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Hydrology and
Earth System
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Discussions

Interactive comment on "Contrasting trends in hydrologic extremes for two sub-arctic catchments in northern Sweden – does glacier melt matter?" *by* H. E. Dahlke et al.

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We would like to thank the three reviewers for their very helpful reviews. We have taken these reviews to heart and added/streamlined with regard to the suggestions of reviewer #2 the introduction to create a better link between the literature review and the objectives of this study. For this we rewrote three paragraphs of the introduction and added clearly formulated objectives at the end of the introduction. We also added a new methods section that is addressing the origin of the glacier mass balance data used in this study and we provided a more detailed description of the statistical methods applied in this paper to test stationarity in the flood quantiles of flood peaks in Abisko and Tarfala catchment. We took the suggestion of reviewer #3 and inserted the supplementary material to the main body of the manuscript. In addition, we streamlined our argumentation and discussion of potential mechanisms responsible for the observed amplification in the hydrologic response in Tarfala catchment. For this, we rewrote three paragraphs in the discussion section. All other comments have been addressed as well. Below the review is given in its entirety with the responses to the reviewer's comments. Thank you again for your efforts.

Manuscript hess-2011-434 Title: Contrasting trends in hydrologic extremes for two sub-arctic catchments in northern Sweden – Does glacier melt matter? Authors: H.E. Dahlke, S.W. Lyon, J.R. Stedinger, G. Rosqvist, and P. Jansson

Reviewer #1: L. Braun (Referee) Ludwig.Braun@kfg.badw.de Received and published: 1 March 2012 General comment: Comment: This paper is a valuable contribution on the changes of runoff totals and extremes as observed in a highly glacierized and an almost non-glacierized catchment in Northern Sweden over the past 50 to 100 years. It gives an impresssive overview on the relevant literature, and it is suggested that it be published as it stands. A minor point that needs clarification: P. 1047, line 20: How can Falkenmark (1972) report on data recorded at Trafala Research station for the period 1965-2009? There needs to be an more up-to-date reference. Response: We thank this reviewer for his positive comments and appreciation of this work. With regards to the reference clarification, there unfortunately is not a more recent reference for the annual precipitation To avoid confusion with regards to timelines (and respond to another review's comment), we removed to reference to Falkenmark (1972) and instead added the following text on lines 168-176): "This annual precipitation amount represents an estimate including the winter mass balance of Storglaciären (i.e. the average amount of precipitation (in m water equivalent) deposited as snow onto the glacier between mid-September and mid-April) and measurements of liquid precipitation at Tarfala Research Station during the summer season (excluding precipitation measurements on days with a daily average temperature less than 0 °C). The mean annual air temperature in Abisko and Tarfala catchment is –0.5°C and –3.4°C respectively. These values were calculated based on long-term daily air temperature data available for Abisko and Tarfala catchment for the time periods 1913-2009 and 1965-2009, respectively.” Comment: One further suggestion: Maybe it would be helpful to include solar radiation data in the analysis. As climatologists have shown there was much less global radiation received at the earth’s surface particularly in the Arctic Regions (arctic haze) in 1960s to 1970s, and the recovery to "normal" values after 1980 as a consequence of reduced air pollution. It could be helpful to also consider solar radiation data in the control of melt apart from air temperature. Response: This comment highlights an interesting potential link. To date, we have not considered looking into the temporal variability in solar radiation as a potential explanation for observed meteorological dynamics in both catchments. Although this sounds like an interesting aspect, we neither have a sufficient database of radiation data from northern Sweden or Scandinavia available nor the possibility to explore potential links between the variability in solar radiation and its effect on glacier melt processes in this current study. These links could potentially be explored using an energy balance melt model (e.g. Hock and Holmgren, 2005), however, this is well beyond the scope of the current work. Hock, R. and B. Holmgren. 2005. A distributed surface energy balance model for complex topography and its application to Storglaciaren, Sweden. J. Glaciol., 51(172), 25–36.

All in all: a very enlightening paper! Response: Thank you for the encouraging review!

Anonymous Referee #2 Received and published: 9 March 2012 General assessment This ms addresses questions related to the effects of climatic variability on peak flows in subarctic catchments located in the discontinuous permafrost zone. The authors use a comparative time series analysis approach, drawing upon discharge and mass balance time series that span almost a century. The questions addressed are important both scientifically and practically, and the data sets are unique in their length, particularly the glacier mass balance record. The analysis generates some novel insights that augment the existing literature on the topic. I recommend that the

ms be accepted for publication following revision to address the specific comments provided below, which are intended to help the authors clarify the presentation and strengthen its contribution to the literature. Specific comments 1. The title includes the term "hydrologic extremes," but the analysis focuses only on flood peaks, not low flows. I recommend that the title be modified to provide an accurate representation of the content. Response: We agree and have changed the title to “Contrasting trends in flooding extremes for two sub-arctic catchments in northern Sweden – Does glacier melt matter?” to emphasis the focus on flood events. 2. The introduction should be revised to provide a more nuanced and complete summary of the literature and to provide a stronger bridge between the literature review and the stated objectives. The next two comments provide more specific directions. Response: We take up response to this comment in following comments. 3. In the introduction, the authors refer to findings of both increasing and decreasing streamflow trends in a rather broad-brush manner. It would be useful to clarify the specific metrics used in the different studies (e.g., monthly vs annual runoff) and to consider the seasonal signatures of streamflow trends associated with warming and glacier response. For example, Milner et al. (2009, Figure 2) showed a hypothetical sequence of streamflow response to glacier volume change. However, that schema did not illustrate changes to spring-season snowmelt associated with spring-time warming. Déry et al. (2009) illustrated empirically the variation in the seasonal pattern of warming-induced streamflow trends for a range of nival and glacier-fed catchments in western Canada. I also recommend that the authors refer to a classic chapter on floods in cold regions by Church (1980) to provide more context for the roles of different flood generating mechanisms and how they might respond to climatic warming and glacier changes. Response: We followed the suggestion of the reviewer and streamlined the introduction of our manuscript. We have rewritten parts of the introduction to specifically address the questions raised by reviewer #2. The following text is replacing the parts of the introduction from page 3 and 4, line 65-124. “Although several studies have focused on the hydrologic effects of climate variability and change, relatively few of them have examined the interactions between climate variability and change, glacier response and the resulting effects on streamflow (Moore and Demuth, 2001; Aziz and Burn, 2006; Burn et al., 2010). Among these hydro-climatological studies there is an emerging body of literature that indicates contrasting hydrologic responses in sub-arctic and arctic catchments to climate variability and change that is depending on the percent glacier cover of a catchment (Fleming and Clarke, 2003 and references therein). These studies indicate that regardless of differences in inter-annual streamflow variability catchments at low elevation and/or with low glacier cover show predominantly decreasing streamflow trends (e.g. Dery et al., 2005; Burn et al., 2010), whereas increasing trends are found in catchments located at high elevation and/or with high glacier cover (Casassa et al., 2009). For example, Hodgkins (2009) found that June through August flows increased by 8% to 11% for glacierized basins (more than 10% glacier cover) in southeastern Alaska, USA and decreased by 3% to 9% for non-glacierized basins. Similarly, Moore and Demuth (2001), Stahl and Moore (2006), Fleming et al. (2006) and Pellicotti et al. (2010) observed increasing mean monthly summer (July-September) and annual streamflows in recent years in several catchments characterized by a greater glacier-covered area in northwestern British Columbia, Canada and the European Alps. In addition, several catchment comparison studies (e.g. Fountain and Tangborn, 1985; Birsan et al., 2005; Hodgkins, 2009) have shown that the inter-annual variability of streamflow is highest in catchments with low (<10%) glacier cover but decreases with increasing glacier-covered catchment area (up to 30–40%) because of the mutual buffering of streamflow variability between ice-free and glacierized parts of the catchment (Fountain and Tangborn, 1985; Röthlisberger and Lang, 1987). This is because the retreat of glaciers due to increasing temperatures can affect catchment streamflow in two ways (Jansson et al., 2003): (i) in the short-term response glacier runoff will increase while the glacier adjusts its volume to a warmer climate; (ii) in the long-term response flow rates will decrease when the glacier volume is adjusting to a new volume-to-area equilibrium or disappearing (e.g. Jansson et al., 2003). According to Hock et al. (2005) glacier melt during the short-term response is further accelerated by positive feedback

