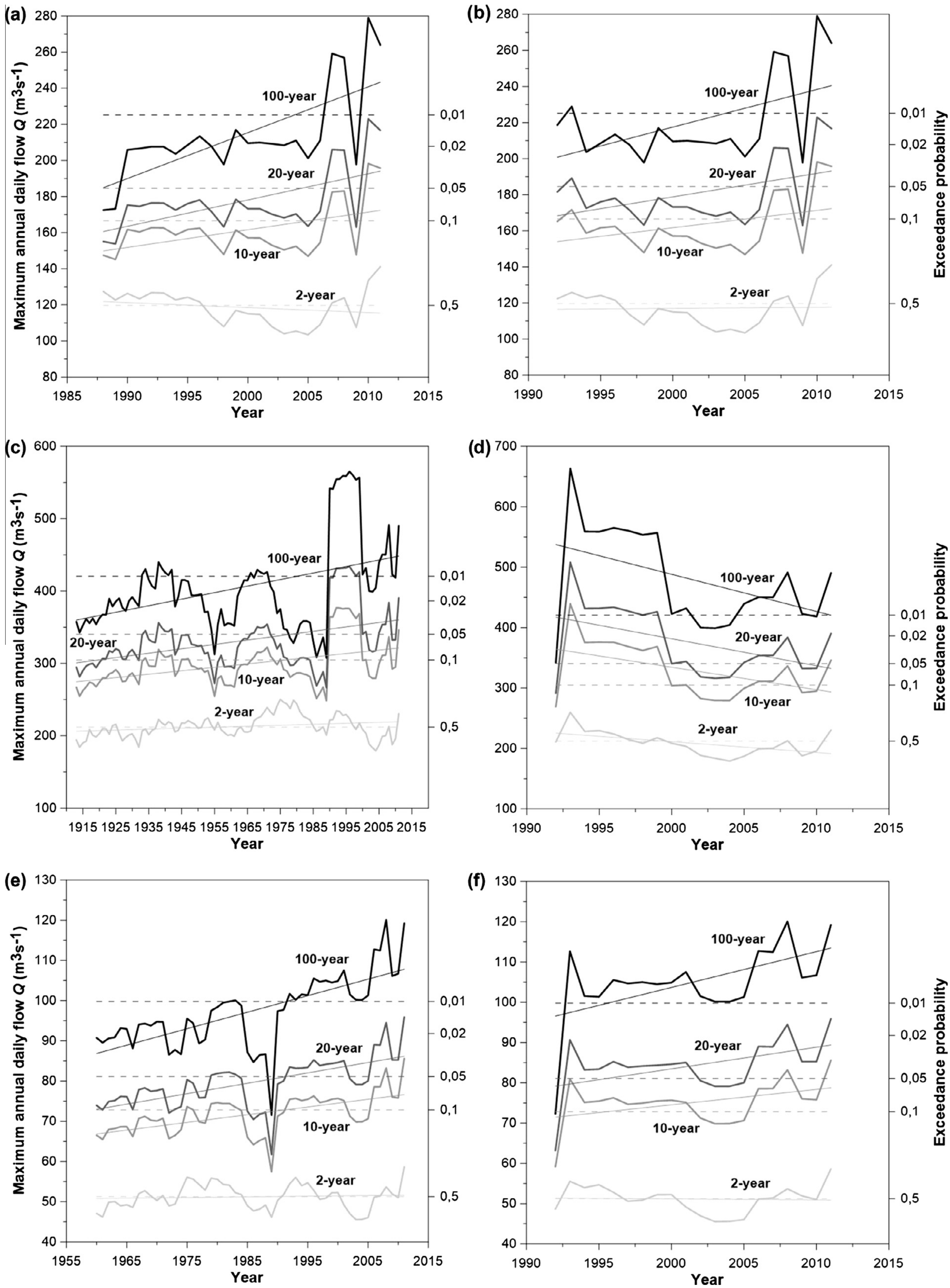

Fig. 4. Trends in the floods with a return period of 2, 10, 20 and 100 years (50th, 90th, 95th, 99th percentiles) over the full periods of record (left graphs) and the common period 1990–2013 (right graphs). Trends were estimated fitting a generalized least squares regression model using a 10-yr moving window. The solid lines represent the linear trends in the flood percentiles and the dashed lines represent the percentile estimates over the full periods of record. The Övre Abiskojåkk (a, b), Solberg (c, d) and Tängvattnet (e, f) catchments are shown as they exemplify the region.

