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Discussions

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 scenario modeling of the up-coming century. The results show that the changes of daily annual high flows in Sweden oscillate between decades, but there is no significant trend for the past 100 years. A small tendency for high flows to decrease by 0.3–0.4 % per decade in magnitude and 10-year flood frequency was noted, but not statistically significant. Temperature was found to be the strongest climate driver for river high-flows, as these are mainly related to snow melt in Sweden. Also in the future there will be oscillations between decades, but these were difficult to estimate as climate projections were not in phase with observations. However, in the long term, 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 generated floods. This should be considered in reference data for design variables when adapting to climate change. 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.

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, 2008; Arheimer et al., 2012; Bergström et al., 2012). Both these methods include potentials and many challenges, as discussed by Hall et al. (2013). 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, 2013; 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., 2013).

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).

Hall et al. (2013) 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:

1. What changes in daily annual high-flows have we experienced in Sweden during the last century, and which future changes can we expect for the next hundred years?
2. Which climate drivers can be attributed to such changes?
3. 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-term records and scenario modelling was aggregated to four regions in Sweden (Fig. 1) defined by Lindström and Alexandersson (2004). The river basins in these regions have similarities in climate and morphology but also represent the Swedish catchments of the marine basins. 69 gauges with long records and no, or very little, up-stream regulation in the catchment, were chosen from the national water archive to represent the four regions (Fig. 1).

2.2 Model approach of the past and the future

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

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

For climate model results, two grids based on different general circulation models (GCMs) were used; HadCM3Q0 (Johns et al., 2003; Collins et al., 2006) and ECHAM5r3 (Roeckner et al., 2006). The projections were chosen to represent different signals concerning the future temperature change. Within the ensemble of 16 climate projections studies by Kjellström et al. (2011), the Hadley projection is among the ones with the largest future temperature increase in Scandinavia whereas the Echam projection is in the small-to-medium range. Both projections simulate effects of the emission scenario A1B (Nakićenović et al., 2000). GCM results from both models were first down-scaled dynamically to 50 km with the RCA3 model (Samuelsson et al., 2011). Thereafter, daily surface temperatures and precipitation were further down-scaled to 4 km and bias corrected, using the Distribution-Based Scaling (Yang et al., 2010) with reference data from the grid based on observations for the period 1981–2010. Finally, gridded values were transformed to each subbasin for the period 1961–2100 to force the S-HYPE model.

2.3 Quality check and analysis

The model skill to predict daily annual high flows was tested in 157 gauging sites without regulation for the S-HYPE version 2010. Model deviation was calculated both for the calibration period and an independent validation period of the same length, using the forcing grid based on observations. Moreover, simulated trends were compared between the various simulations. Observed and modeled time-series were overlapping for the period 1961–2010 and this 50-year period was thus used to check agreement between simulations. Observed and modelled results from the 69 river gauges were extracted and compared for different time-slots. Simple linear regression was used as trend test, as previous studies have shown that there is no large difference in results from different trend test used for Swedish flood data (Lindström and Bergström, 2004). Statistical significance ($P = 0.05$) was estimated based on the formula by Yevjevich (1972; p. 239).

To explore the spatial variability of climate change, the high resolution results from the S-HYPE modelling was plotted as maps for two time-windows (mid-century: mean of 2035–2065 and end of century: mean of 2071–2100), showing estimated change for each climate projection.

To quantify temporal changes of annual high flows in the past and future, recorded values for the 69 gauges and modeled data from the 37 000 subbasins were divided with the average value of the reference period (1961–1990) to get the relative anomalies in each site. Then these anomalies were averaged for the country and each region, respectively, so that a relative change was received for each domain and each year. Frequency analysis was based on how many of all sites that were exceeding the 10-years flood for each year in each region.

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

To distinguish major long-term changes in the flood generating mechanisms, seasonal changes in magnitude and frequency of high flows were analyzed by separating peaks appearing in March–June and July–February, respectively. Spring peaks, which appears in March–June along the climate gradient from south to north of the country, are mostly driven by snow melt, while autumn/winter peaks are primarily rain-driven in Sweden. Analyzing each group separately will thus give a hint about a shift in hydrological regime and dominant processes causing the high flows.