mechanisms. For example, enhanced meltwater production occurs due to earlier and more extensive disappearance of high-albedo glacial snow and firn. The reduction in firn area and thickness, and greater exposure of low-albedo bare ice will reduce the water retention capacity, allow greater melt, and potentially increase water flow over the glacier surface (Hock et al., 2005). For example, Braun et al. (2000), Box et al. (2005) and Knuden and Hasholt (2003) reported for different glacierized catchments that streamflow reached greater stream discharges during years with low snow accumulation that lead to extreme glacier ice melting. Knudsen 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 these studies elucidate the existence of a glacier coverage threshold that determines the hydrologic response of glacierized catchments to climate change.

Many of the observed increasing trends in summer streamflow in catchments with greater glacier cover are connected to climate variability and/or changes in climate or both. Most studies attribute the observed changes in streamflows to increasing trends in air temperature (e.g., Fleming and Clarke, 2003; Birsan et al., 2005). However, much of the observed variability in historic streamflow trends is also related to low-frequency climatic forcing and climate pattern indices such as the North Atlantic Oscillation (NAO) or the Pacific Decadal Oscillation (PDO). For example, Fleming et al. (2006) and Hodgkins (2009) observed positive glacial streamflow anomalies in late spring and early summer in years dominated by the positive-phase of the PDO and Arctic Oscillation (AO), which caused warmer air temperatures and increased winter precipitation. Similarly, Birsan et al. (2005) found high correlations between summer streamflow and the NAO index of the previous winter season, which caused increased winter precipitation and subsequently increased spring and summer melt. However, studies of Woo and Thorne (2008) and Birsan et al. (2005) indicate that despite the fact that climate forcing can impart a strong signal on streamflow response, not all catchments within the same climate forcing show the same trajectory in the observed hydrologic response because factors such as location, topography and storage can overwhelm the climatic influence. On the contrary, temperature and precipitation anomalies caused by climate variability can influence and change the current flow regime and runoff generation mechanisms in a catchment, which could impact the nature of extreme flows, such as flood events. For example, increased winter temperatures can be expected to cause a reduction of the snowpack before the onset of the spring melt, which might lead to a decrease in snowmelt-related flood magnitudes. This may lead to a greater importance of rainfall-runoff flood events, especially if changes occur in the magnitude or intensity of severe rainfall events (Burn et al., 2010). Kane et al. (2003) for example found for the Upper Kuparuk watershed in Alaska that a few high-intensity precipitation events appear to generate greater runoff amounts (three times greater) 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. However, it remains largely unknown how climate induced transient changes in the glacier-covered catchment area and the short-term and intermediate-term glacier storage manifest themselves in the catchment hydrologic response and flood extremes in sub-arctic and arctic environments. ” 4. At the end of the introduction, the authors provide two sentences that indicate the types of analysis that were conducted. I recommend that the authors restate these as objectives, hypotheses or questions in a way that they clearly relate to gaps in our understanding and link back more strongly to the literature review; doing so would clarify the novel contributions made by this study. In particular, the reference to large scale teleconnection patterns does not relate to any of the reviewed literature. The authors should consider adding a paragraph that reviews the hydrologic consequences of these climatic oscillations and why they might influence flood generation in the study catchments. Response: We followed the suggestion of the reviewer and streamlined the presentation of objectives. The revised paragraph containing our objective is: “With the ongoing and expected reduction in global glacier volume, there is a need to better understand how changes associated with the reduction in glacial volumes affect glacial meltwater runoff and thereby terrestrial hydrology. Assessment of gradual hydrologic change induced by climate and change in the causal mechanism of flood extremes 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 test the hydrologic response for climate induced trends and shifts in the runoff generating mechanisms by analyzing and comparing trends in the magnitude and timing of flood extremes and the mean summer discharge in two sub-arctic catchments with differing glacier cover in northern Sweden. For this study the Tarfala 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 Abisko catchment, which has a continuous 98-year record of climate observations, were compared. In both catchments trends in the catchment hydrologic response and the flood quantiles will be assessed using the Mann-Kendall trend test and generalized least squares regression. In addition, potential links to climate variability and climate change will be identified by relating hydrologic trends to annual and seasonal trends in the minimum, maximum and mean temperature, the maximum and total precipitation and annual and 3-months averaged large-scale climate teleconnection patterns (e.g. Northern Atlantic Oscillation, Atlantic Multidecadal Oscillation).” page 5, lines 127-145. 5. The authors should include information on changes in glacier area within Tarfalajokk catchment over the period of record. Response: We followed the suggestion of the reviewer and added a more concise description of information on changes in the glacier mass balance, the glacier area and volume in the manuscript by adding a new method section called “glacier mass balance data”. In this section we provide key references to the glacier mass balance data available for Storglaciären. The most recent glacier mass balance time series was published by Zemp et al. (2009) for the period 1946-2007. Given that the current manuscript consists already of 10 tables and 6 Figures we decided to not add an additional figure showing the cumulative glacier mass balance of Storglaciären, but instead to refer to specific key figures in existing publications based on the fact that this new figure would show only an additional 2 years of data. The cumulative glacier mass balance of Storglaciären for the period 1946 – 2009 for comparison to Zemp et al. (2009, Fig. 3) is shown in Figure 1 (attached file):

