Hydrological Change: Climate Change Impact Simulations for Sweden
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Hydrological Change – Climate Change Impact Simulations for Sweden

Climate change resulting from the enhanced greenhouse effect is expected to give rise to changes in hydrological systems. This hydrological change, as with the change in climate variables, will vary regionally around the globe. Impact studies at local and regional scales are needed to assess how different regions will be affected. This study focuses on assessment of hydrological impacts of climate change over a wide range of Swedish basins. Different methods of transferring the signal of climate change from climate models to hydrological models were used. Several hydrological model simulations using regional climate model scenarios from Swedish Regional Climate Modelling Programme (SWECLIM) are presented. A principal conclusion is that subregional impacts to river flow vary considerably according to whether a basin is in northern or southern Sweden. Furthermore, projected hydrological change is just as dependent on the choice of the global climate model used for regional climate model boundary conditions as the choice of anthropogenic emissions scenario.

INTRODUCTION

Anthropogenic climate change induced from the enhanced greenhouse effect is projected to lead to a global mean rise in surface temperature for the future climate (1). This change will not be uniformly distributed. The Nordic Region is expected to bear generally higher increases than the global average. Concurrent changes to precipitation are also expected to vary regionally. Changes to the climate system will give rise to *hydrological change* that will potentially impact on many sectors (2). As with the change in climate variables, the changes in hydrological systems are not expected to be uniform around the globe. To plan for coming hydrological change, impact studies directed at local and regional scales should be carried out to assess how different regions will be affected.

The primary objective of the Swedish Regional Climate Modelling Programme (SWECLIM) was to produce and deliver regional simulations of climate change for Sweden and the Nordic Region (3–5). Analysis of the hydrological impacts from climate change was an integral part of SWECLIM (6). This concentrated primarily on performing hydrological model simulations using different scenarios of climate change from climate models (7). The regional approach included both analyses of basin-scale hydrological impacts in Sweden and large-scale hydrological impacts for the entire Baltic Sea Drainage Basin. The present paper concentrates on six test basins in Sweden, and an application for the total national territory of Sweden. Details on the large-scale hydrological impacts to the Baltic Basin can be found in Graham (8).

Predictions of the hydrological impacts of future climate change are uncertain. The use of different global scenarios provides a range of possible outcomes. It has also been shown that different methods for interfacing between climate and hydrological models have a substantial influence on results (9). The results presented in this paper have all been obtained using the *delta change* approach. This is a common method used also in several other studies (e.g. 10–13). This means that the changes in relevant climate model variables, from control to scenario simulations, are transferred to the simulation of climate change impacts on hydrology. The hydrological impact simulations are further influenced by the choice of model structure and parameter estimation difficulties (14, 15).

This paper presents a summary of the hydrological impact studies of climate change carried out within SWECLIM. The ensemble of simulations represents variation in:

- Future climate emission scenarios.
- Climate model parameterizations and resolution.
- Methodology for the transfer of climate change to the hydrological model.
- Hydrological model parameterization.

In addition to the value of the individual simulation results, the collection and comparison of an ensemble of scenario simulations, all plausible, provides insight into the uncertainty associated with predictions of future water resources.

TOOLS FOR ANALYZING HYDROLOGICAL CHANGE

Studies of the impacts of climate change on water resources were produced from the combined use of global climate models, a regional climate model and a hydrological runoff model. A schematic diagram over how these different models fit together along with supporting databases is shown in Figure 1. More detail on the components in the Figure follow.

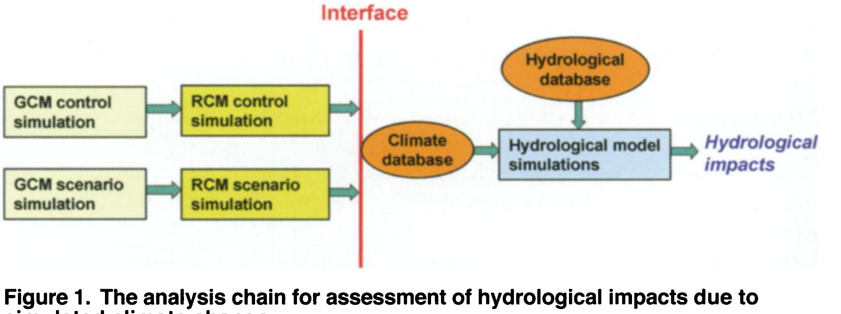

Figure 1. The analysis chain for assessment of hydrological impacts due to simulated climate change.