streamflow parameters explored (Table 3), those showing significant trends exhibited consistent patterns across all 18 catchments. These patterns included a negative slope in the mean summer flows and earlier timings for snowmelt onset and center of mass. The diversity in trends, with only a few catchments exhibiting significant trends, is consistent with previous trend studies conducted in northern Europe, which detected high variability in trends at regional scales, indicating that there is considerable variability in the processes and first order controls that locally influence the hydrology in these catchments (Burn et al., 2010; Wilson et al., 2010; Hannaford et al., 2013; Hall et al., 2014).

Especially the loss of permafrost reported in recent years appears to have a significant influence on a catchment's hydrology by increasing the storage capacity and altering the shape of the hydrograph through enhanced winter flows (e.g. Callaghan et al., 2013; Sjöberg et al., 2013). Increasing trends in annual minimum daily flows, which are influenced by winter precipitation and the state of permafrost, were found for most catchments in this study and are consistent with findings by Sjöberg et al. (2013). Increasing trends for annual minimum daily flows and mean summer flows are consistent with permafrost-thaw-induced changes in streamflow. Numerous studies in the Swedish Sub-Arctic have shown an accelerated degradation of permafrost and a thickening of the active layer causing higher storage capacity and increasing subsurface flows due to enhanced thawing of ground ice creating new flow paths in the ground which dampen the hydrograph (e.g. Åkerman and Johansson, 2008; Dahlke et al., 2012; Callaghan et al., 2013; Sjöberg et al., 2013; Fleming and Dahlke, 2014).

Snow, in specific snow duration and snow depth, have further a profound influence on a catchment's flow characteristics in cold regions by affecting for example storage capacity, snowmelt onset and timing and magnitude of the snowmelt flood trough changes in the albedo and insulating effects on the ground (particularly in permafrost areas) (e.g. Stewart et al., 2005; Åkerman and Johansson, 2008; Andrews et al., 2011; Callaghan et al., 2013). Our results for trends in snowmelt onset are consistent with findings from other studies, which observed an earlier onset of snowmelt in North America, northern Europe and the Alps (e.g. Birsan et al., 2005; Stewart et al., 2005; Brabets and Walvoord, 2009; Callaghan et al., 2013). Likewise, a significant trend toward an earlier onset of snowmelt was found for eight catchments over their full periods of record (Table 3), which is consistent with increasing trends in precipitation and air temperature showing an accelerated increase in the winter season (Callaghan et al., 2013). Numerous studies computed in North America and northern Europe linked changes in the timing of snowmelt onset to the increase in winter precipitation and air temperature leading to enhanced snowmelt during winter (e.g. Birsan et al., 2005; Stewart et al., 2005; Cunderlik and Ouarda, 2009; Burn et al., 2010).

4.2. Changes in flood extremes and shift in flow regime

The absence of an overall pattern in flood magnitude and flood occurrence trends is consistent with previous studies on streamflow in northern Sweden, which likewise found inconsistent trends in these parameters. Such a lack of consistent patterns could be attributed, at least in part, to the increase in floods seen in recent years for some of the catchments influencing the slope of the trend (Wilson et al., 2010; Hannaford et al., 2013; Hall et al., 2014). Woo and Thorne (2008) concluded that changes in the flood magnitude are likely driven by winter precipitation whereas air temperatures during winter influence the flood occurrence. This is further corroborated by the fact that ice break up was occurring earlier in recent years due to increasing winter air temperatures and enhanced streamflow, which further alters the streamflow peak during snowmelt explaining the decreasing trends in flood magnitude (Woo and Thorne, 2008; Callaghan et al., 2013).