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

3 Results

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

3.1 Observed annual maximum of daily high flows during the past

During the last hundreds years, the observed anomalies in annual maximum of daily flow is normally within ±30 % deviation from the mean of the reference period (Fig. 2). During the 1980's to 2010 the variability in flood frequency has been less pronounced, except from the extended event in 1995 when most of the 69 sites experienced at least a 10-year flood. This was linked to the outstanding spring flood, especially in the north, where previous maximum discharge records were exceeded at some sites by as much as 60 %. Spring floods normally correspond to the annual high flow (cf. the two middle panels of Fig. 2), with a few exceptions. One such exception is the autumn flood of the year 2000 which affected the central-southern parts of Sweden.

For the past hundreds years of this study, no obvious trends in magnitude of high flows can be seen in the observed time-series for Sweden. A slight decrease in flood frequency can be noted. In a shorter perspective, however, autumn floods seem to have increased substantially over the last 30 years, but before that the tendency was falling. 1970 appears as the turning point and the summer and autumn floods in the 1920s were actually higher than in recent decades.

4 Model performance and comparison of trends in simulations

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

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

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

4.1 Future climate projections of Sweden

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

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

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

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

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

4.2 High flow in the future and climate drivers

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

The annual maximum of daily flow does not show any trend for the past 50 years but a decreasing trend in the future. This can be explained by lower spring peaks from snow-melt as the snow period will be shorter and evapotranspiration higher due to higher temperature. The results did not show any clear trend in the frequency of the 10-years flood. For Sweden, temperature thus seems to be a stronger climate driver for river high-flow than the precipitation. This is probably reflecting that high flows are mainly related to snow melt in this country.

4.3 Changes in the flood regime

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

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

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

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

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

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

5 Discussion

5.1 Changes of high flows in Sweden

The study shows that no tremendous changes in high flows have been recorded so far, or are expected from climate change in Sweden. Although not significant, there was a small negative trend of 0.4 % per decade in 10-year flood frequency. This confirms previous findings by Wilson et al. (2010) for Scandinavia, who found a decrease of peak-flow events in long time-series from Sweden, Finland, and parts of Denmark, while increase was found for western Norway and Denmark. The changes we found for future changes, however, were statistically significant ($P = 0.05$) and of some larger magnitude. Daily annual high-flows may decrease by 1 % per decade in the future, while autumn flows may increase by 3 % per decade, but the trends are far from linear. The high deviation versus the reference period shows that this period (1961–1990) cannot be used as a reference in the future. Most design variables for infrastructure in Sweden are based on this period, but must thus be recalculated using a new reference period to adapt with climate change. Unfortunately, when looking at the past century, it seems like this period was not very representative for natural variability either, especially not for autumn floods.

The merging of Gauss curves using both 100 years of observations and 100 years of climate projections, clearly visualize the relative changes and influence from long-term oscillations (Fig. 7). This combined way to analyze both observations and model results simultaneously, increases the understanding of natural versus accelerated changes in long time-series. The Gauss filtering removes the effect of individual years and helps the eye in distinguishing the trends from oscillations. Using shorter time scales of observed climate gives a very different picture. For instance, when starting the analysis during the 1960's (Figs. 5 and 6) the trends in increased autumn floods seem very strong already, but this trend disappears when using 100 years of observations (cf. Table 2 and Fig. 7). For Swedish climate, 50 years is thus not enough for trend detection. Lindström and Bergström (2004) found that trend detection is very sensitive to starting and ending years. These results are coherent with previous finding for other climate regions, for instance by Yue et al. (2012) or Chen and Grasby (2009).

Spatial patterns can also be noisy and make it difficult to detect overall trends due to local events. In this study we used 69 sites and considered the mean of relative deviation as representative for the country. The frequency analysis also shows how extensive in spatial terms the specific high flows were. Originally, the analysis was made in four hydroclimate regions (Fig. 1) but as the results showed very little difference between those regions for observed changes, they were considered too small to represent climate change. However, for climate projections of the future, the two different projections showed large differences between the Northern and Southern regions (Fig. 4). For instance, the positive trend for autumn flows when using the Hadley projection was mainly seen in the north. Only spatially aggregated results for the whole domain were used in this study, as the projections showed so large discrepancy on local or regional level, the uncertainty in climate model results was judged to be very large.

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

5.2 Methodological uncertainties

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

Precipitation is even more difficult to monitor and model. The observations are influenced by changes in vegetation, wind, snow/rainfall, and monitoring equipment. Probably the 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).