Climate Modeling

Central to these studies was the use of the Rossby Centre Regional Atmosphere Model (RCA1) (3, 4) and the Rossby Centre Regional Atmosphere-Ocean Model (RCAO) (16). RCA1 does not include full dynamic coupling to the sea, while RCAO is a coupled atmosphere – Baltic Sea regional climate model.

Results from two different global General Circulation Models (GCMs) were used as input boundary conditions for the RCA models. For RCA1, these were the HadCM2 (17) from the Hadley Centre of the Meteorological Office, UK and the ECHAM4/OPYC3 from the Max Planck Institute for Meteorology in Hamburg, Germany (18). Although they were not based on exactly the same emissions scenario, both fall under the business as usual (BaU) scenario assumption of a 1% increase of equivalent CO_2 concentration per year after 1990 (19).

The RCAO simulations were based on GCM results from HadAM3H (Hadley Centre) and additional simulations from ECHAM4/OPYC3 (20). For these, the A2 and B2 emission scenarios defined within the suite of SRES scenarios were used (21).

All of the RCA simulations used the *time slice* approach whereby model simulations representing a slice of time in present climate (control) and in a future climate (scenarios) were performed. The length of the time slices was 10 years for the RCA1 simulations and 30 years for the RCAO simulations. Two horizontal resolutions for the RCA simulations were also used. Table 1 summarizes the important characteristics of the regional climate model simulations that were used to generate the assessment of hydrological impacts presented below.

el, using an observed database as a control climate. Changes in meteorological variables, i.e. precipitation, temperature and evapotranspiration, between the control and the scenario simulations from the regional climate model were processed in a model interface before being transferred to the observed climate database, as depicted in Figure 1. This can be referred to as the *delta change* approach (e.g. 10) and is a common method of transferring the signal of climate change from climate models to hydrological models (30–37).

Using results from single climate model grid cells has shown to be problematic as there is commonly some noise in the output. Therefore, the climate model output was averaged over larger regions before transfer *via* the interface to the hydrological model. The earlier RCA1 impact simulations used output averaged over three regions in Sweden as shown to the left in Figure 2. To improve the geographical representation, this was modified to six regions for the RCAO impact simulations, as shown to the right in Figure 2.

Table 1. Summary of RCA simulations used in SWECLIM hydrological impacts simulations.

RCA version	GCM	Emissions scenario	GCM resolution (deg)	RCM resolution (deg)	RCM resolution (km)	Global CO_2 equiv. (ppm)	Length of time slice (years)	RCA ΔT Sweden (°C)
RCA1	HadCM2	BaU	2.5°x3.75°	0.8°	88	882	10	3.2
	ECHAM4/OPYC3	BaU	2.8°	0.8°	88	706	10	3.5
	HadCM2	BaU	2.5°x3.75°	0.4°	44	882	10	3.7
	ECHAM4/OPYC3	BaU	2.8°	0.4°	44	706	10	3.8
RCAO	Had/AM3H	A2	1.25°x1.875°	0.44°	49	1143	30	3.6
	ECHAM4/OPYC3	A2	2.8°	0.44°	49	1143	30	4.5
	Had/AM3H	B2	1.25°x1.875°	0.44°	49	822	30	2.5
	ECHAM4/OPYC3	B2	2.8°	0.44°	49	822	30	3.5

(Notes: "RCA ΔT Sweden" is the mean annual change in 2 m temperature over all of Sweden in the regional climate models.)

Hydrological Modeling

In this study, the conceptual hydrological model HBV has been used (22, 23). It is the most common model used for climate change impact assessments in the Nordic countries (24). It has, however, also been used in several other countries (e.g. 25–27). The HBV model is a conceptual semidistributed runoff model originally developed at the Swedish Meteorological and Hydrological Institute (SMHI) for operational runoff forecasting. The model is usually run on a daily time step and includes routines for snow accumulation and melt, soil moisture accounting, groundwater response and river routing.