Significant, decreasing trends in flood magnitude, flood occurrence and onset of snowmelt (Table 3) suggest that Swedish Sub-Arctic catchments will likely experience a shift from the more pronounced snowmelt-dominated to a more dampened rainfall-dominated flow regime within the next decades, which agrees with modeling results across much of Sweden (e.g. Teutschbein et al., 2011; Arheimer and Lindström, 2015). With the snowmelt floods showing a decreasing trend and the increasing trend in autumn floods a bi-modal flood regime is likely to develop as detected in sub-arctic catchments in Canada (Cunderlik and Ouarda, 2009). Since the spring flood, caused by snowmelt, is approximately twice the autumn flood (caused by rainfall events) in northern Sweden a seasonal analysis would need to be applied on the annual maximum daily flows separating the floods in spring and autumn in order to explore trends in the seasons separately (Stahl et al., 2010; Arheimer and Lindström, 2015). This was however outside the scope of this current study but highlights a future potential line of research.

The hypothesis of a shift in flow regime is further strengthened by the contrasting trends found in the annual minimum daily flows and the annual maximum daily flows, both of which indicate dampening of the hydrograph and a shift in flow regime (Dahlke et al., 2012). While annual minimum daily flows are influenced by winter precipitation, annual maximum daily flows are driven by the snow accumulation during winter and subsequent spring snowmelt or by heavy rainfall events during summer and autumn (Cunderlik and Ouarda, 2009; Burn et al., 2010; Sjöberg et al., 2013; Hall et al., 2014).

4.3. The effect of record length on statistical results

Results from our study indicate that the total record length in general and particularly the starting and ending date potentially have a large impact on the outcomes of the trend analysis, which opens the need for more detailed investigation of long records and multi-temporal approaches, especially when linking streamflow to multi-decadal climate fluctuations caused by atmospheric circulations (Khaliq et al., 2009; Hannaford et al., 2013). For example, when analyzing the streamflow record of the Stenudden catchment, which offered one of the longest periods of record (starting in 1916), large variability in annual maximum daily flows was observed across decadal time scales. That catchment showed a wet period with high flood magnitudes in the 1920s and the 1990s, whereas in the 1950 and 1960s annual maximum daily flows were noticeably lower. That also translated into significant higher (lower) annual maximum daily flows during those periods as indicated by the higher flood magnitudes observed in 1995, 2004/2005 and 2011/2012/2013 for most of the catchments (Figs. 2 and 3). Similar inter-decadal variability in streamflow signatures was observed by Lindström and Bergström (2004), who analyzed 61 streamflow series throughout Sweden. In contrast to the Stenudden catchment, the Solberg catchment showed a significant increase in the flood percentiles (for the 10 and the 20-yr floods), although this catchment contained a long period of record starting in 1911. The trend arises from the absence of a large flood in the 1920s, whereas the flood in the year 1995 showed a return period of 180 years (calculated over the period 1911–2013) (Fig. 4c and d).

Such variability in flood magnitudes and mean annual flows have a profound influence on the trend statistics if the analyzed time series started or ended in a significantly drier or wetter period than the long-term average (Jones, 2011; Hannaford et al., 2013). For example, the remarkable flood of 1995 was likely the main reason why most catchments showed significant decreasing trends over the common period (1990–2013), including the Kaalasjärvi catchment, which showed a significant increasing trend in the flood percentiles over the full record period (1947–2013). For catchments that exhibited a decreasing trend over the common period the flood in 1995 was either the largest magnitude event or the only flood event in recent years. Catchments that showed an increasing trend over both the full record periods and the common period of record were characterized by at least one extreme flood in the years 2010–2013 causing the positive slope indicating an increase in extreme events.

This is especially true for the high-magnitude event happening in the Övre Abiskojåkk catchment in 2012. That particular event likely contributes to the explanation for the difference seen between our flood frequency analysis conducted for the Övre Abiskojåkk catchment and the findings presented by Dahlke et al. (2012) for the same catchment (Fig. 4a and b). While Dahlke et al. (2012) found significant decreasing trends ($p < 0.02$) in all flood percentiles (2, 10, 20, 50 and 100-yr floods) over the record period 1919–2009, increasing trends were detected in this study for the record period 1986–2013 ($p < 0.04$) in all flood percentiles except the 2-yr flood. Considering the record period investigated by Dahlke et al. (2012), their conclusions could be corroborated (data not shown). These contrasting trends obtained considering different record periods emphasize the importance of the record length to distinguish actual trends from natural variability in time series.