5.2.1 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.

5.2.2 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 et al., 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.

5.2.3 Hydrological model uncertainties in the region studied

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

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

The present scenarios consider changes in atmospheric emissions and concentrations of climate gases. However, there may as well be additional changes in other drivers of the hydrological regime in the future, such as land use and vegetation changes, or constructions in the river channel (Merz et al., 2012). These can also have large impact on flood generation (e.g. Hall et al., 2013) and add uncertainties to the results of flood frequency and magnitude in the future. Arheimer and Lindström (2014) recently reconstructed the total impact of Swedish hydropower on the river-water regime and spring peaks was found to have decreased by 15 % on a national scale. The Swedish hydropower was mainly established during 1910–1970. This human alteration of the water resources have thus had a larger impact on river high flow than what can be expected from climate change.

6 Conclusions

This study of climate impact on floods in Sweden, show that:

- the changes of daily annual high flows in Sweden oscillate between decades, but there is no significant trend during the past 100 years. A small tendency for high flows to decrease by 0.3–0.4 % per decade in magnitude and 10-year flood frequency was noted, but not statistically significant.
- Also in the future there will be oscillations between decades, but these were difficult to estimate as climate projections were not in phase with observations. Temperature was found to be the strongest climate driver for 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) due to higher temperatures and shorter snow season. On the contrary, autumn flows may increase by 3 % per decade due to more intensive rainfall.

- This indicates that there will be a shift in flood generating processes in the future, with more influence of rain generated floods. This should be considered in reference data for design variables when adapting to climate change. However, uncertainties and simultaneous changes from other drivers than climate must also be accounted for.

Acknowledgements. This study was performed at the SMHI Hydrological Research unit, where much work is done in common, taking advantages from previous work and several projects running in parallel in the group. Hence, input from more persons than the authors was essential for the background material, and we would especially like to recognize the work by Johan Strömqvist and Thomas Bosshard. Funding was achieved from Swedish research councils; analysis of recorded flows was done by grants from HUVA/Elforsk, and work on model scenarios was funded by the projects Hydroimpacts2.0 (Formas) and CLEO (Swedish EPA). The study will contribute to the IAHS scientific decade Panta Rhei on changes in hydrology and society and its working group on Floods. S-HYPE results and observations from gauges are available for free down-loading at http://vattenwebb.smhi.se/ as well as tools for model uncertainty check and maps of climate scenario estimates.

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Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Strömqvist, J., Arheimer, B., Dahné, J., Donnelly, C., and Lindström, G.: Water and nutrient predictions in ungauged basins – Set-up and evaluation of a model at the national scale, Hydrolog. Sci. J., 57, 229–247, 2012.

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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-year flood, and spring and autumn flood, respectively. Bold numbers show a significance level of $P = 0.05$ (Yevjevich, 1972).

		Frequency of 10-year flood		Annual high flow		High flows March–June		High flows July–February	
		Fraction	Trend	Deviation	Trend	Deviation	Trend	Deviation	Trend
Data source	100-years period	mean (%)	slope	mean (%)	slope	mean (%)	slope	mean (%)	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

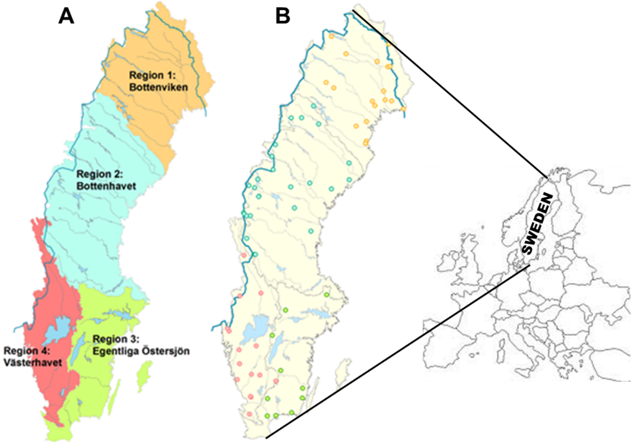

Figure 1. (A) Map showing the four climate regions of Sweden. **(B)** Map showing locations for the 69 gauges with long-term records from unregulated rivers across Sweden.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
I◀ ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

