Climate impact on floods – changes of high-flows in Sweden for the past and future (1911-2100)

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Abstract: There is an on-going discussion whether floods are more frequent nowadays than in the past and whether they will increase in a future climate. To explore this for Sweden we merged observed time-series from 69 sites across the country (450 000 km^2) for the past century with high-resolution dynamic model projections of the up-coming century. The results show that the changes of daily annual high flows in Sweden oscillate between dry and wet periods, but there is no significant trend of the past 100 years. Temperature was found to be the strongest climate driver for changes in river high-flows, as these are mainly related to snow melt in Sweden. In the future, the daily annual high-flows may decrease by on average -1% per decade, mainly due to lower peaks from snow melt in the spring (-2% per decade) caused by higher temperatures and shorter snow season. On the contrary, autumn flows may increase by 3% per decade due to more intensive rainfall. This indicates a shift in flood generating processes in the future, with more influence of rain-fed floods. Climate impact may be more significant in some specific rivers than what it found on the average for the whole country. For selected catchments, the temporal pattern of daily high-flow in the future was found to shift to about one month earlier spring floods in the North/Central part of Sweden and more frequent high flows in the south. Moreover, the current border between snow-driven floods in North/Central Sweden and rain-driven floods in the South, may be moved towards higher latitudes due to less snow accumulation in the south and at low altitudes. A tendency towards the modelled projections could be found for the last 25 years regarding timing in daily high flow. Uncertainties related to the study are discussed in the paper, both for observed data and for the complex model chain of climate impact assessments in hydrology.

Key-words: long-term records, S-HYPE, climate change, catchment modelling, river flow, trend analysis

1. Introduction

Numerous severe floods have been reported globally in recent years and there is a growing concern that flooding will become more frequent and extreme as an effect of climate change. Generally, a warmer atmosphere can hold more water vapor and, in effect, there is a growing potential for intense precipitation that may cause floods (Huntington, 2006). Some scientists have argued that the observed changes in climate (e.g. observed increase in precipitation intensity) already have an impact on river floods (e.g. Kundzewicz et al. 2007, 2008; Bates et al., 2008). However, detection of changes in floods is associated with methodological problems and large uncertainties arise when exploring trends in both past and future high flows.

Changes of the river flood regime are traditionally analyzed either through statistical approaches using observed data (e.g. Lindström and Alexandersson, 2004; Stahl et al., 2010; Schmocker-Fackel and Naef, 2010), or through process-based numerical modeling using the scenario approach (e.g., Dankers and Feyen, L., 2008; Arheimer et al., 2012; Bergström et al., 2012). Both these methods include potentials and many challenges, as discussed by Hall et al. (2014). To sum-up, the fundamental problems with climate impact assessments is that: 1) observed time-series may include natural long-term cycles, which may be induced by climatic

oscillations or persistent memory of hydrological processes (Markonis and Koutsoyiannis, 2012; Montanari, 2012). This will influence all statistical trend analysis and make them very sensitive to the period chosen for the study; 2) Global climate models (GCMs) do not correspond to the observed climatology (Murphy et al., 2007) and uncertainties arise in each step of the model chain in hydrological impact assessments (Bosshard et al., 2013; Donnelly et al. 2014). As a response to the difficulties and uncertainties involved, much scientific efforts during the last decade have been put on compensating for these two major problems to find methods for more robust trend analysis and scenario-model results (see full review in Hall et al., 2014).

Most of the published works relate changes in climate to mean annual flow, while impact studies on high flows are rare and specific drivers are usually not examined. One way to understand the change of flood generating processes is the analysis of seasonality. Some of the main driving processes such as synoptic precipitation, convective precipitation, and snowmelt events are highly seasonal. The flood occurrence within the year may therefore give clues on the flood producing drivers and their changes (e.g. Parajka et al., 2009; Petrow and Merz, 2009; Kormann et al., 2014).

Hall et al (2014) argue that future work should aim to draw upon, extend, and combine the strength of both the flow record analysis and the scenario approach. The present study is in line with this idea to merge analysis of long time-series of the past with dynamic scenario modeling of the future. Moreover, climate change detection should be based on good quality data from observation networks of rivers with near-natural conditions (e.g. Lindström and Bergström, 2004; Hannah et al. 2010) and time-series of more than 50-60 years are recommended to account for natural variability (Yue et al., 2012, Chen and Grasby, 2009).

In this study, we therefore used 69 unregulated rivers with gauged time-series for 100 years (1911-2010) to examine recorded changes in flood frequency and magnitude. The modeling of the future was performed according to the typical impact modelling chain: 'emission scenario–global climate model–regional downscaling–bias correction–hydrological model–flood frequency analysis', using the national hydrological-model system S-HYPE for Sweden with observed climatology, and for two climate model projections of 100 years (2000-2100). An overlapping period of 50 years was used to check the agreement between observed and modelled trends in high flows. The following scientific questions are being addressed in this paper:

i) What changes in daily high-flows have we experienced in Sweden during the last century, and which future changes can we expect for the next hundred years?
ii) Which climate drivers can be attributed to such changes?
iii) How will flood regime and dominating flood-generation processes change in the future?

2. Data and Methods

2.1 Landscape characterization and observed high-flows of the past

Sweden is situated in Northern Europe and has a surface area of about 450 000 km^2. About 65 % is covered by forest, but there are significant agricultural areas in the south of the country. Sweden is bordered by mountains to the west and a long coastline to the south and east, meaning that the country is drained by a large number of rivers which start in the west and run eastwards to the Baltic Sea and southwest to the North Atlantic Sea. Most of the rivers are regulated as some 50% of the Swedish electricity consumption originates from hydropower. To search for general tendencies in flood change, results from analyses of long-

92 term records and scenario modelling was aggregated to four regions in Sweden (Fig. 1)
93 defined by Lindström and Alexandersson (2004). The river basins in these regions have
94 similarities in climate and morphology but also represent the Swedish catchments of the
95 marine basins. 69 gauges with long records and no, or very little, up-stream regulation in the
96 catchment, were chosen from the national water archive to represent the four regions (Fig. 1).

97

2.2 Model approach of the past and the future

99 Water discharge and hydrometeorological time-series of the past and the future was extracted
100 from a national multi-basin model system for Sweden, called 'S-HYPE'. The model system
101 covers more than 450 000 km^2 and produces daily values of hydrological variables in 37 000
102 catchments from 1961 and onwards. It is based on the processed-based and semi-distributed
103 HYdrological Predictions for the Environment (HYPE) code (Lindström et al., 2010). The S-
104 HYPE application (Strömqvist et al., 2012, Arheimer and Lindström, 2013) covers the
105 Swedish landmass including transboundary river basins. The first national model-system was
106 launched in 2008, but S-HYPE is continuously improved and released in new versions every
107 second year. Observations are available in 400 sites for model evaluation of daily water
108 discharge. The present study on changes in flood magnitude and frequency was made using
109 the S-HYPE version from 2010.

110 The S-HYPE model was forced with daily precipitation and temperature, using national grids
111 of 4 km based on observations and climate model results, respectively. The grid based on
112 observations is produced daily by optimal interpolation of data from some 800 meteorological
113 stations considering variables such as altitude, wind speed and direction, and slopes
114 (Johansson, 2002). For this study on floods, gridded values were transformed to each subbasin
115 for the period 1961-2010 to force the S-HYPE model.

116 For climate model results, two grids based on different general circulation models (GCMs)
117 were used; HadCM3Q0 (Johns et al., 2003, Collins et al., 2006) and ECHAM5r3 (Roeckner et
118 al., 2006). The projections were chosen to represent different signals concerning the future
119 temperature change. Within the ensemble of 16 climate projections studied by Kjellström et
120 al. (2011), the Hadley projection is among the ones with the largest future temperature
121 increase in Scandinavia whereas the Echam projection is in the small-to-medium range.
122 Bosshard et al. (2014) showed that from all possible selections of two projections from this
123 ensemble, the chosen ones span a larger uncertainty range than at least 70 % of the other
124 combinations. Both projections simulate effects of the emission scenario A1B (Nakićenović et
125 al., 2000). GCM results from both models were first down-scaled dynamically to 50 km with
126 the RCA3 model (Samuelsson et al. 2011). Thereafter, daily surface temperatures and
127 precipitation were further down-scaled to 4 km and bias corrected, using the Distribution-
128 Based Scaling (Yang et al. 2010) with reference data from the grid based on observations for
129 the period 1981-2010. Finally, gridded values were transformed to each subbasin for the
130 period 1961-2100 to force the S-HYPE model.