Input data include precipitation, temperature and potential evapotranspiration estimated either with the Penman formula (28) or with a simple temperature index method (23). For lakes, which are an important characteristic of the Scandinavian landscape, potential evapotranspiration is adjusted upward to account for the higher evaporation from a free water surface and subjected to a lag time to account for the delay in warming and cooling of waterbodies. The model is calibrated against river flow observations, typically with the help of an automatic calibration routine (29) to obtain optimal performance in terms of both seasonal dynamics and volume balance.

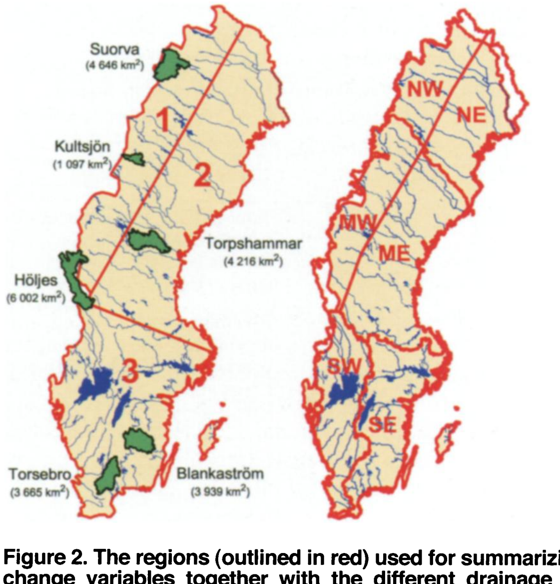

Figure 2. The regions (outlined in red) used for summarizing climate change variables together with the different drainage basins (in green) used for hydrological impact assessment studies. The map to the left shows the three regions used for the RCA1 simulations; the map to the right shows the six regions used for RCAO simulations.

Interfacing the Climate Model to the Hydrological Model

Transfer of the signal of climate change from climate models to hydrological models requires an interface. Although the performance of climate models has improved considerably in recent years, systematic biases still persist in precipitation, the most important climatological variable for hydrological applications. Biases occur not only with precipitation amounts but also with its seasonal representation. Therefore, the hydrological impact studies were done with off-line simulations with the HBV mod-

For precipitation, the monthly average relative change was first smoothed to a 3-month-running-mean and then applied to each daily observation. The same monthly change factors were used for all years of the impact simulations, for extreme values as well as for average conditions. As a relative change was applied to an observed database, the method does not alter the number of days with precipitation in the scenario climate. A drawback of this procedure is that information about changes in climate variability is lost in the process. However, this was considered the most appropriate method at present, due to apparent precipitation biases in the climate simulations.

The temperature change was transferred using a set of seasonal linear transfer functions, in which the temperature change depends on the temperature itself. This accounts for the fact that the changes in temperature in the scenarios are strongest at low temperatures and less pronounced at high temperatures. An example of these transfer functions is presented in Figure 3, which shows results from two RCA regional simulations where the only difference is the GCM providing boundary conditions. The relationships derived for each of the four seasons are shown in Figure 3.

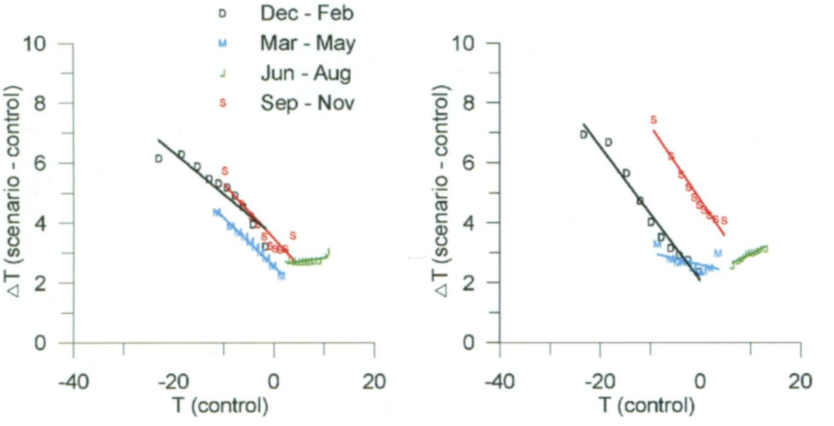

Figure 3. Representation of temperature dependent change in temperature from region 1 (shown in Fig. 2) of RCA1 simulations for HadCM2 (left) and ECHAM4/OPYC3 (right). The points show the frequency distribution in steps of 10% and the lines show the linear functions used to transfer the temperature dependency to the hydrological model simulations.