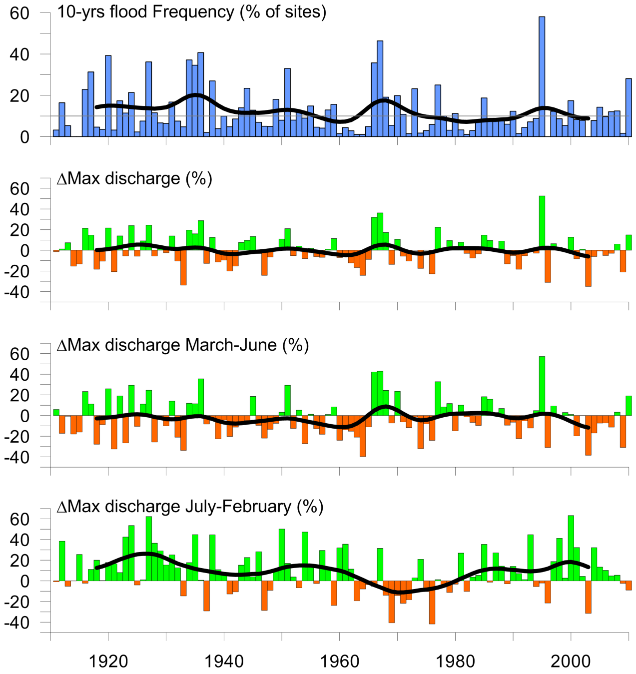

Figure 2. Observed annual high flow (1911–2010) vs. reference period (1961–1990) for the 69 rivers: Fractions of stations exceeding the 10-year flood each year; mean deviation in magnitude of annual daily maximum discharge; Mean deviation in magnitude of daily maximum discharge during March–June and July–February, respectively. The line shows a 10-year Gauss filter.

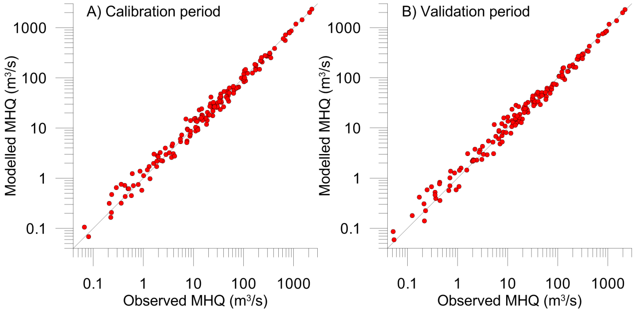

Figure 3. Observed vs. predicted annual high flow using the S-HYPE model for **(A)**: calibration period (1999–2008) and **(B)**: validation period (1988–1998).

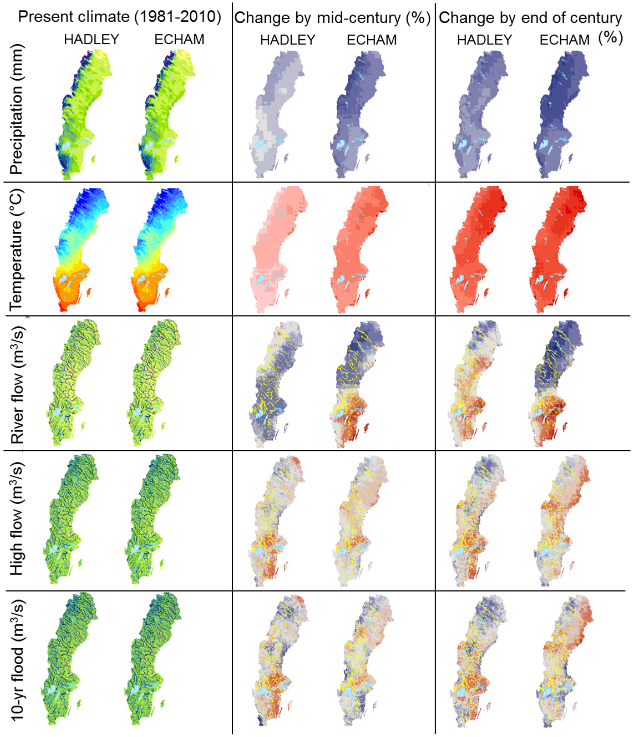

Figure 4. Spatial patterns of climate change impact across Sweden, when using two downscaled and bias-corrected climate projections in S-HYPE. Mean values at mid-century (2035–2065) and End of century (2071–2100) are compared to the mean of a reference period (1981–2010). Red means warmer/dryer and blue means colder/wetter. Results are not shown for highly regulated rivers (yellow).