131

2.3 Quality check and Analysis

133 The model skill to predict daily annual high flows was tested in 157 gauging sites without
134 regulation for the S-HYPE version 2010. Model deviation was calculated both for the
135 calibration period and an independent validation period of the same length, using the forcing
136 grid based on observations. Moreover, simulated trends were compared between the various
137 simulations. Observed and modeled time-series were overlapping for the period 1961-2010
138 and this 50 year period was thus used to check agreement between simulations. Observed and
139 modelled results from the 69 river gauges were extracted and compared for different time-

140   slots. Simple linear regression was used as trend test, as previous studies have shown that
141   there is no large difference in results from different trend test used for Swedish flood data
142   (Lindström and Bergström, 2004). Statistical significance (*P=0.05*) was estimated based on
143   the formula by Yevjevich (1972; page 239).

144   To explore the spatial variability of climate change, the high resolution results from the S-
145   HYPE modelling was plotted as maps for two time-windows (mid-century: mean of 2035-
146   2065 and end of century: mean of 2071-2100), showing estimated change for each climate
147   projection. Moreover, the annual distribution of high-flows was plotted for the past and future
148   in 15 selected catchments across the country to identify emergent patterns.

149   To quantify temporal changes of annual high flows, recorded values for the 69 gauges and
150   modeled data from the 37000 subbasins were divided with the average value of the reference
151   period (1961-1990) to get the relative anomalies in each site. Then these anomalies were
152   averaged for the country and each region, respectively, so that a relative change was received
153   for each domain and each year. Frequency analysis was based on how many of all sites that
154   were exceeding the 10-years flood for each year in each region.

155   To attribute climate drivers to changes, time-series of temperature and precipitation were
156   extracted from the S-HYPE modeling for each subbasin and dataset (1961-2010, and 1961-
157   2100). Also these data were averaged for regions, based on site specific annual anomalies
158   compared to the long-term average for the reference period in each site. Relative changes
159   were considered for average and extreme precipitation, but for temperature absolute values
160   (^{o}C at 2 m) were used as the variability is less and it is not area dependent.

161   To distinguish major long-term changes in the flood generating mechanisms, seasonal
162   changes in magnitude and frequency of high flows were analyzed by separating peaks
163   appearing in March-June and July-February, respectively. Spring peaks, which appears in
164   March to June along the climate gradient from south to north of the country, are mostly driven
165   by snow melt, while Autumn/Winter peaks are primarily rain-driven in Sweden. Analyzing
166   each group separately will thus give a hint about a shift in hydrological regime and dominant
167   processes causing the high flows. In addition, changed timing of daily high flow in specific
168   rivers was explored in 15 selected catchments to attribute changes to catchment specific
169   processes. In this latter exercise, the last 25 years were highlighted to illustrate any tendency
170   of shift towards the projected future.

171   Model results are presented after Gauss filtering, with a standard deviation corresponding to a
172   moving average of 10 years, to distinguish flood rich and flood poor periods in the long time-
173   series. The trend of the Gauss curves will reflect the possible climate trend more clearly
174   without the noise from single years. In addition, results of single years from a climate model
175   should not be considered to be representative for that specific year as the climate models
176   gives a projection for long-term mode, and not a forecast for specific years.

177   ## 3. Results

178   The four regions of Sweden were analyzed separately and lumped for the country as a whole,
179   respectively, using the 69 catchments or the S-HYPE model. However, no clear difference in
180   trends between regions was found and therefore only results for entire Sweden are presented
181   below.

182

183   **3.1 Observed annual maximum of daily high flows during the past**

184 During the last hundreds years, the observed anomalies in annual maximum of daily flow is
185 normally within ±30% deviation from the mean of the reference period (Fig 2). During the
186 1980's to 2010 the variability in flood frequency has been less pronounced, except from the
187 extended event in 1995 when most of the 69 sites experienced at least a 10-year flood. This
188 was linked to the outstanding spring flood, especially in the north, where previous maximum
189 discharge records were exceeded at some sites by as much as 60%. Spring floods normally
190 correspond to the annual high flow (cf. the two middle panels of Fig. 2), with a few
191 exceptions. One such exception is the autumn flood of the year 2000 which affected the
192 central-southern parts of Sweden.
193
194 For the past hundreds years of this study, no obvious trends in magnitude of high flows can be
195 seen in the observed time-series for Sweden. A slight decrease in flood frequency can be
196 noted. In a shorter perspective, however, autumn floods seem to have increased substantially
197 over the last 30 years, but before that the tendency was falling. 1970 appears as the turning
198 point and the summer and autumn floods in the 1920s were actually higher than in recent
199 decades.
200

201 **3.2 Model performance and comparison of trends in simulations**

202 The median absolute error was on 15% for daily annual high flows of the S-HYPE model
203 (version 2010) in 157 sites results both for calibration and validation periods (Fig. 3). For
204 calibration there was a median underestimation of -0.7%, while the validation period resulted
205 in a median underestimation of -3.5%. The major outliers could be related to some missing
206 lakes in this model version, and for those catchments the model overestimated high flows as
207 the dampening effect was missing in the model set-up.

208 When comparing S-HYPE simulations using different forcing data, no significant trends were
209 found in observed or modelled high flows for the full overlapping period of 50 years (Table
210 1). Some small deviation could be found between the full overlapping period and reference
211 period, which was only 20 years shorter. Accordingly, no significant trends for shorter periods
212 were found either, except for the Hadley projection, which shows significant trends during the
213 independent period and the reference period. Climate projections are not necessarily in phase
214 with observed climate fluctuations, which was the case with the projections used in this study.
215 This was also found for the longer time-period of 50 years, when the Echam projection show
216 opposite sign of slope compared to Hadley as well as to observed climate.

217 The slope in the modelled time-series using observed climate was generally larger than in
218 observed trends. This indicates that the S-HYPE model may overestimate the sensitivity to
219 changes in forcing data or that there are compensating processes not included in the S-HYPE
220 model (e.g. changes in land-use, vegetation, abstractions). It may also be an artifact from bias
221 in precipitation data as discussed by Lindström and Alexandersson (2004) and Hellström and
222 Lindström (2008). In 4 out of the 5 examined time slices, the S-HYPE model forced with
223 observed climate show the same sign of slope as observed gauges. Again, it should be noted
224 that none of these trend slopes are significant.

225

226 **3.3 Future climate projections of Sweden**

227 Figure 4 shows the large differences in spatial patterns when forcing S-HYPE with the two
228 future projections of annual precipitation and average temperature across Sweden. The results
229 for the reference period (1981-2010) are similar for the two climate projections (Hadley and
230 Echam) since precipitation and temperature have been scaled against the same 4 km grid,
231 which is based on observations. For future climate change, however, there are in many cases

232 large differences and sometimes conflicting results between the climate models, in particular
233 for local conditions.

234 According to both projections, the mean temperature will increase with between 3 and 5
235 degrees for different parts in Sweden. The increase is faster in the Hadley model compared to
236 Echam, although Echam eventually shows high temperature for more extended areas by the
237 end of this century. The average precipitation will increase by 100-400 mm per year
238 depending on location in Sweden. The Hadley projection shows a faster and more significant
239 increase in precipitation.

240 The predicted change in average river flow varies between 30% increase and 30% decrease
241 for different parts of Sweden. The model results based on the Echam projection shows higher
242 flow in the northern mountains and a decrease for the rest of the country. The decrease is most
243 pronounced at the mid-century (Fig. 4). Hadley, on the other hand, shows increased river flow
244 in all of northern Sweden and a decrease mainly in the south-western part of the country. The
245 difference in river flow is mainly a combined effect of precipitation and evapotranspiration in
246 the hydrological model. The precipitation is received from the climate models while the
247 evapotranspiration is calculated in the HYPE model, based on temperature from the climate
248 models. The large difference between the results of the climate projections means that the
249 uncertainty in estimating future conditions is large.