Table 2. Explanation of the different methods used to model evapotranspiration in the HBV model and the different methods used to transfer the climate change signal into the hydrological model from the climate scenarios.

Model designation	Potential Evapotranspiration method	Transfer of evapotranspiration change to hydrological simulations
HBV-a	Temperature index	Temperature index
HBV-b	Penman monthly values	Penman monthly values + yearly delta change of actual evapotranspiration (percent). Thereafter adjusted to the same yearly relative change (percent) in actual evapotranspiration as between the control and scenario simulations of the climate model.
HBV-c	Temperature index	Temperature index adjusted to the same yearly relative change (percent) in actual evapotranspiration as between the control and scenario simulations of the climate model.
HBV-d	Penman monthly values	Penman monthly values + monthly delta change (absolute values). Thereafter adjusted to the same yearly relative change (percent) in actual evapotranspiration as between the control and scenario simulations of the climate model.

Changes in evapotranspiration can be as important as changes in precipitation for the outcome of hydrological impact simulations. To gain an understanding of the sensitivity to different parameterizations, four methods to estimate evapotranspiration in the hydrological impact simulations were used. These methods are summarized in Table 2. For the temperature based calculations, *HBV-a*, the changes in evapotranspiration were assumed to correspond solely to the changes in temperature. This method, however, was found to give a larger increase in evapotranspiration than that given by the climate models. Therefore, in the other three methods, an adjustment of the calculated actual evapotranspiration from the HBV model is made, so that it results in the same yearly increase as given by the climate models. *HBV-c* is simply a modification of *HBV-a* that includes such an adjustment.

For *HBV-b*, where the evapotranspiration is estimated from monthly mean values of potential evapotranspiration, the relative change given by the climate model was transferred to the hydrological model on an annual basis. Although this method gives the same relative annual change in the hydrological model simulations as in the climate models, the seasonal distribution is not changed. It results in evapotranspiration that is too high during the warm part of the year and too low during the cold part of the year. This is due to monthly mean evapotranspiration close to zero, during wintertime in Sweden, under present day conditions. To modify this, instead of directly adjusting the actual evapotranspiration to the same relative change on a yearly basis, absolute values of monthly change (mm month^{-1}) in potential evapotranspiration from the climate models are added to the estimated monthly mean values in *HBV-d*. Thereafter, the actual evapotranspiration is adjusted to the same relative yearly change as given by the climate models.

None of the evapotranspiration methods used takes possible feedback from changing land use, vegetation dynamics or changing plant use of water at increasing CO_2 concentrations into account, nor do these regional climate model simulations.

Analysis Methods

Results from the climate change impact simulations were evaluated in terms of runoff volumes, seasonal distribution and frequency analysis of peak values. The frequency analysis addressed changes in different return periods. It was performed on a yearly basis but also for spring and autumn to enable analysis of the impact on seasonal dynamics. The months defining spring and autumn varied slightly between basins to ensure that the recession of the spring flood fell within the defined period. The Gumbel distribution (Extreme Value Type I) was used for the frequency analyses. The validity of using frequency analysis of extremes from the delta change approach may be questionable, as much of the change in climate variability is lost through the interface. Many of the flood generating processes are, however, caused by factors other than the extreme precipitation itself, such as periods of prevailing rainfall or combinations of rain and snowmelt. Therefore, it may be relevant to carry out such studies as long as intense rainfall floods at small scales are not the primary focus. Results must, however, be interpreted cautiously. Improved modeling of intense rainfall in the climate models and more realistic handling of the interface in this respect is a matter of high priority for future research.