To provide more information on the glacier mass balance data available for Tarfala catchment we added the following text on page 7, line 193-203: 2.2.2. Glacier mass balance data For the Tarfala catchment continuous long-term mass balance data are available for the 2.9 km2 Storglaciären (65° 55'N, 18° 35'E) located in the southwest of the catchment at an elevation range of 1130 to 1700 m a.s.l. Storglaciären is described as a polythermal glacier with a perennial cold surface layer in the ablation area (Pettersson et al., 2003). For this glacier, estimates of the annual winter (bw), summer (bs), net balance (bn), the equilibrium line altitude (ELA), and the ablation area ratio (AAR) are available since 1946 through the Tarfala Research Station. In addition time series data of Storglaciären's glacier mass balance, including volume and area estimates and changes have been published by among others Holmlund and Jansson (2005), Jansson and Pettersson (2007), and most recently Zemp et al. (2009: Fig. 3, for 1946-2007) and Koblet et al. (2010). 6. The authors used a correlation test to support the validity of the Gumbel distribution for fitting flood frequency relations for the entire periods of streamflow record. However, they then showed that the assumption of stationarity is not valid, using the trend analysis on quantiles from 10-year moving windows. I am not an expert on frequency analysis, but was taught in my undergraduate hydrology courses that the classical approaches are based on an assumption of stationarity, which is clearly not valid in this case. Another potential issue is that the peak flow events were generated by at least two different processes: Table 6 reveals that some events were associated with high air temperatures, with the implication that they were dominated by meltwater, and others were associated with intense rainfall. Would a simple Gumbel distribution be valid for a mixed-population frequency analysis? Church (1980) and Waylen and Woo (1982) conducted frequency analyses that explicitly accounted for multiple flood generation mechanisms. A further concern is that, even if the assumptions underlying frequency analysis were valid, estimates of

100-year floods from 10-year samples would be associated with high uncertainty. The authors need to address these concerns when preparing the revised ms, possibly through additional analysis. Response: The review is clearly correct that one of the central underlying assumptions in flood frequency analysis is stationarity over the period of analysis. However, even though flood peaks might not be stationary in a first approximation of the flood frequency analysis values are typically assumed to be independent and identically distributed (Khaliq et al., 2006). As such, Figures 5a and 5b in the original manuscript show the results of a flood frequency analysis assuming that the values are independent and identically distributed. The fit of a Gumbel distribution to the data simply provides a basis for the comparison using the time-varying, moving window estimated flood quantiles. As pointed out in several publications (e.g., Khaliq et al., 2006; Stedinger and Griffith, 2011) the problem of non-stationarity in flood quantiles in the context of, for example, climate change is of most concern when using distributions to predict the probability of future occurrences of some events of interest (the problem of projection). Such long-term and forward-looking analysis is not the central focus in this current study. In this study we are assessing whether past extreme events show any sign of a climate change impact. Thus, the original motivation for testing the flood peaks with regards to stationarity was to highlight that non-stationary trends should be considered in future probability of exceedance estimates (which is in agreement with this review comment). We have adjusted the revised text to better reflect this. Further, we have investigated incorporating the effects of non-independence and non-stationarity in the flood frequency analysis in each catchment using the approach by Stedinger and Griffis (2011). This is done by letting the location and scale parameter of the Gumbel distribution vary in time using the North Atlantic Oscillation (NAO) index:

Based on this analysis (shown below in the attached Figure 2) flood quantile estimates can be adjusted in time. While this influences the analysis somewhat, it does not alter the main findings of the study with regards to the current state of flooding extremes in these two catchments with different glacier cover.

With regards to the validity of a simple Gumbel distribution for a mixed-population frequency analysis, the reviewer raises a good concern. In the flood frequency analysis presented in this manuscript we did not explicitly distinguish a priori the underlying runoff generation mechanisms that lead to the flood events. If the flood peaks observed in both catchments had shown an obvious difference (e.g. clear offset or deviation in observed maximum annual discharge amounts from the fitted probability distribution) in the quantile plots, this would have suggested two different flood generation mechanisms justifying the separation of two different distributions (Khaliq et al., 2006). However we did not see such a "jump" and the probability plot correlation test (which was significant) indicated that all observations had been drawn from the same distribution. In addition, as shown in Table 6 flood events in Abisko did not show a clear relation to either the maximum annual temperature or maximum annual rainfall events, which suggested that in this catchment there is no clear distinction of flood peaks into snowmelt or rainfall-induced flood events possible. Regarding the uncertainty of the 10-year moving window estimates Figure 3 (see attached file) shows the results of the probability plot correlation (PPCC) test statistic for each of the 10-year moving window estimates of flood quantiles using the Gumbel distribution. As shown in Figure 4a the PPCC test results of the 10-year moving window estimates of flood quantiles performed for Tarfala catchment shows values well above the lower critical value (assuming n=10 values, significance level of 5%, Vogel, 1987). This indicates that in all cases the Gumbel distribution provided a good fit for the observed flood peaks and one can trust the estimated exceedance probabilities. The PPCC test results for Abisko catchment show in two instances values below the lower critical value. However, these PPCC results are still within the 99% confidence interval, which has a lower critical value of pi=0.863. Thus, for flood peaks of Abisko catchment the Gumbel distribution provided a sufficient fit in most cases.

In order to provide the reader with a better uncertainty estimate of the 10-year moving window analysis we inserted the following text "The lowest probability plot correlation test statistic reached for the 10-year moving window estimates was r=0.94 and r=0.90

for Tarfala and Abisko catchment, respectively. Assuming a significance level of 1% the lower critical value of the PPCC test statistic for n=10 values equals r=0.863. Thus, for all 10-year moving window estimates the Gumbel distribution provided a good fit. " on page 12, lines 480-484. 7. To analyse quantiles derived from the flood frequency analyses, the authors used generalized least squares (gls) regression so as to account for temporal autocorrelation in the residuals (given that flood quantiles from consecutive 10-year windows would be based on 9 years of common data, and thus should be strongly autocorrelated). Further detail on the gls regression approach would be appreciated. For example, what order of autocorrelation was included? It would be useful for less statistically minded readers of this article to have some clarification of and rationale for the methodological choices made in the analysis, especially for readers interested in applying these methods to other data sets. Response: We followed the reviewer's suggestion and added a more detailed explanation of methodologies used to test the stationarity in the flood quantiles. For this we replaced the text at lines 261-273with "In order to explore how the annual flood extremes have varied over time, flood quantiles (computed from the full 45-year record) were tested for stationarity by estimating trends in the time-varying probability of exceedance of selected flood percentiles using a 10-year moving window. The key flood percentiles considered are the 50th, 90th, 95th, and 99th percentiles of the data computed with the Gumbel distribution from the full 45-year record. These percentiles correspond to floods with return periods of 2, 10, 20, and 100 years, respectively. The time-varying, moving window probability of exceedance of each key percentile is estimated by fitting the Gumbel distribution to all flood records within the moving window. . For these 10-year moving window estimates model adequacy of the fitted Gumbel distribution was likewise tested using the probability plot correlation test (Vogel, 1987). Finally, trends in these key flood percentiles versus calendar year were estimated by fitting a generalized least squares (GLS) regression using a maximum likelihood estimator. An autoregressive (AR2) polynomial from the ARMA(2,0) structure is fit to the errors in the GLS model to account for the autocorrelation in the residuals of the time-varying, moving window flood percentiles (Fox and Hartnagel, 1979). Autocorrelation in the time-varying, moving window flood percentiles was estimated using the Durbin-Watson test (Durbin and Watson, 1950). A general pattern of the autocorrelation and partial autocorrelation functions in the shape of a sinusoidal decay with two spikes, one positive, the other negative, is suggestive of an AR2 process, which means that only an autoregressive model is fit to the data (Chatfield, 1989)." (page 9, lines 261-278). 8. In relation to the trends in the flood quantiles, I would find it interesting to know the extent to which these are reflecting changes in the mean versus the standard deviation. Response: Since we fitted the Gumbel distribution for each 10-year moving widow the location and scale parameter of the Gumbel distribution changed. If one would fit the Gumbl distribution with the "methods of moments" the mean and variance are used to fit the location and scale parameter. For this study we estimated the location and scale parameter of the Gumbel distribution with the "method of maximum likelihood", which results typically in similar parameter estimates as estimated using the mean and standard deviation of the flood peak population. In order to answer the reviewer's comment we went back and estimated the mean and standard deviation for each 10-year moving window. The results are shown below in Figure 4 (see attached file). Since the trajectory and variability of the change in the location (i.e. mean) and scale (i.e. standard deviation) parameter is similar to the ones shown in Figure 6 of the manuscript for the trends in the return period of 2, 10, 20, and 100 years, we did not see the need to add an additional figure to the manuscript showing the change in the mean and standard deviation of the flood peak distribution.