250 The future changes in mean high flow as well as the magnitude of the 10- year flood show a
251 spatial variation between 50% increase and 50% decrease (Fig. 4), but for most of the country
252 the change is 15%. Highest levels are estimated for Northern part of the mountain range and
253 in southwestern Sweden. Lower 10-year floods were detected in the mountains of Jämtland,
254 which is one of the most snow rich areas in Sweden. There is a large spread in results between
255 the two projections so results on high flows should be treated carefully on the local scale. The
256 Hadley projection results in larger changes for the whole country while Echam indicates
257 smaller changes compared to the reference period.

258 The results confirm that there are large differences when assessing future climate change,
259 dependent on which climate model that is being used, although they are using the same
260 emission scenario. The two projections shown here are far from covering the full range of
261 uncertainty; however, a close analysis shows that they do cover the range of an ensemble of
262 16 climate projections, used at the Rossby Center, especially at the higher end of the
263 extremes. The corresponding river flows calculated with S-HYPE falls within the 25-27%
264 range of the larger ensemble when using the HBV model (Bergström et al., 2012).

265

3.4 High flow in the future and climate drivers

267 Figure 5 shows that even though the forcing datasets are out of phase to each other and the
268 observations, similar trends for the future can be detected. Most substantial is the temperature
269 rise with 5 degrees by the end of the century in both projections. Also the precipitation shows
270 a strong increase, both in annual means and in maximum daily precipitation. Similar trends
271 are found in the observed data, although only 50 year and the Gauss filter result in a rather
272 short overlapping period for trend analysis. However, the strong trend in precipitation is not
273 reflected in the river flow. Note that the temperature signal during the 50 years in Figure 5 is
274 not representative for the 20th century as a whole (Lindström and Alexandersson, 2004).

275 The annual maximum of daily flow does not show any trend for the past 50 years but a
276 decreasing trend in the future. This can be explained by lower spring peaks from snow-melt as
277 the snow period will be shorter and evapotranspiration higher due to higher temperature. The
278 results did not show any clear trend in the frequency of the 10-years flood. For Sweden,
279 temperature thus seems to be a stronger climate driver for river high-flow than the

280 precipitation. This is probably reflecting that high flows are mainly related to snow melt in
281 this country.

282

3.5 Changes in the flood regime

284 The most significant result of changes in floods for Sweden was found when comparing
285 annual maximum of daily flows during the spring and autumn separately. Figure 6 shows a
286 significant decrease in magnitude of spring floods and a significant increase of autumn floods.
287 For spring floods, the trend when using observed forcing data is weak, but the trend for
288 climate projections reduces the spring flood by some 20% by the end of the century vs the
289 1970s.

290 Autumn floods show a trend in the opposite direction, with some 20% higher magnitudes by
291 the end of the century. However, it should be noted that autumn floods are in general only
292 about half as high as the spring floods, except from southern Sweden where autumn floods are
293 usually higher. This is also why this change in flow regime is not detected when only looking
294 at maximum annual values for the whole country, which are dominated by the spring peak
295 due to snow melt. The observed increase in autumn peaks shows a very significant trend for
296 the last 50 years, while for climate projections, the Hadley projection show the largest
297 increase in trend for the future. The results indicate an on-going shift in flow regime, which
298 can be referred to flow generating processes; there will be less impact from floods generated
299 by snow melt in the spring and more frequent floods generated from intensive rainfall in the
300 autumn.

301

3.6 Combined results to detect long-term changes in high flows

303 For the past 100 years, no significant trends and very small mean deviation could be detected
304 for maximum daily high flows (Table 2). The mean deviations for the autumn floods *vs* the
305 reference period in the 69 river gauges was 9%, which means that the reference period is not
306 representative for autumn floods. This was also detected in Figure 2. In contrast to the results
307 for the last 50 years (Fig. 6), the autumn high flows show a negative trend for the last 100
308 years, although not significant.

309 When using 100 years of climate-model data with future projections, significant trends were
310 detected for up-coming changes. Both projections showed trends in the same direction but of
311 different magnitude and significance. The annual high flows show a declining trend, which is
312 even more pronounced when looking at only spring peaks. S-HYPE using Echam forcing
313 shows the largest negative trend with in average more than 2% reduction per decade of spring
314 peaks. Autumn peaks, on the contrary, show positive trends in the future, especially when
315 using the Hadley climate-model data, which resulted in 3% higher autumn peaks per decade.
316 These trends for the future were all significant at *P=0.05* levels and confirm the visual
317 inspection of Gauss curves on changes in flow regime (Fig. 7).

318 Figure 7 show that there have been large climate induced long-term oscillations in maximum
319 daily high flows during the last 100 years and that these are expected to continue for the next-
320 coming hundred years. The observed oscillations of flood frequency are larger in past
321 observations than in future projections. This may be an artifact of grid size in climate
322 projections, which may underestimate local extremes. Future long-term trends were consistent
323 between climate projections, but only one statistically significant for each trend (cf. Table 2).

324 When exploring the seasonal cycle of high-flow distribution in selected catchments, we found
325 a temporal shift in maximum daily high-flows between the past, present and future (Fig. 8).
326 The last 25 years (present) have been warm and wet and show a tendency towards the results

327 of the climate projections. Note that the time periods as combined in Figure 8 are of different
328 length and show absolute values instead of changes, which makes it difficult to compare the
329 magnitudes and the figure thus only illustrate temporal changes during an average year. The
330 results show that the timing of daily high flows may change with about one month earlier
331 spring floods in the North/Central part of Sweden and more frequent daily high flows in the
332 south. This is probably due to less snow accumulation in the south and at low altitudes.

333 Moreover, Figure 8 indicates that the spatial pattern of flow regimes across the country may
334 change at some locations. There is a distinct border between snow-driven high flows in
335 North/Central Sweden and rain-driven high flows in the South. For historical data the Fyrisån
336 River belongs to the Northern part with a distinct snow-melt peak during spring, but for the
337 last 25 years as well as for the climate projections, this peak in high flow is no longer found.
338 Climate impact on floods may thus be much more significant in some specific rivers than
339 what it found in the average for the whole country. In this particular case, the risk for floods
340 will become much lower than in past climate.

341

4. Discussion

4.1 Changes of high flows in Sweden

344 The study shows that no tremendous changes in magnitudes of high flows have been recorded
345 so far, or are expected from climate change in Sweden. However, only rivers were studied
346 here and not the small scale flooding due to changes in intense local precipitation, which may
347 be more crucial in the future, e.g. for urban areas (Arnbjerg-Nielsen et al., 2013; Olsson and
348 Foster, 2014). Although not significant, there was a small negative trend in river high flow of
349 0.4% per decade in 10-yr flood frequency. This confirms previous findings by Wilson et al.
350 (2010) for Scandinavia, who found a decrease of peak-flow events in long time-series from
351 Sweden, Finland, and parts of Denmark, while increase was found for western Norway and
352 Denmark. The changes we found for future changes, however, were statistically significant
353 ($P=0.05$) and of some larger magnitude. Daily annual high-flows may decrease by 1% per
354 decade in the future, while autumn flows may increase by 3% per decade, but the trends are
355 far from linear. The high deviation versus the reference period shows that this period (1961-
356 1990) cannot be used as a reference in the future. Most design variables for infrastructure in
357 Sweden are based on this period, but must thus be recalculated using a new reference period
358 to adapt with climate change. Unfortunately, when looking at the past century, it seems like
359 this period was not very representative for natural variability either, especially not for autumn
360 floods.

361 The merging of Gauss curves using both 100 years of observations and 100 years of climate
362 projections, clearly visualize the relative changes and influence from long-term oscillations
363 (Fig. 7). This combined way to analyze both observations and model results simultaneously,
364 increases the understanding of natural versus accelerated changes in long time-series. Using
365 shorter time scales of observed climate gives a very different picture. For instance, when
366 starting the analysis during the 1960's (Fig. 5 and Fig. 6) the trends in increased autumn
367 floods seem very strong already, but this trend disappears when using 100 years of
368 observations (c.f. Table 2 and Fig. 7). For Swedish climate, 50 years is thus not enough for
369 trend detection. Lindström and Bergström (2004) found that trend detection is very sensitive
370 to starting and ending years, which is coherent with findings for other climate regions (e.g.
371 Hannaford et al., 2013; Yue et al., 2012; Chen and Grasby, 2009).