HESSD
11, 7551–7584, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

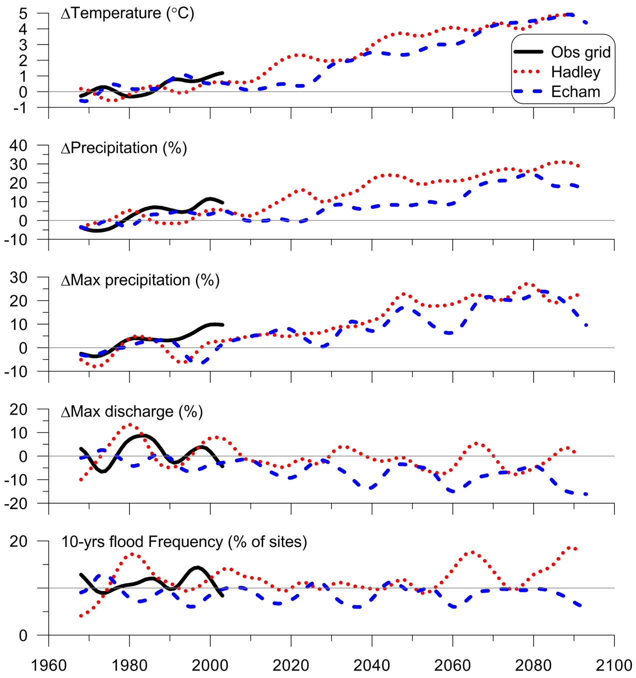

Figure 5. Modelled deviation in annual regional estimates 1961–2100 vs. the reference period (1961–1990) using S-HYPE for annual mean temperature and precipitation, maximum daily precipitation, daily annual-high flow and number of sites exceeding the 10-years flood. Annual results are filtered using 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.

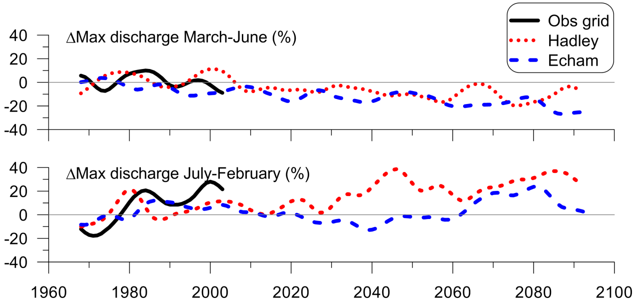

Figure 6. Modelled annual maximum daily flows of spring flood (on top) and autumn/winter flood (bottom) for the period 1961–2100. Deviation (%) in magnitude vs. reference period (1961–1990). The line shows a 10-year Gauss filter.

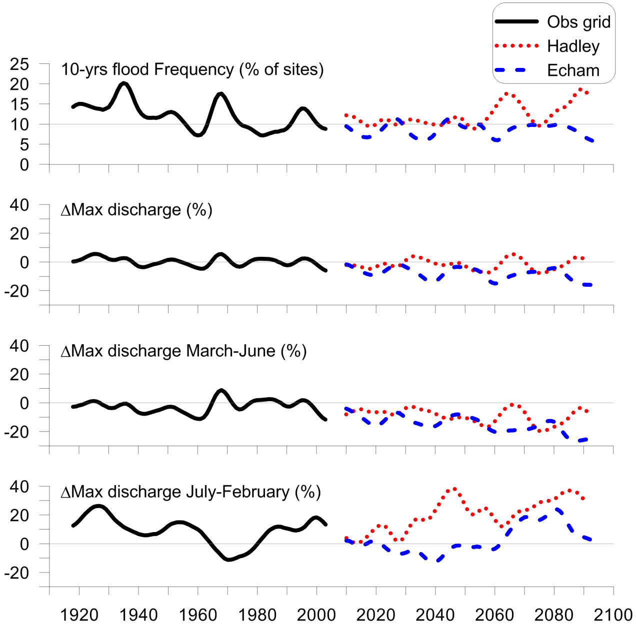

Figure 7. Merged time-series of deviations (%) against the mean of the reference period in observations (1910–2010) and modelling (2010–2100) of past and future maximum annual high-flows in Sweden.