9. In the caption for Figure 5, the last sentence indicates that the variability around the longer-term trends is a "response to decadal and interannual forcings." First, this sentence should be moved to the main body of the paper. Second, did the authors conduct a formal analysis upon which to base this comment, for example, by regressing deviations in quantiles from the longer term trends against indices such as NAO? I recommend that the authors conduct additional analyses to try to link the correlations illustrated in Table 7 with the temporal patterns in flood quantiles. Response: We did

indeed look at the spectral frequency in the temperature, precipitation, summer streamflow and flood peak data to identify how slowly varying climate states (i.e. represented by climate indices such as the North Atlantic Oscillation) may affect finite sample flood and meteorologic metrics. However, we decided to exclude these results from this manuscript due to the already large amount of information presented. In order to reduce confusion for the reader we deleted the following sentence in the figure caption: "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." (Figure 5 of main manuscript). 10. The process-based speculations for the cause of the declining flood magnitudes for Abiskojokk appear straightforward and are plausible in the context of the relevant literature. However, I am less convinced about the proposed explanations for the increasing trends for Tarfalajokk. The authors argue that the relative lack of response to rainfall events at Abiskojokk could be associated with permafrost thaw, which would reduce the responsiveness of the catchment to snowmelt and rainfall. Wouldn't this process also be active over the 70% of the Tarfalajokk catchment that is glacier-free? Response: Not necessarily. The mean annual air temperature in Tarfala is -3.4 °C compared to -0.5 °C in Abisko and the mean summer (JJA) air temperature is 5.8 °C and 10.0 °C, respectively. Thus, one can expect a shallower active layer depth in Tarfala compared to Abisko. In addition, from the 70% non-glacierized area in Tarfala catchment approximately 40% is bare rock. Only the valley floor has soils that can store water. However, these soils are not very developed and of shallow depth (i.e. 5-10 cm). Thus, the flow dampening effect of increased soil water storage capacity due to increased permafrost thaw in these shallow soils is likely masked by the discussed increase in glacier melt, and rainfall-induced storm runoff. Still, we have expanded the discussion text to include this reasoning. Please see our response to reviewer #3 for the changes made in the manuscript. How about generation of rainfall-runoff from the 30% of the catchment that is glacierized? The authors speculate (p. 1061, line 23ff) that the decrease in glacier area has increased responsiveness of Tarfala catchment. How substantial was the change in glacier area? As an alternative hypothesis, perhaps decreased snow accumulation (in combination with thinning and decreasing area of firn cover) could be resulting in greater response of the glacier to rainfall events. I encourage the authors to consider a range of alternative hypotheses about the processes that may be responsible for the shifts in flood magnitudes, and to evaluate each as much as possible given the existing information base. Response: To answer these questions and to streamline our argumentation of potential mechanisms responsible for the observed increase in flood magnitudes and the mean summer discharge in Tarfala catchment. Please see our response to reviewer #3 for the changes made in the manuscript. 11. There a number of minor grammatical and typographical errors that should be corrected during revision. Response: We checked and corrected the manuscript for typographical and grammatical errors. References References Church, M. 1980. Floods in cold climates. In: V.R. Baker, R.C. Cochel and P.C. Patten (editors), Flood Geomorphology. John Wiley, New York, pp. 205-229. Déry, S.J., Stahl, K., Moore, R.D., Whitfield, P.H., Menounos, B. and Burfield, J.E. 2009. Detection of runoff timing changes in pluvial, nival and glacial rivers of western Canada. Water Resources Research, 45, W04426, doi:10.1029/2008WR006975. Milner A.M., Brown L.E., and Hannah D.M. 2009. Hydroecological response of river systems to shrinking glaciers. Hydrological Processes, 23, 62–77. Waylen, P. and Woo, M.-K. 1982. Prediction of annual floods generated by mixed processes. Water Resources Research, 18, 1283-1286.

T. V. Schuler (Referee) t.v.schuler@geo.uio.no Received and published: 13 March 2012 This manuscript (MS) presents trend analyses of meteorological and hydrological time series of two sub-arctic catchments having differing properties. Although temperature and precipitation display comparable trends in the overlap period (1985-2009), discharge from the glacierized catchment develops differently from that of the (nearly) non-glacierized one. The trends are further analysed in context of climatic indices such as AMO etc and glacier mass balance. The presented longterm records are valuable and the findings are interesting and emphasize the importance of taking glaciercoverage into account in land-surface/ hydrological modeling. However, I have discovered