372 In contrast to the trend analysis, more radical changes of high flows were found within the
373 annual dynamics and in specific catchments. The earlier spring floods in the North/Central
374 part of Sweden, more frequent high flows in the south and even disappearing spring peak
375 (Fig. 8) could be attributed to less snow accumulation in the south and at low altitudes.
376 Similar findings has been noted for Austria, where runoff trends could be linked to altitude
377 also within catchments and attributed to changes in different processes dominating at different
378 elevations (Kormann et al., 2014).

379 Spatial patterns can be noisy and make it difficult to detect overall trends due to local events.
380 In this study we used 69 sites and considered the mean of relative deviation (not absolute
381 values) as representative for the country. The frequency analysis also shows how extensive in
382 spatial terms the specific high flows were. Originally, the analysis was made in four
383 hydroclimate regions (Fig. 1) but as the results showed very little difference between those
384 regions for observed changes, they were considered too small to represent climate change.
385 However, for the climate projections of the future, there was a large difference between the
386 North and the southernmost regions (Fig. 4 and Fig. 8). For instance, the positive trend for
387 autumn flows when using the Hadley projection was mainly seen in the north. Only spatially
388 aggregated results for the whole domain were used for trend detection in this study, as the
389 projections showed so large discrepancy on local or regional level. The uncertainty in climate-
390 model results was judged to be too large for high resolution analysis. Nevertheless, the
391 observed high flow during the last 25 years show a slight tendency towards the temporal
392 changes suggested by the projections for individual catchments (Fig. 8).

393 Also in the literature, we find large discrepancies in results of climate change impact on
394 frequency and intensity of floods for the Northern European countries. For instance, Dankers
395 and Feyen (2008) and Hirabayashi et al. (2008) indicated decrease, while Lehner et al (2006)
396 suggested increase, and Arheimer et al (2012) projected over all very little change in water
397 discharge for the Baltic Sea region. Discrepancies in conclusions regarding the future can be
398 referred to uncertanties in GCMs, downscaling methods, and hydrological models (e.g.
399 Bosshard et al., 2013; Donnelly et al., 2014; Hall et al., 2014).

400

401 4.2 Methodological uncertainties

402 Both observations from the past and modelling of the future involve uncertainties. The
403 observed time-series of river flow from the Swedish archive of national monitoring are based
404 on measurements of water level. The water flow is then calculated using a traditional rating
405 curve based on an observed relationship between water level and flow in each site. Hence,
406 each rating curve involves a number of variables to be decided and it is well known that rating
407 curves change over time (e.g. Tomkins, 2014; Westerberg, 2011) or may be over-simplistic
408 due to hydraulic conditions at the gauging site (Le Coz et al., 2014). The gauging sites for the
409 Swedish rivers are considered as rather stable but recently an up-dated rating curve changed
410 the estimated water flow by some 30%. When rating curves are up-dated, the historical flow
411 is reconstructed to avoid sudden shifts in the time-series. Nevertheless, this can be a major
412 source of error in all analysis using observations of river flow. Peak events and extreme high
413 flows are more uncertain than normal conditions, as the flow may then be out of the calibrated
414 range of the rating curve and the water may take new flow paths, which by-pass the gauging
415 station. In Sweden, ice jam is another common monitoring problem and observed time-series
416 are corrected for ice-jams and reconstructed each year. These corrections can be crucial for
417 estimates of spring peaks in some of the northern rivers and is a source of uncertainty.

418 Precipitation is even more difficult to monitor and model. The observations are influenced by
419 changes in vegetation, wind, snow/rainfall, and monitoring equipment. Probably the
420 monitoring technique at the beginning of last century underestimated precipitation (Lindström

and Alexandersson (2004). We also know by experience that the 4 km precipitation grid for operational hydrology, which we used in this study, underestimates precipitation in the mountains by some 10-20%. This will of course affect the hydrological model results when using this grid for observed climate. The validation of high flows in S-HYPE resulted in a median absolute error of 15% and -3.5% in underestimation in unregulated rivers (Fig 3). When the S-HYPE model is up-dated with gauged flow for national statistics and design variables, the underestimation is -5% for mean high flows at 400 gauging stations, also including regulated rivers (Bergstrand et al., 2014). The underestimation of high flow is affected by the underestimated precipitation.

For estimates of floods in the future, major uncertainties are related to the following components in the model chain: 1) climate model projections, 2) downscaling/bias correction techniques, and 3) hydrological model uncertainties in the region studied, and interaction between these three components (e.g. Bosshard et al., 2013).

4.2.1. Climate models

The discrepancy between the climate model projections show that local results are very uncertain and we often found the opposite direction of trends in climate signals between the projections. Accordingly, it is well known that climate models differ considerable in precipitation pattern for parts of Europe (e.g., van Ulden and van Oldenborgh, 2013). The uncertainty further increases when extreme events are simulated by GCMs and RCMs (e.g., Blöschl et al., 2007). Hence, there is a large uncertainty in the calculations and the results should be treated with caution in this part of the world. Therefore, only aggregated results for the country are analyzed in this study on changes in floods. It is normally recommended that the ensemble mean from using many different climate projections should be the basis for decisions and for impact modeling (e.g. Bergström et al., 2012), but it is not certain that this will actually reduce the overall uncertainties. Ensemble runs correspond to a "sensitivity analysis" (inter-comparison among models) and not to an uncertainty estimation in the statistical sense. Ensembles may also be biased by using many versions of some model, and the GCM/RCMs often include similar descriptions of the physics. In addition, some processes are not well represented in any climate model.

4.2.2. Downscaling and bias correction

Statistical down-scaling and bias correction techniques consist of correcting the simulations of precipitation/temperature empirically by fitting simulated mean and quantiles to the available observations and applying the same correction to future simulations (e.g. Yang et al., 2010). It is therefore assumed that the observed biases in mean and variability of those climate variables is systematic and will be the same in the future, but it needs clarification whether the climate model errors are stationary in time (Maraun et al. 2010). When bias correction methods are applied, the fit of the hydrological model output increases, the variability bound are narrower and the observed runoff regimes are improved compared to uncorrected climate-model data (Bosshard, 2011; Teutschbein and Seibert, 2012). Nevertheless, bias correction may also introduce inconsistency between temperature and precipitation, which highly effects the simulation of snow variables (Dahné et al, 2013) and thereby also flood predictions of the future. Bias correction is also very sensitive to the reference dataset being used, which may result in very different conclusions of hydrological impact of climate change even when everything else is kept constant (Donnelly et al, 2013). Therefore, Donnelly et al. (2014) urged that as well as climate model and scenario uncertainty, the uncertainties in the bias-correction methodology and the impact model should be taken into account in climate change impact studies.

4.2.3 Hydrological model uncertainties in the region studied

469 Although, hydrological models are normally seriously evaluated against observed data and
470 uncertainties are well known and recognized, they are rarely evaluated especially on skills for
471 climate change impact predictions on a process level. The latest S-HYPE version (2012) has
472 an average NSE = 0.81 for 200 stations unaffected by regulation and an average relative
473 volume error of ±5% for the period 1999–2008. For all 400 sites, including both regulated and
474 unregulated rivers, average NSE = 0.70. All criteria for calibration have some drawbacks and
475 one issue with for NSE is that it focuses on timing and can thus underestimate the magnitude
476 of the high flow when the timing is not perfect.

477 The S-HYPE model is assumed to be valid also for ungauged basins, which has been
478 validated in blind tests for independent gauges, resulting in similar values as in calibrated
479 ones for groups of similar catchments (Arheimer and Lindström, 2013). The model does not
480 show any change in bias due to different climate across the country, although Sweden has
481 gradients in temperature and precipitation that are larger than the estimated change in climate
482 projections. However, variables that are sensitive to temperature, for instance
483 evapotranspiration, should be validated especially to test if their parameters are realistic for a
484 changing climate. It is also recommended to use several impact models, for instance Stahl et
485 al (2012) found that the ensemble mean from eight global hydrological models over Europe
486 provided the best representation of trends in the observations.

487 The present scenarios consider changes in atmospheric emissions and concentrations of
488 climate gases. However, there may as well be additional changes in other drivers of the
489 hydrological regime in the future, such as land use and vegetation changes, or constructions in
490 the river channel (Merz et al., 2012). These can also have large impact on flood generation
491 (e.g. Hall et al., 2014) and add uncertainties to the results of flood frequency and magnitude in
492 the future. Arheimer and Lindström (2014) recently reconstructed the total impact of Swedish
493 hydropower on the river-water regime and spring peaks was found to have decreased by 15%
494 on a national scale. The Swedish hydropower was mainly established during 1910-1970. This
495 human alteration of the water resources have thus had a larger impact on river high flow than
496 what can be expected from climate change.