4.4. On the spatial similarity of observed changes

The few significant trends found in this study highlight the importance of physical catchment properties on the generation of runoff. When analyzing the spatial distribution of catchments with significant trends in extreme events over the full periods of record (Gauträsk, Kaalasjärvi, Övre Abiskojåkk, Tängvattnet and Solberg), it is notable that all these catchments are located along the Norwegian border in the Scandinavian mountain range (Fig. 1). These catchments appear to manifest a clear signal for extreme events, while trends are buffered for larger or downstream catchments (nested systems) due to competing catchment-hydroclimatic interactions (Pattison et al., 2014). Further, all catchments with significant trends in flood extremes show an above-average mean elevation and their area is smaller than 1500 km^2 (Table 1). The catchments' close proximity to the Scandinavian mountain range in combination with the state of permafrost likely influences the hydrology. These findings are consistent with Birsan et al. (2005), who positively correlated streamflow to the catchment's elevation in Switzerland. Winter precipitation falling as snow is especially important in these catchments as it determines the snowmelt flood in spring. This further concurs with our results for the trend analysis on flood magnitude and summer flows, where significant trends were detected for catchments with high maximum elevation (>2000 m a.s.l.) or a more southern location within the study area.

Altogether the spatial patterns of our results suggest that shifts in large-scale atmospheric circulation patterns are likely influencing changes in extreme events and variability in precipitation and temperature, especially during winter (Birsan et al., 2005). Additionally, catchment properties such as the state of permafrost, which influences a catchment's water storage capacity (especially for the catchments located in the south of the study area), a catchment's elevation (both mean and maximum), and its location with respect to the Scandinavian mountain range have an influence on the exhibition of significant trends (e.g. Walvoord et al., 2012; Dahlke et al., 2014; Tetzlaff et al., 2015). Whereas other studies (e.g. Cunderlik and Ouarda, 2009; Wilson et al., 2010; Burn et al., 2010) found similar hydrological response patterns across regions with comparable climate input and catchment characteristics our results showed that these factors are all interconnected making the prediction of how climate trends will manifest themselves in cold regions difficult.

5. Concluding remarks

Our study showed that clear drivers of changes in hydrological systems in the Swedish Sub-Arctic are difficult to identify due to the complexity of cold climate systems and landscape interactions. The hydrology is determined by changes in air temperature and precipitation at seasonal, annual and multidecadal time scales, caused by large-scale atmospheric circulation patterns over the North Atlantic. But additionally to the climate variables, catchment properties such as the state of permafrost, storage capacity and mean elevation also seem to have a significant impact on runoff generation and have to be taken into account analyzing cold region hydrology.

To be able to improve knowledge on cold climate hydrological systems such as in northern Sweden, analyses of climate variables such as air temperature, precipitation in combination with catchment variables such as permafrost are desired. Development of approaches that are capable of, for example, addressing the influence of permafrost thaw in spring and its influence on the spring flood is of special interest in cold regions. Further, cross-correlations should be applied between changes in the hydrology, climate variables and atmospheric circulations on both annual and seasonal scales (Stahl et al., 2010; Wilson et al., 2010; Dahlke et al., 2012). Hannaford et al. (2013) suggested improvements for trend analyses on hydrological purposes using a multi-temporal approach to be able to get an appropriate trend accounting for multi-decadal variability in climate caused by large-scale atmospheric circulations. It is further desired to apply a trend analysis on long (e.g. several decades) periods of record to be able to account for the effect of long-term variability on the results of trend statistics. Hall et al. (2014) further suggested that a combined approach of data-based trend analyses covering the past and models predicting the future is desirable to be able to give recommendations for water management strategies. To be truly effective, such analysis must also consider the evolution of the landscape and, specifically the cryosphere, in cold regions.

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