a number of weaknesses in the presentation of the material and the discussion of the results. In my view, most of the presented conclusions cannot be drawn based on the discussed material. Nevertheless the job to repair the discussion is manageable and, in my view the MS may become publishable subject to major revisions. Criticism: 1) relationship glacier mass balance - discharge I do agree that glacier mass loss is driving the discharge trends in the glacierized catchment, however, I do have problems with the presentation of the material in the MS and the related argumentation. The authors relate the increase of summer discharge to an increasing contribution of glacier melt (p1059), however, the statistical analysis (Table S1) does not reveal significant correlation between glacier mass balance components and summer discharge. This is contrary to the statement (p1059 L8-10) that Q_JJA "had a significant negative correlation with" b_w. The value of -0.31 is not suggesting a strong statistical relationship between winter balance and summer discharge and it is not marked as significant the table (Table S1). Actually, I was surprised that the statistical relationship between net or summer mass balance and summer discharge is not stronger since release of water from a longterm storage (as indicated by negative net balance) should directly enhance Q_JJA. This indicates that these relationships are more complex. Therefore it would be helpful to discuss the physical view of such statistical relationships: what are the mechanisms/ processes thought to explain the correlation? Throughout the entire MS, the authors do not discuss this point. However, for instance explaining a relationship between winter balance and summer discharge is not straightforward. One expects that the melt contribution from the glacier is expressed by its summer balance (dominated by ablation), rather than the winter balance which is dominated by accumulation). There may be a line of arguments explaining the observed correlation between bw and Q_JJA (high bw –> lots of snow –> later snow cover depletion –> less melt water production during summer (albedo effect)) but as mentioned such explanation is never provided. Also the observation that flood peaks coincide with precipitation events rather than temperature maxima is difficult to explain in absence of a significant precipitation trend, and I do not agree that warming "cannot explain the observed trends in magnitude and timing of floods" (p1059L23). Actually warming and associated glacier retreat may explain flood intensification considering the following feed-back mechanism: negative mass balance–>reduction of firn area –> reduction of retention capacity –> faster response, (see also e.g. Hock et al, 2005). Further, the authors need to account for that the presented glacier mass balance values represent specific quantities (per unit area) but discharge is expressed as a volume flux (m3/s). For a glacier of constant surface area, the specific balance relates linearly to a volume of water, but this is not the case for a shrinking glacier (retreat of Storglaciären mentioned on p1059 L15)! This must be adressed, a specific mass balance does not indicate the volume of water released from the glacier without stating the associated surface area! There is lots of current literature discussing reference vs conventional glacier mass balance. Furthermore, material crucial to the discussion need to be presented in the MS, not in a supplement. Response: We agree and streamlined the argumentation of potential mechanisms explaining the observed trends in Tarfala. We rewrote the first and second paragraph of Discussion section 4.2 and inserted the following text on page 16-18, lines 505-557. “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 Abisko and Tarfala catchments. Analysis of hydrological trends in the Tarfala 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 period of 1985-2009 (Fig. 3). Flood peaks showed a significant correlation to the mean summer discharge, suggesting that generally wetter conditions in the catchment either due to above-normal precipitation amounts, as found in years with above-normal sea surface temperatures across the North Atlantic (indicated by a significant correlation to the AMO index [Table 7]), or due to increased glacier melt, reflected by a more negative glacier net balance, could increase the propensity of high-magnitude flood events. In addition, mean summer discharge in Tarfala catchment showed a significant correlation (r=0.4) with the equilibrium line altitude (ELA) of Storglaciären (Table 8). This is suggesting that runoff generation is increased in years with a higher ELA, which corresponds to a more negative annual glacier net balance and a lower ablation area ratio. Together these relationships suggest the following mechanistic changes in Tarfala catchment. The continued decreasing trend in Storglaciären’s net balance, associated with a decrease in winter mass balance leads to a reduced snow/firn cover on the glacier. As indicated by the significant correlation between ELA and the mean summer discharge (Table 8) this could potentially increase meltwater production due to earlier and more extensive disappearance of high-albedo glacial snow and firn. The reduction in firn area and thickness, and greater exposure of low-albedo bare ice is likely reducing the water retention capacity, allowing greater melt, and potentially increasing the volume and peak flows of water over the glacier surface (Hock et al., 2005). Similar linkages between air temperature, variations in the seasonal snow accumulation and ablation and streamflow trends have been observed by Fleming and Clarke (2003), Hodgkins (2009), and Pellicciotti et al. (2010) in catchments with increased (> 10%) glacier cover, which are supporting our results. Trends in air temperature alone cannot explain the observed trends in the magnitude and timing of flood peaks in the Tarfala catchment, because 50% of the flood events coincided with the annual 1-day maximum precipitation and only 14% coincided with the annual 1-day maximum temperature (Table 6). The temperature-induced decrease in the net glacier mass balance of Storglaciären and the associated increased melt water contribution could represent an important precursor for an increased flood generation in Tarfala catchment by increasing streamflow and providing fast runoff pathways when glacial snow/firn cover is low. However, the high coincidence between flood events and the maximum annual precipitation suggests that large precipitation events, especially when occurring late in the summer season when the catchment snow cover cover is removed and the glacial snow/firn cover is lowest, could be the primary reason for the observed amplification of flood extremes. This is also supported by the observed increase in extreme precipitation during the last decade. In addition, we found that a low AAR and negative glacier net balance in Tarfala catchment occurred predominantly in years with the seasonal summer EA index in the positive phase, which is characterized by above-average precipitation over Scandinavia (Table 7). Together, these results indicate the increasing importance of rainfall for flood generation. These findings are consistent with studies from Kane et al. (2003) and Cunderlik and Ouarda (2009). 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 and steep topography. However, catchment size and the orientation of the catchment to predominant weather patterns are also important factors (Kane et al., 2003). 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." In addition we have reformulated parts of the last paragraph (lines 603-606)of the discussion section in line with the review comments to read: "In the glacierized Tarfala catchment, trends in hydrological extremes (floods) indicate that this catchment is becoming more efficient in transmitting water to its outlet. This can be attributed in large parts to the negative trends in the glacier mass balance and associated reduction in snow/firn cover and, thus, water retention capacity (Hock et al., 2005).". And we replaced the text in lines 567-573 with "We suggest that the increase in mean summer discharge in the glacierized Tarfala catchment is due to warmer temperatures promoting enhanced meltwater production due to earlier and more extensive disappearance of high-albedo glacial snow and firn, earlier melt of the catchment snow cover, and increased summer precipitation (positive but insignificant trend), which could promote wetter conditions and increased connectivity of hydrologic flow pathways within the catchment. On the other hand, the increase in flood magnitudes of Tarfala is likely due to the increase in extreme precipitation events in conjunction with catchment properties that promote fast runoff such as low glacial snow/firn cover, high antecedent wetness in years with above-normal precipitation and increased mean streamflow due to increased glacier melt.". Regarding the comment: "This must be adressed, a specific mass balance does not indicate the volume of water released from the glacier without stating the associated surface area! There is lots of current literature discussing reference vs conventional glacier mass balance." Response: A reference surface balance is difficult to apply to Storglaciären since there is significant variation in snow accumulation that affect the balance and which are directly tied to surface concavities and convexities. In the paper Holmlund et al. (2005) we re-analysed the mass balance data using progressive maps. We first of all obtained better data, especially regarding the elevation dependence, but this study also made clear that differences in estimated glacier net balance are exceptionally small when changing maps. Hence it seems the small elevation changes associated with the reduction in area is not appreciably affecting the balance calculation and applying a reference surface would have no impact on the upper parts of the glacier. This question alone provides grounds for a critical review paper on mass balance methodology on its own but that is clearly completely outside of the scope of the present paper. 2) title Reformulate the title, it raises wrong expectations because a) the MS does not analyse hydrological extremes, but just one of them (flood) and has almost equal focus on summer mean discharge (throughout the entire MS, not only title) b) in my view" does glacier melt matter" is questioning the obvious. If the title keeps this question, one would at least expect a discussion of possible other explanations for the different behaviour (differences in scale, climate conditions, topography and spatial distribution of meteorological variables, etc). For instance one may discuss whether Tarfala (1000-2100 m asl) has an increasing efficiency in capturing orographic precipitation than Abisko (300-1800 m asl), however, such a discussion is completely missing. This means the question raised in the title is not really addressed. Response: We agree and changed the title to "Contrasting trends in flooding extremes for two sub-arctic catchments in northern Sweden – Does glacier presence matter?" to emphasis the focus on flood events. Since most of the discussion and analysis of flood peaks in Tarfala is correlated to Stoglacieren mass balance estimates we find that the title "does glacier presence matter?” is appropriate. The reviewer suggested to discuss possible other explanations for the different behavior and mentioned differences in scale, climate conditions, topography, and spatial distribution of meteorological variables. From these explanations we address explicitly the spatial distribution of meteorological variables and the climate conditions in our study by first comparing the meteorological parameters temperature and precipitation from Abisko and Tarfala catchment for the existence of similar or different climatic trends. We then also related the hydrological trends to climate pattern indices to explicitly derive linkages that might explain anomalies in the observed summer streamflow and flood peak variability due to climate variability. We also discuss the influence of topography on flow pathways in the discussion of potential first order controls on runoff generation for Tarfala catchment, however, the reviewer is questioning the topographic influence himself by commenting on P1062L8-10 "It is not clear how invariable properties should be responsible for intensification of floods”. The ability to explore the reviewer’s request to discuss differences in scale is unfortunately limited due to the general setup of this study. In this manuscript we investigate climatic and hydrologic trends for two catchments with differing glacier cover. This study did not compare climatic and hydrologic trends across a larger region such as northern Scandinavia or the Alps (e.g. see Birsan et al., 2005). Thus, estimation and comparison of trends at different scales is only to a certain extent possible. However, we are currently planning on expanding this study to several other catchments in northern Sweden, which will allow comparison of observed trends across different scales. We have both shifted the title question and improved our discussion by streamlining our argumentation of potential mechanisms responsible for the observed amplification in the hydrologic response in Tarfala catchment. Please see our comments in response to the main criticism. In addition, we explicitly answer the question raised in the title of the manuscript in lines 623-626 in the sentence: “However, does glacier presence matter for the observed trends in flooding extremes? Based on our results we conclude that for flood extremes it appears that glacier presence and particularly the amount of glacier melt in response to climatic forcing play a key role in runoff production in mountain catchments.”