497

498 **4.3 Gauss filtering**

499 Statistical trend analysis were made using discrete values of annual high flows, while the
500 visual inspections where made using a Gauss filter with a standard deviation corresponding to
501 a moving average of 10 years. The Gauss filtering removes the effect of individual years and
502 helps the eye in distinguishing the trends from oscillations. The filter does not remove all
503 noise and some oscillations remains also in a random dataset; however, the filter does not
504 introduce any new oscillations. For instance, the difference between periods in Figure 2 is
505 real, and not artefacts introduced by the filtering. For instance the 1970s was a dry period in
506 practically all of Sweden, whereas the 1920s, 1980s and 1990s were mostly wet years, with a
507 higher frequency of high autumn flows. The same periods stand out in other Nordic countries
508 as well. A Gauss filtered signal, which is based on random values does not show trends (as for
509 instance in the Fig. 5) although it creates persistence.

510 Hence, the filtering is merely used for smoothing the signal and computing decadal averages,
511 but without the disadvantages of an ordinary running average. The Gauss filter acts as a low-
512 pass filter. It removes most of the year to year variation, and thus allows changes with a
513 longer time scale, for instance decades, to be more visible. It might be interesting to note that
514 the same pattern of more persistent periods of drier and wetter years as have occurred in the
515 past (and which are not introduced as an artefact by filtering), seems to be preserved in the
516 climate projections for the future. For climate projections, it is very important not to analyze
517 specific years as the climate models do not have that predictability but only show general

518 trends and fluctuations that may not be in phase with the observed climate. Therefore, we
519 chose not to show specific years from climate impact modelling but only the general
520 tendencies, which are seen more clearly by the filtering.

5. Conclusions

522 The results indicate that there will be some shifts in flood generating processes in the
523 future, with more influence of rain generated floods in Sweden. Climate impact may be
524 more significant in some specific rivers than what it found on the average for the whole
525 country. Uncertainties and simultaneous changes from other drivers than climate must
526 also be accounted for; nevertheless, the results show that:

527 • The changes of daily annual high flows in Sweden oscillate according to observed
528 variability in weather between clusters of years, but there is no significant trend over
529 the past 100 years. A small tendency for high flows to decrease both in magnitude and
530 10-yr flood frequency was noted, but not statistically significant.
531

532 • Temperature is the strongest driver for river high-flows, as these are related to snow
533 melt in most of Sweden. In the future, the daily annual high-flows may decrease,
534 mainly due to lower peaks from snow melt in the spring due to earlier spring flood. On
535 the contrary, autumn and winter flows may increase due to more intensive rainfall and
536 less snow accumulation.
537

538 • The temporal pattern of daily high flow in the future shift to about one month earlier
539 spring floods in the North/Central part of Sweden and more frequent high flows in the
540 south, due to less snow accumulation in the south and at low altitudes. Observations
541 from the last 25 years already show a tendency towards this projected change.
542

543 • The spatial pattern across the country shows a border between snow-driven high flows
544 in North/Central Sweden and rain-driven high flows in the South. This border may be
545 moved towards higher latitudes, e.g. for the lowlands North of Stockholm (at 60
546 degrees) where the spring peak vanishes.
547

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7. References

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725

Tables

Table 1. Deviation (%) against the mean of the reference period (1961-1990) and Trends (slope in percent per decade) for annual anomalies of high flows in the 69 river gauges, using observed discharge from gauges and S-HYPE modelled discharge with observed climate, or climate from the projections by Hadley and Echam, respectively. Bold numbers show a significance level of *P=0.05* (Yevjevich, 1972).

	Full overlapping period 1961-2010		Independent period 1961-1980		Reference period 1961-1990		S-HYPE calibration period 1999-2008		DBS calibration period 1981-2010	
	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope
69 gauge stations	1.2	0.0	1.9	0.7	0.2	0.1	-1.8	0.2	0.7	0.1
S-HYPE with:										
Obs climate	0.6	0.2	-2.1	1.1	0.0	0.5	-0.7	0.5	0.7	-0.2
Hadley climate	0.6	0.2	-2.9	**1.4**	0.0	**0.7**	6.5	-1.0	3.0	-0.2
Echam climate	-1.0	-0.1	1.2	-0.1	0.0	-0.1	-2.4	0.6	-2.5	0.2

Table 2. Summary from analyzing daily high-flows in observed time-series of 100 years for the past, and in modelled time-series of 100 years for the future. Deviation (%) against the mean of the reference period (1961-1990) and Trends (slope as percent per decade) are given for annual high flows, frequency of 10-yr flood, and spring and autumn flood, respectively. Bold numbers show a significance level of *P=0.05* (Yevjevich, 1972).

|		Frequency of 10-yr flood		Annual high flow		High flows March-June		High flows July-Febr	
Data source	100 yrs Period	Fraction mean (No)	Trend slope	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope	Deviation mean (%)	Trend slope
Observations in:									
69 gauge stations	1910-2010	12	-0.4	0.0	-0.3	3.0	0.0	8.9	-1.1
S-HYPE with:									
Hadley climate	2000-2100	12	0.4	-1.3	-0.4	-7.7	-1.1	19.9	**3.0**
Echam climate	2000-2100	8	-0.2	-8.5	**-1.3**	-15.3	**-2.1**	2.7	1.1

Figures
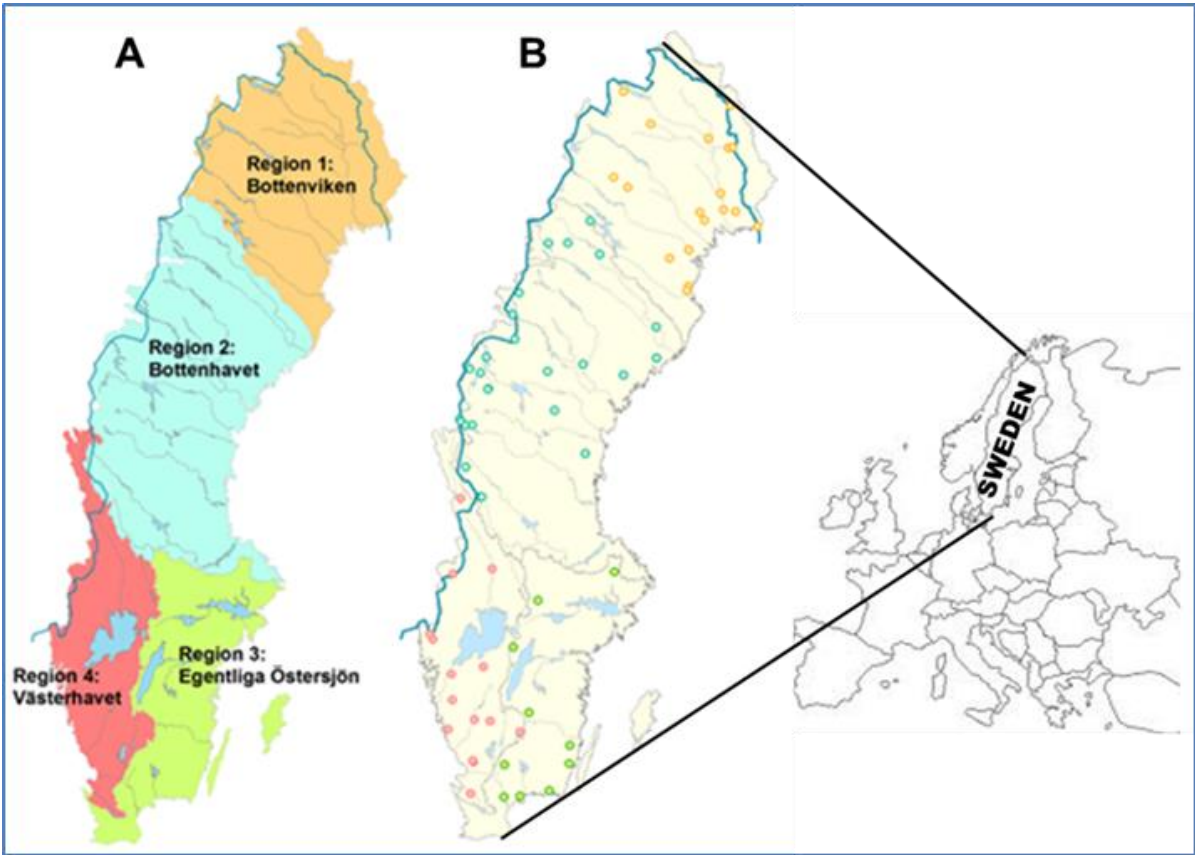
Figure 1. A) Map showing the four climate regions of Sweden. B) Map showing locations for the 69 gauges with long-term records from unregulated rivers across Sweden.
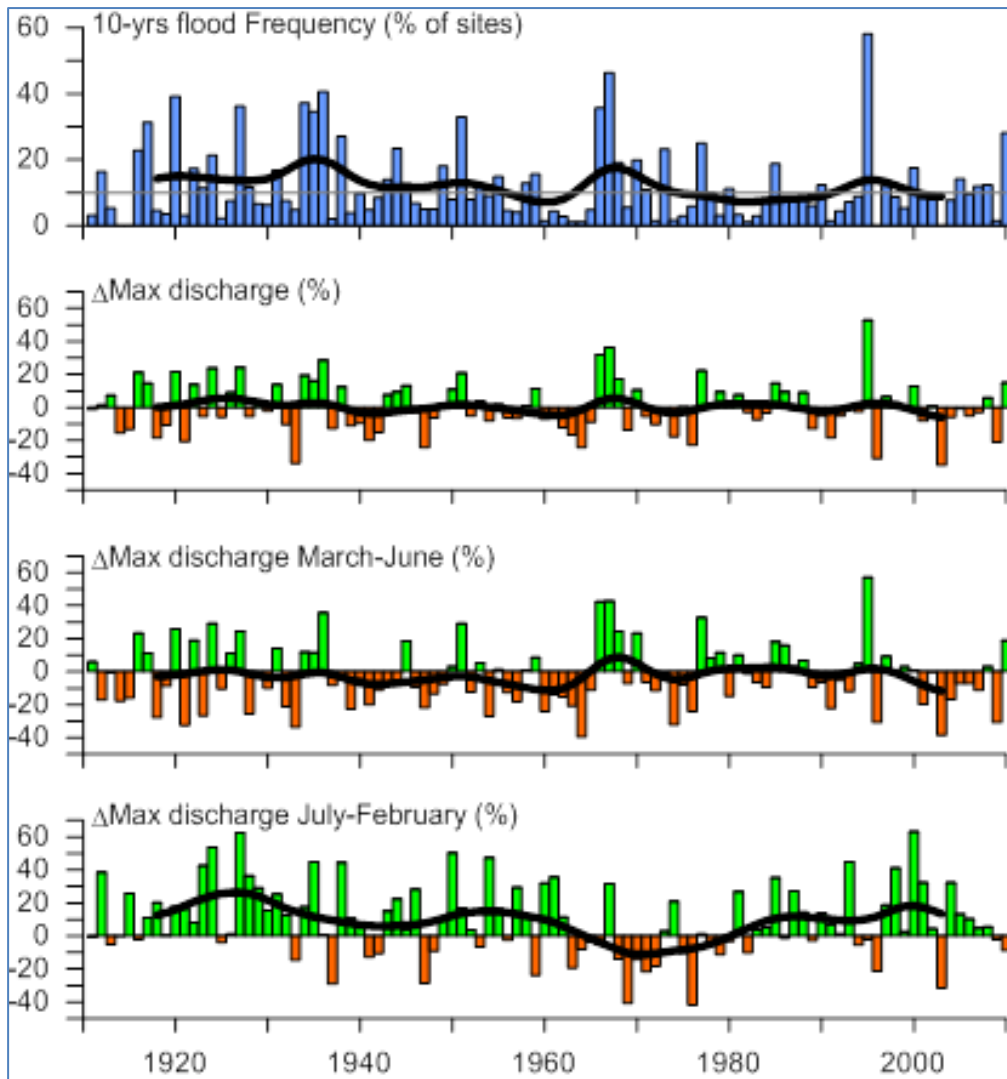
Figure 2. Observed annual high flow (1911-2010) *vs* reference period (1961-1990) for the 69 rivers: Fractions of stations exceeding the 10-year flood each year; Mean deviation in magnitude of annual daily maximum discharge; Mean deviation in magnitude of daily maximum discharge during March-June and July-February, respectively. The line shows a 10-year Gauss filter.
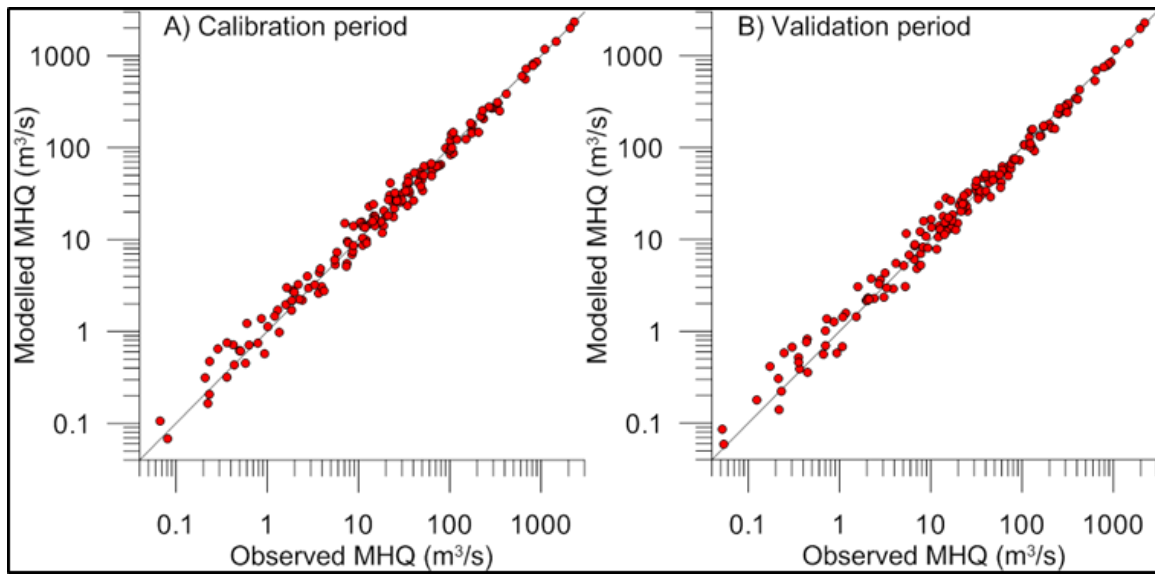
Figure 3. Observed vs Predicted annual high flow using the S-HYPE model for A: calibration period (1999-2008) and B: validation period (1988-1998).
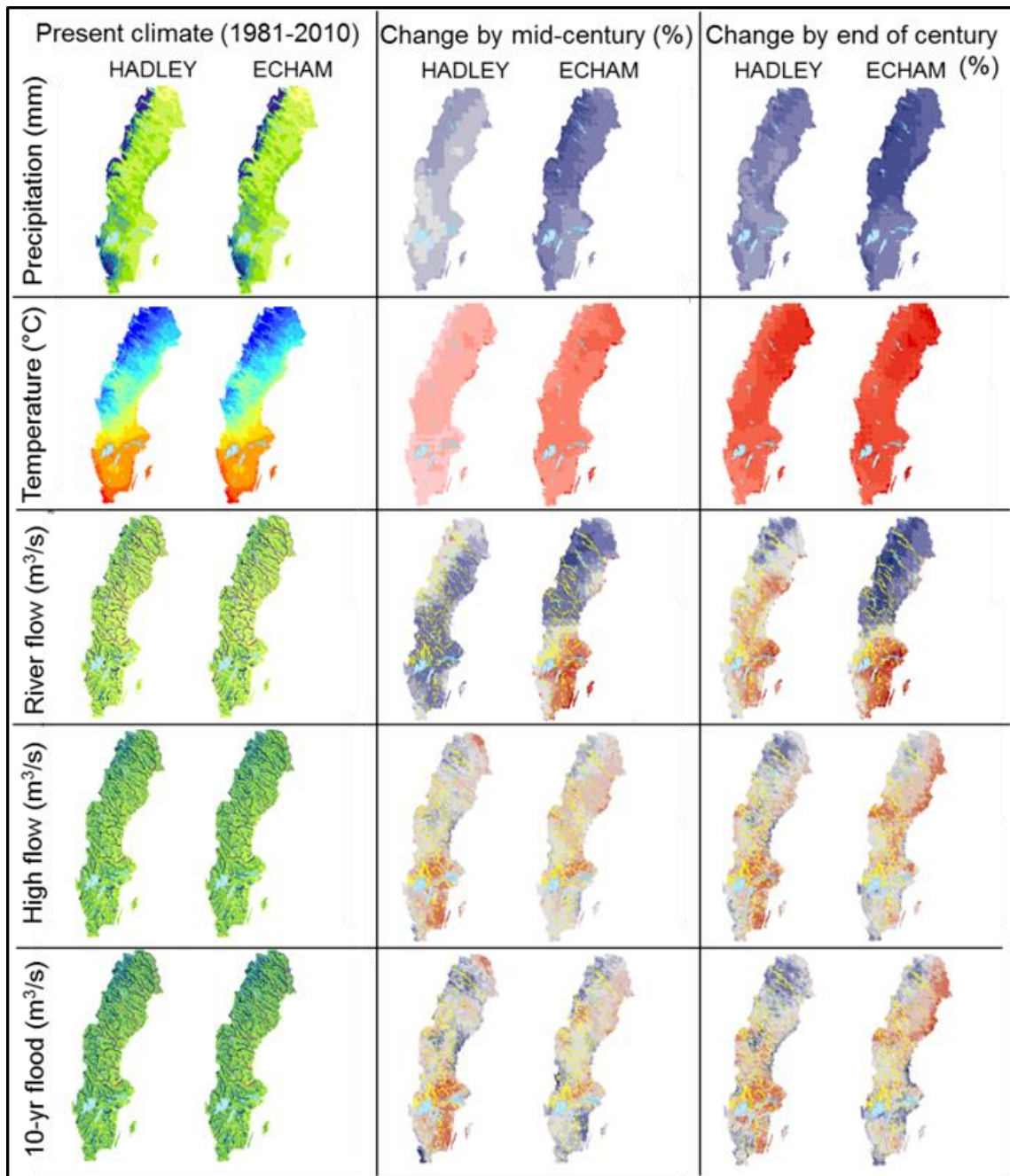