3) data periods Most focus should be on the overlap period for which meteorological and hydrological data exist for both sites (1985-2009). The presentation of longterm trends for individual variables that do not have correspondance with other records is confusing. It may be useful to discuss the overlap period in context of the longterm evolution. However, since longterm trends are only available for some variables/ sites, the MS should focus on the overlap period and use the longterm trends only as discussion material. The common presentation of trends over different subperiods and for different variables is confusing. Response: One of the central novel aspects of this study is that both catchments have streamflow, meteorological, and (in the case of Tarfala catchment) glacier mass balance records exceeding a 30-year period. In order to make the discussion of observed trends for different time period easier for the reader we restructured the results sections 3.1 and 3.2 such that first trends observed during the comparison period (1985-2009) are presented, followed by a presentation of trends for the maximum available record period of Tarfala time series data (available since 1965), and thirdly we discussed trends for the full record period of data available for Abisko catchment (i.e. 1913-2009). We also changed the order of Tables 2, 3 and 4. Table 2 is now presenting first statistics for the comparison period (1985-2009), while Tables 2 and 4 summarize statistical trends in the temperature and precipitation data for the respective full record periods. Minor points: Generally, the English should get some polishing, there are many instances of incorrect usage of language: "data area available FROM SMHI" (not "through")... "associated with HIGH temperature periods" (not warm)...I do not list all. Also, adding synonyms or oral language in parentheses makes the language less precise, please stick to a unique terminology. Response: We changed “through SMHI” to “from SMHI”. We could not find the phrase “. . .high temperature periods. . .” in the text. We replaced “warmer temperatures” with “higher temperatures” or “greater” if in the context of increasing rates. Consistent terminology: use either Abisko-catchment or Abaiskojokk-catchment (same for Tarfala and Tarfalajokk). Response: We agree and reduced “Tarfalajokk catchment”

and “Abiskojokk catchment” to “Tarfala catchment” and “Abisko catchment”. First sentence of the abstract: "it is not clear..." the uncertainty is never specified: what is unclear? Response: We replaced the first sentence of the abstract “It is not clear how climatic change will influence glacial meltwater rates and terrestrial hydrology in the Sub-Arctic and Arctic.” with “Our understanding of how transient changes in glacier response to climate warming will influence the catchment hydrology in the Arctic and Sub-Arctic is limited.”. We further replaced “This uncertainty. . .” with “This understanding is particularly. . .” (lines 1518, pg. 1) use "glacierized" (referring to present glacier coverage) instead of "glaciated" (past glacier coverage) throughout the MS Response: We agree and replaced “glaciated” and “nonglaciated” with “glacierized” and “non-glacierized”. P1042 L17 (and several instances in the MS): ..."lacked significant trends...", replce with "...do not show..." Response: We followed the reviewer’s suggestion and replaced “. . .lacked significant trends. . .” with “. . .did not show significant trends. . .”. P1042 L21-23: "hydrologic trends indicated an amplification of the hydrologic response..." this sentence is vague, response in terms of what? Response: We changed “hydrologic response” to “. . .streamflow and flood response. . .” (page 2, line 33). P1047L20 the doubtful prophecy by Falkemmark 1972 has been pointed out by another reviewer and needs to be clarified Response: As pointed out in response to reviewer #1 there unfortunately is not a more recent reference for the annual precipitation. It is very difficult to measure snowfall during the winter months in Tarfala valley since measurements are especially impacted by drifting snow due high wind speeds of up to 80m/s, making reliable measurements almost impossible. We removed the reference to Falkenmark, 1972 and instead added the following text in lines 168-176): “This annual precipitation amount represents an estimate including the winter mass balance of Storglaciären (i.e. the average amount of precipitation (in m water equivalent) deposited as snow onto the glacier between mid-September and mid-April) and measurements of liquid precipitation at Tarfala Research Station during the summer season (excluding precipitation measurements on days with a daily average temperature less than 0 °C). The mean annual air temperature in Abisko and Tarfala catchment