Figure 4. Spatial patterns of climate change impact across Sweden, when using two downscaled and bias-corrected climate projections in S-HYPE. Mean values at mid-century (2035-2065) and End of century (2071-2100) are compared to the mean of a reference period (1981-2010). Red means warmer/dryer and blue means colder/wetter. Results are not shown for highly regulated rivers (yellow).
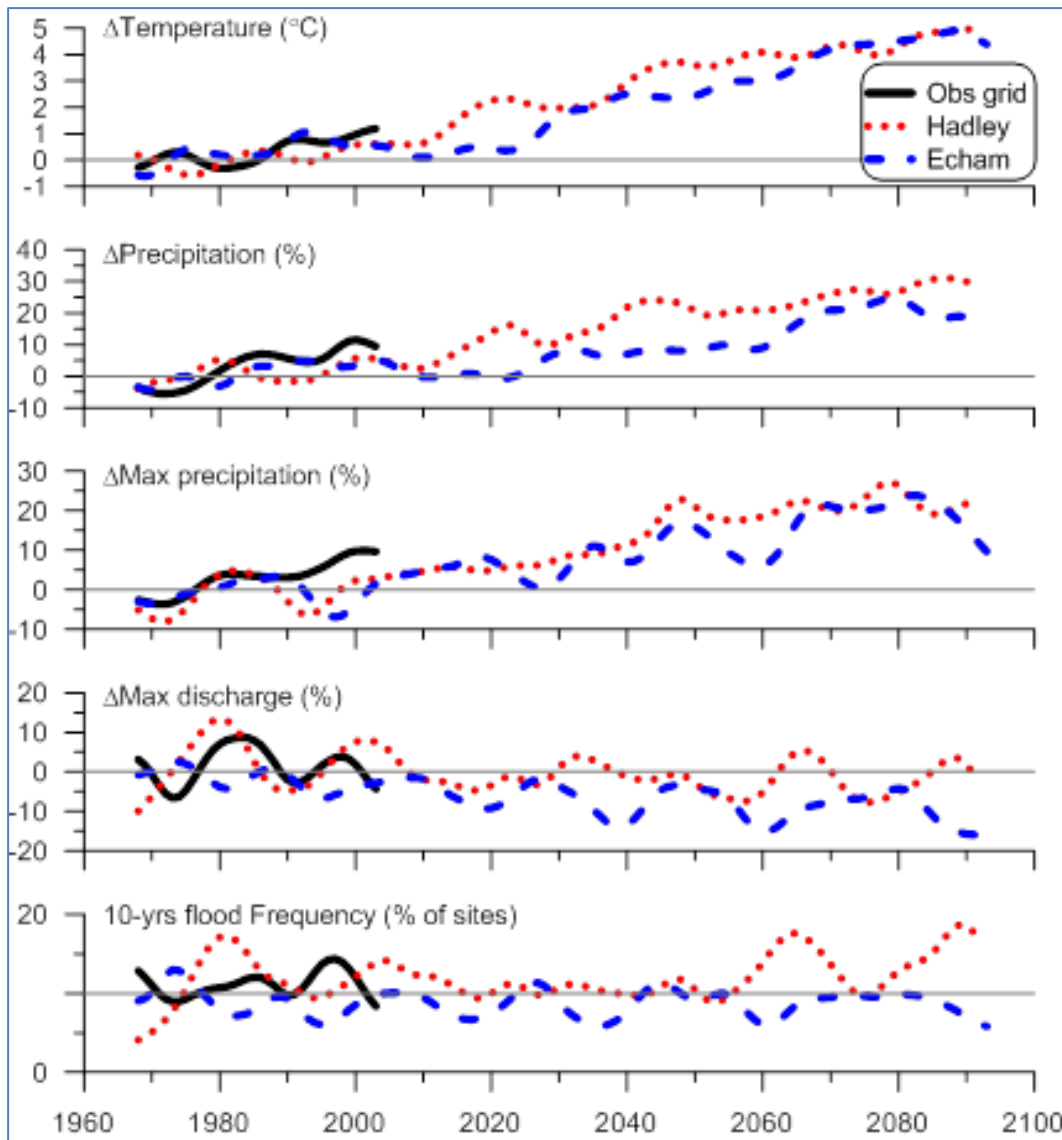
Figure 5. Modelled deviation (%) in annual regional estimates 1961-2100 *vs* the reference period (1961-1990) using S-HYPE for annual mean temperature and precipitation, maximum daily precipitation, daily annual-high flow and number of sites exceeding the 10-years flood. Annual results are filtered using a 10-year Gauss filter. Solid lines represent modeling with forcing data based on observations, while dotted lines represents modeling with forcing data based on climate models.