is –0.5°C and –3.4°C respectively. These values were calculated based on long-term daily air temperature data available for Abisko and Tarfala catchment for the time periods 1913-2009 and 1965-2009, respectively. “. P1047L1 vs P1048L2: Gauge vs gage, please use consistent terminology throughout the MS Response: We agree and replaced “gage” with “gauge”. P1049L21 "julian day" = interval of time in days and fractions of a day since January 1, 4713 BC, is not the same as day-of-year (which is used here). Response: We agree and replaced “Julian Day” with “day-of-year”. P1052L16, increase of precipitation during winter: Førland and Hanssen-Bauer (2000) discuss apparent precipitation increases due to increase of winter temperatures and the associated change in rain-snowfall partitioning. Station undercatch for snow is usually much larger than that for rainfall. Response: For the analysis of statistical trends in the meteorological data in Abisko catchment we used precipitation and temperature data provided by the Abisko Scientific Research Station. This data is measured following the world-meteorological standard, quality controlled and post-processed by the scientific staff from Abisko Scientific Research Station. Further, the long-term increase in winter precipitation found in Abisko catchment is consistent with precipitation trends observed by for example Callaghan et al., 2010 (Geophysical Research Letters) for northern Sweden. P1053 L14&15: "minimum flood" seems an odd expression. Response: We followed the reviewers suggestion and changed “minimum flood” in the Abisko and Tarfala sections to the following sentences respectively: “Maximum annual discharge values ranged between 6.6 m3 s–1 and 23.4 m3 s–1 for the 1985-2009 record period.” and “Maximum annual discharge values varied between 75.3 m3 s–1 and 174.1 m3 s–1 with a median of 122 m3 s–1.”. P1054 L14: "trend analysis on the moving window results" ...is awk wording, better: "...of the smoothed record" Response: We changed the wording to “The test for stationarity in the flood quantiles. . .”. 1055 1rst par: stick to either "return period" or "probability" to characterize flood characteristics Response: We disagree. Not every reader is necessarily familiar with the stochastic relationship between probability of exceedance and the return period of floods. Thus, we think it would be helpful to state both in the description of the flood frequency analysis performed in this study. P1055 L6: "Climatological controls..." replace by " "Climatic controls..." (the climate exerts some control on floods but not the science of climate) Response: We followed the reviewers suggestion and changed the heading to “Climatic controls on floods”. P1056 L25&26: "...one should expect larger floods...when both SCAN and EA are in negative phase" why is that? Can you discuss the process chain leading to such a relationship? Response: This correlation was only found to be significant at the 10% significance level. Therefore we removed this relationship from the section 3.3.2 by removing the text “. . .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).” (Page 13, lines 403-406). P 1057 L2&3:"significant negative correlation" between DOY and EA in MAM...a correlation of -0.38 is not very impressive. It seems a bit farfetched to draw conclusions about causal relationships based on weak correlation. I suggest to cut down the entire paragraph to just showing the Table and discuss only the significant relations. Response: The correlation between the occurrence date (DOY) of floods in Abisko catchment and the spring average (MAM) of the EA index stated in Table 7 was found to be statistically significant at the 5% level. P1058 L20 "...Tarfalajokk do not show significant, increasing or decreasing trends" Response: We could not find a match for the cited phrase in this comment. P1059 L56: "floods are traditionally snowmelt-generated"...I think they do not care about traditions, but I agree that they are "usually/typically" generated from snowmelt Response: We replaced “traditionally” with “typically” (page 17, line 510). P1060 L13-15: "showed significant correlations to NAO and AMO...(Table 7)", Table 7 does NOT show significant correlations between the mentioned quantities! Response: The reviewer is right. We referred wrongly to the AMO index in this section. We corrected the references to the climate pattern indices asÖ “The mean summer discharge and flood magnitudes in Abisko catchment showed significant correlations to the annual NAO index and the EA index of the previous winter season (Table 7). Because both the NAO index and the EA 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.” (lines 525-530). P1060 L27 "climate records" replace by "meteorological records" Response: We followed the reviewer’s suggestion and replaced “Climate records” with “meteorological records” on page 17, line 538. P1061 L4: "thawing permafrost...that can lead to increased catchment permeability..." is awk wording. Better: " can lead to increased retention capacity of unfrozen ground" Response: We followed the reviewer’s suggestion and replaced “catchment permeability” with “retention capacity of unfrozen ground” (page 18, line 544). P1061 L19-xx: "our results suggest that ...can fundamentally change the hydrologic responses" but you do not discuss mechanisms that would explain the observed trends, therefore you cannot really conclude about fundamentals. L21 "our observations indicate that sub-arctic mountain catchments..." this conclusion cannot be substantiated by the present study. You compare sub-arctic catchments of different glacier coverage not a mountainous to a low-elevation catchment. L25 "...attributed in large parts to the decreased size of the glacier" This statement is wrong, the mentioned attribution is never made. Reduced retention capacity may results from shrinkage of the firn area. How shrinkage of the glacier may lead to similar reduction needs to be discussed. How large is the area reduction of the glacier over the considered period? Response: The reviewer is right. Please see our response to the main criticism for the main changes made in the manuscript. In order to support the discussion of potential mechanisms that would explain the observed hydrological trends in Tarfala catchment we also added a new sub-section to the methods and data section that provides information on the glacier mass balance data and data regarding the glacier volume and area changes of glaciers in Tarfala catchment. Since most of this data has been published recently (e.g. Zemp et al., 2009; Koblet et al., 2010; see references in the manuscript) the authors do not see the need to provide this information with a figure in this manuscript. As mentioned, we added the following text at lines 193-203: 2.2.3. Glacier mass balance data For the Tarfala catchment continuous long-term mass balance data are available for the 2.9 km2 Storglaciären (65° 55’N, 18° 35’E) located in the southwest of the catchment at an elevation range of 1130 to 1700 m a.s.l. Storglaciären is described as a polythermal glacier with a perennial cold surface layer in the ablation area (Pettersson et al., 2003). For this glacier, estimates of the annual winter (bw), summer (bs), net balance (bn), the equilibrium line altitude (ELA), and the ablation area ratio (AAR) are available since 1946 through the Tarfala Research Station. In addition time series data of Storglaciären’s glacier mass balance, including volume and area estimates and changes have been published by among others Holmlund and Jansson (2005), Jansson and Pettersson (2007), and most recently Zemp et al. (2009) and Koblet et al. (2010). P1062L8-10: "...catchment properties that promote fast runoff such as high-gradient topography, limited soil storage" It is not clear how invariable properties should be responsible for intensification of floods. Same statement is repeated in the conclusions Response: Topography is exerting a first order control on the hydraulic gradient and thus the flow velocity of water in a catchment. We agree that topography is not changing and therefore not primarily responsible for the amplification of the hydrologic response in Tarfala. However, this gradient effect is more efficient if the snow cover, which potentially acts as a storage or buffer, is reduced in the catchment, thus promoting faster flow pathways over perhaps longer time periods (if snow cover is melting earlier in the summer). This effect could be even enhanced if increased wetness within the catchment (for example due to occurrence of more liquid summer precipitation late in the season after snow has melted) promotes higher connectivity of surface flow pathways. This topographic effect is reduced in catchments that have a lower topographic gradient and a larger storage (i.e. natural soil storage or lakes and wetlands) as it is the case in Abisko catchment. Similar relationships have been found by for example Birsan et al. (2005) for glacierized catchments in Switzerland. However, this text was removed when streamlining the discussion and replaced with the following sentence “On the other hand, the increase in flood magnitudes of Tarfala is likely due to the increase in extreme precipitation events in conjunction with catchment properties that promote fast runoff such as low glacial snow/firn cover, high antecedent