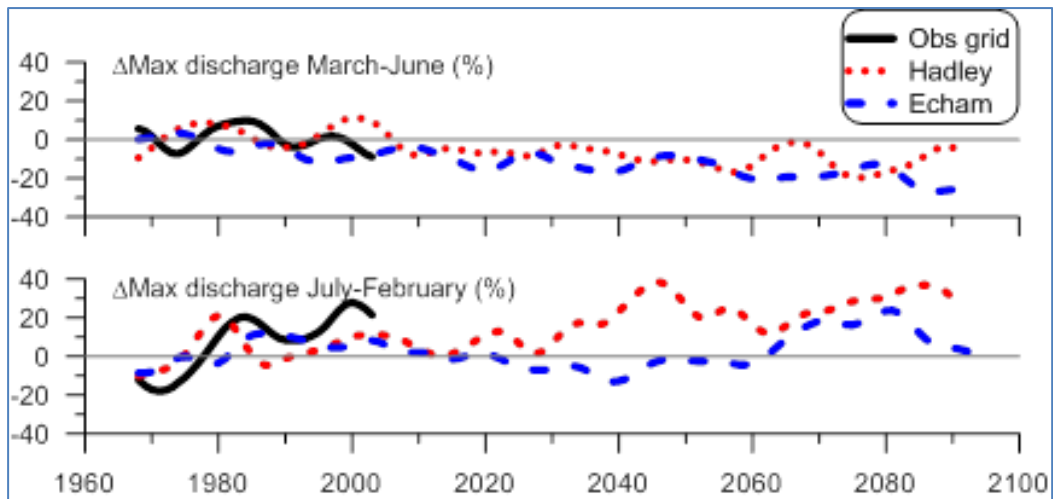
Figure 6. Modelled annual maximum daily flows of spring flood (on top) and autumn/winter flood (bottom) for the period 1961-2100. Deviation (%) in magnitude *vs* reference period (1961-1990). The line shows a 10-year Gauss filter.
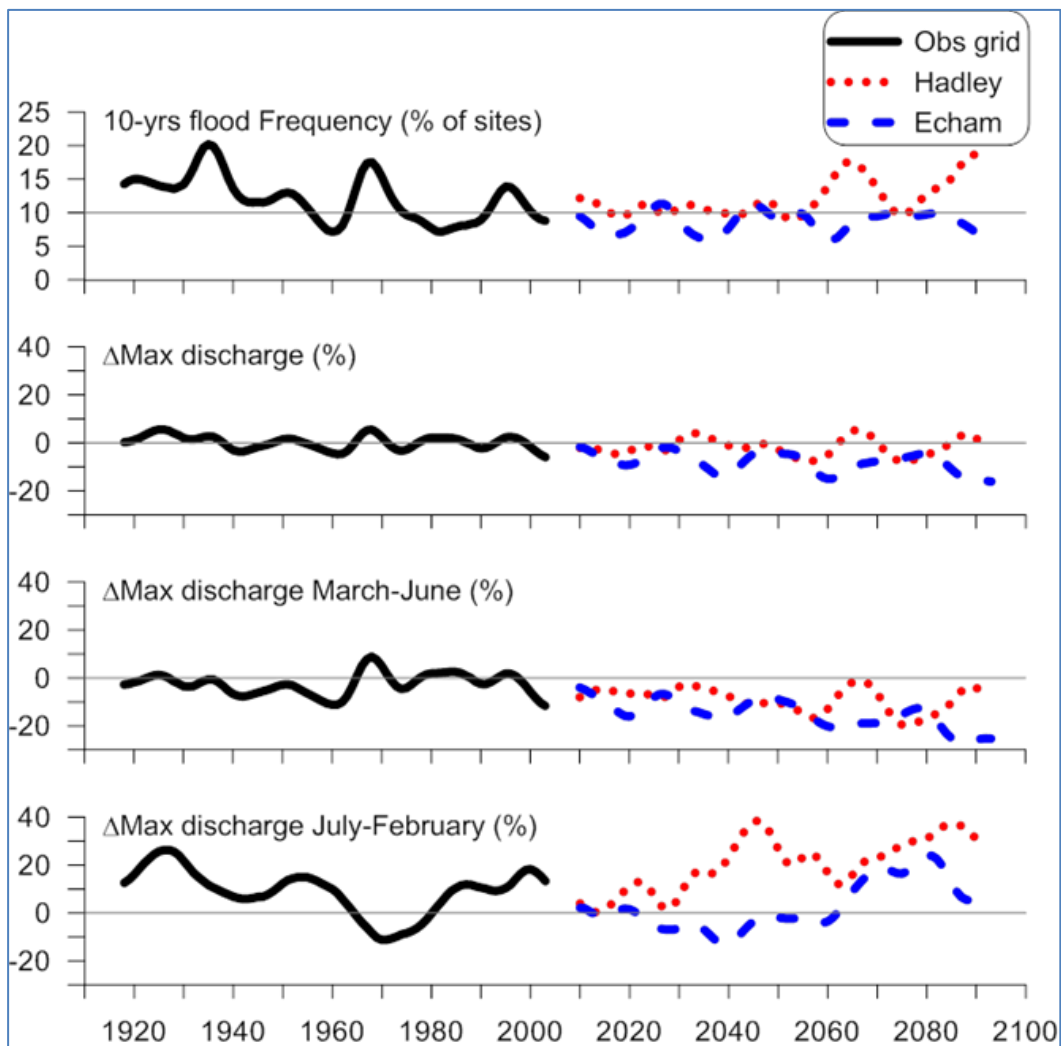
Figure 7. Merged time-series of deviations (%) against the mean of the reference period in observations (1910-2010) and modelling (2010-2100) of past and future maximum annual high-flows in Sweden.
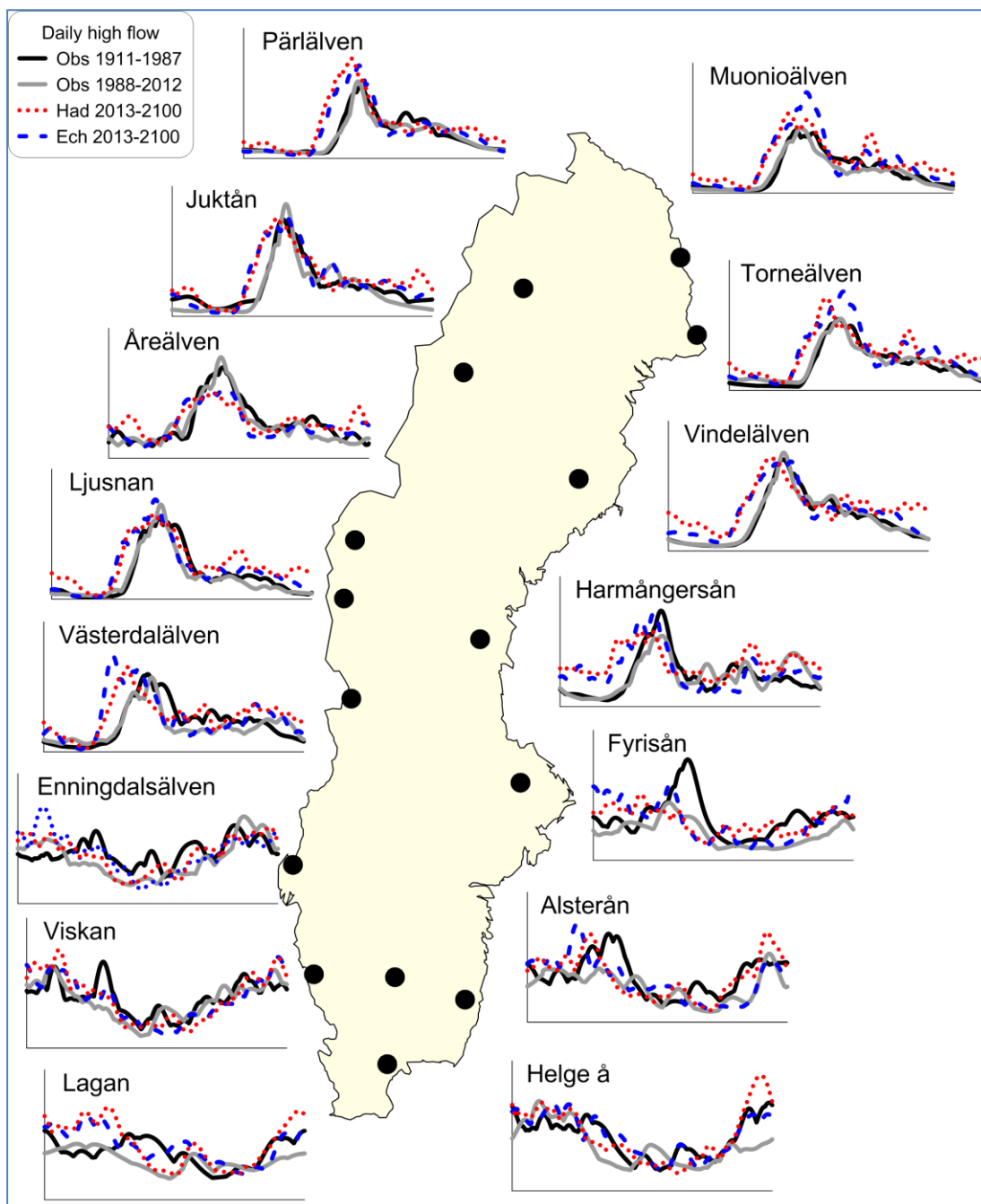
Figure 8. Annual distribution of daily high flow (Jan – Dec) for selected catchments across Sweden, using a 1 month Gauss filter for observed and projected time-series. Note: magnitudes between observed and projected values are not comparable, only timing of high flows should be compared.