wetness in years with above-normal precipitation and increased mean streamflow due to increased glacier melt.” page 20, lines 618-622. Likewise we replaced this statement in the conclusions and inserted the following text: “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 low glacial snow and firn cover, high antecedent wetness in years with above-normal precipitation and increased mean streamflow due to increased glacier melt.” page 21, lines 661-663. P1063 L20-xx The captions to Tables 6 and 7 should make clear to which period the presented statistics refer to. Response: We agree and added the following sentence to both figure captions: “The results are shown for the comparison period of 1985-2009.”. In addition we recalculated the statistics shown in Table 6 for the 1985-2009 period only. Fig 6 should also show important glacier properties such as location of the equilibrium line and the firn area since these need to be discussed when interpreting the observed trends in summer discharge. Response: We disagree. Changes in snow cover (which is indicated in Figure 6) ultimately translate into a change in AAR or ELA. Since this relationship is explained in the test, we do not see the need to add these concepts to Figure 6 and increase the complexity of the figure. Supplementary material: should be presented in the MS rather than in the supplement since the material is crucial to the discussion. Response: We followed the reviewer’s suggestion and moved the Table S1 shown in the supplementary material to the main body of the manuscript. This table is now Table 8. In addition we merged Table S2 with Table 7, which was showing the correlation between climate pattern indices and the flood magnitudes, the flood timing and the mean summer discharge in Abisko and Tarfala catchment for the comparison period 1985-2009. Table S1 does not present numbers "indicated by a star" as mentioned in the caption Response: The reviewer is right. We removed the reference to “indicated by a star”. The abbreviations of the climate indices in Table S2 should be explained in the caption. Response: We followed the reviewers suggestion and explained abbreviations in the figure caption.

References: Hock, R., P. Jansson and L. Braun, 2005. Modelling the response of mountain glacier discharge to climate warming. In: Huber, U. M., M. A. Reasoner and H. Bugmann (Eds.): Global Change and Mountain Regions - A State of Knowledge Overview. Springer, Dordrecht. 243-252. Førland E. And Hanssen-Bauer, I. 2000. Increased precipitation in the Norwegian Arctic: true or false? Climatic Change 46: 485-509.

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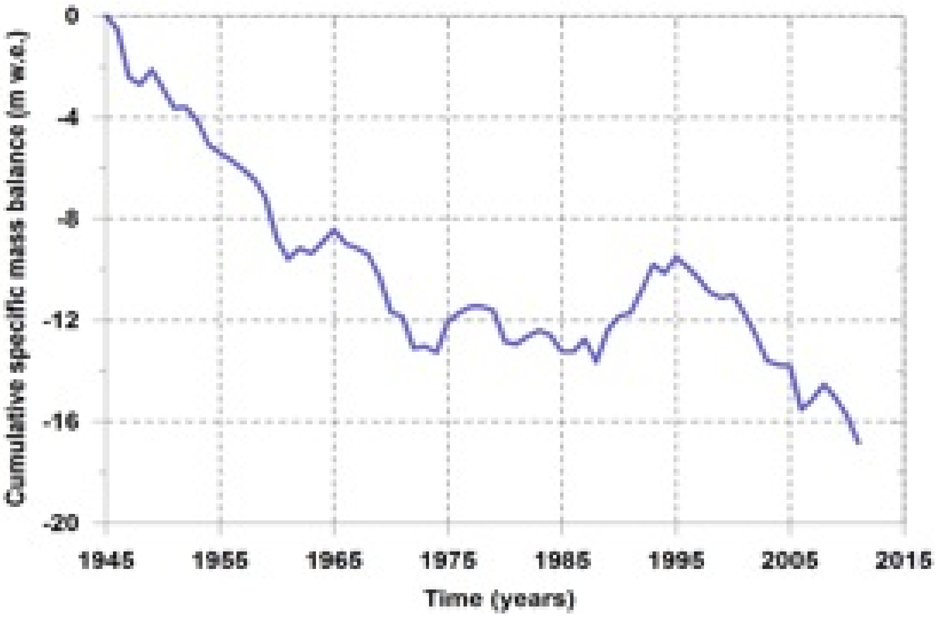

Fig. 1. Cumulative glaciological mass balance of Storglaciären for the period 1946-2009.

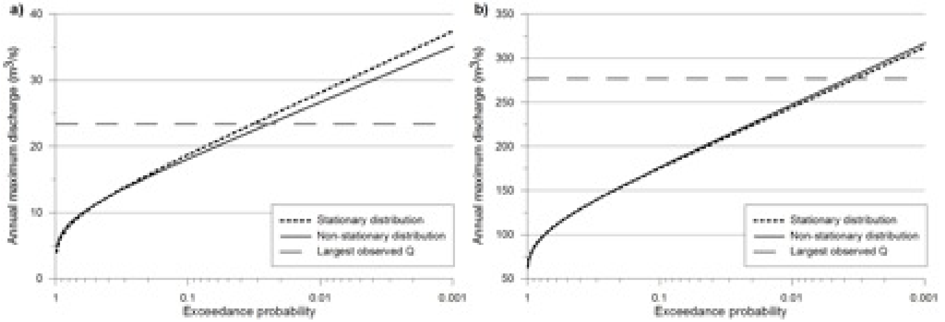

Fig. 2. The average distribution of flood risk (solid line) estimated based on all flood peaks observed in the Tarfala (a) and Abisko (b) catchment. Dashed lines show models conditioned on observed and foreca

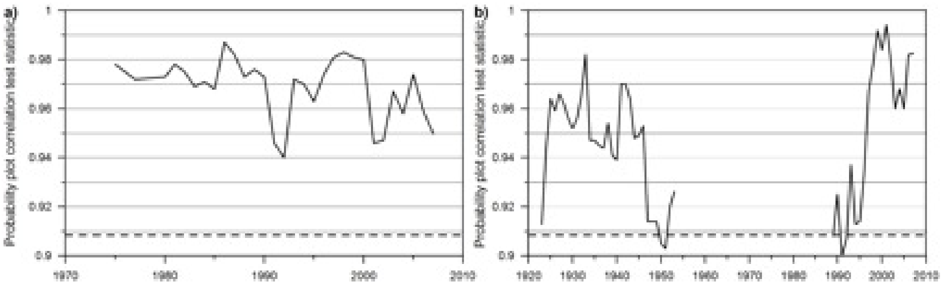

Fig. 3. Results of the probability plot correlation test statistic (solid lines) for the 10-year moving window estimates of flood quantiles using the Gumbel distribution for Tarfala (a) and Abisko (b) catchme

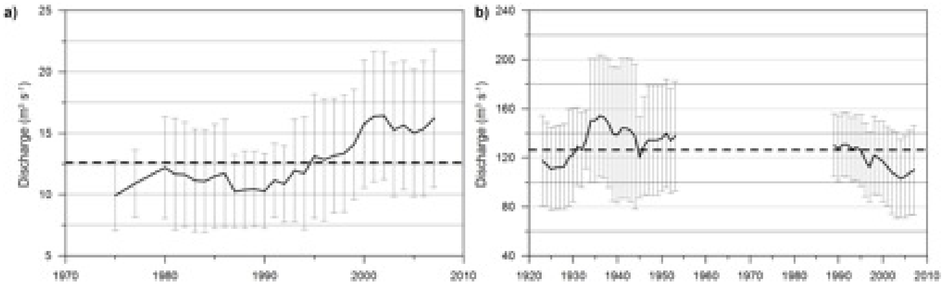

Fig. 4. Time series off the mean and standard deviation (vertical error bars) of each 10-year moving window flood distribution.