RESULTS FROM HYDROLOGICAL IMPACT STUDIES

Hydrological impact studies were conducted over a range of drainage basins in Sweden that were chosen to represent quite different conditions. This includes differences in climate, geographical characteristics, basin size and impacted water-use sectors. Some of the basins studied are shown in Figure 2. The applications can be grouped into three categories. The first category is a suite of six test basins geographically distributed over the country (7, 9). This category has been used both for model development and impact studies on river basins. The second category, not presented in this paper, consists of more specialized studies. Examples of these studies are impact assessments on the water resources in the River Luleälven (38), Lake Vänern (39), and on soil frost depth in the Svartberget Experimental Forest (40). The third category is mapping of the climate change impacts on the hydrology for the total national territory of Sweden, which is referred to as the Sweden Model.

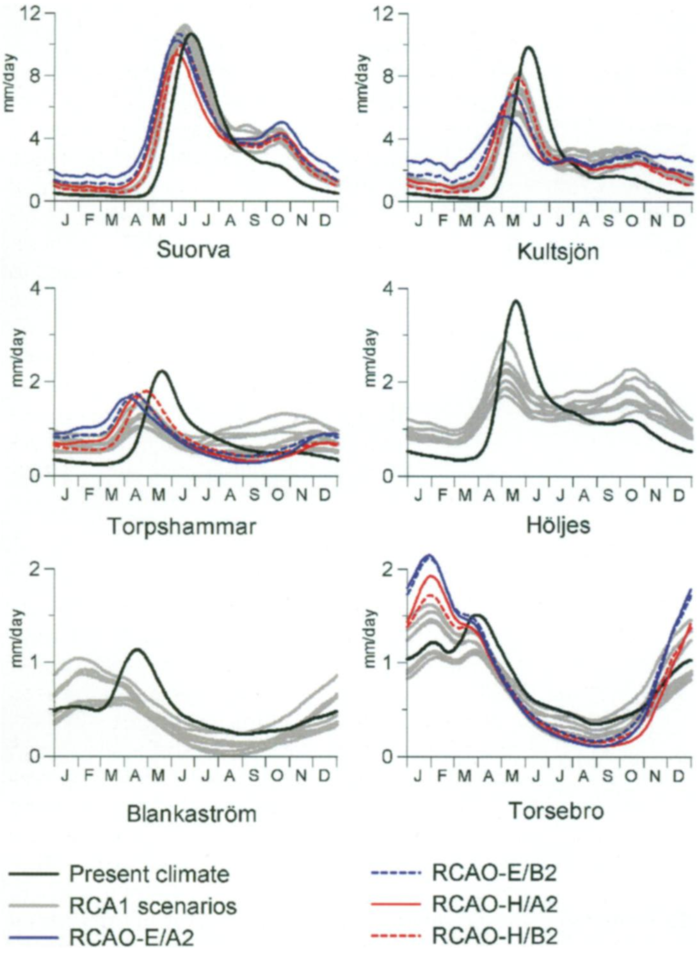

Figure 4. Changes in mean daily runoff for the six test basins in Sweden. The eight RCA1 simulations are shown in gray (cf. Table 1). The four RCAO simulations used HBV-d.

Table 3. Changes in mean annual runoff in percent (%) for the six test basins. H and E correspond to SWECLIM studies based on HadCM2 and ECHAM4/OPYC3 simulations specified in Table 1.

		RCA1 - 88 km		RCA1 - 44 km		RCAO - 49 km	
		BaU		BaU		A2	B2
		HBV-a	HBV-b	HBV-a	HBV-b	HBV-d	HBV-d
Suorva	H	25	30	29	33	18	13
	E	23	28	18	28	43	30
Kultsjön	H	13	23	22	32	12	9
	E	11	22	14	24	36	26
Torpshammar	H	10	38	5	41	-1	2
	E	-19	2	-12	14	9	14
Höljes	H	1	14	16	40	–	–
	E	-1	12	5	29	–	–
Blankaström	H	-41	-10	-21	16	–	–
	E	-38	-21	-34	-22	–	–
Torsebro	H	-21	3	-15	14	-9	-7
	E	-26	-11	-26	-13	3	8

(Note: Hydrological simulations were not performed in all basins for all the model and scenario combinations. "–" indicate where hydrological simulations were not performed.)

Suite of Six Test Basins

The suite of six test basins, as shown in the left map of Figure 2, vary in size from 1100 km^2 to 6000 km^2 and represent different climate regions and hydrological regimes in Sweden. Hydropower plants are located in all the selected basins. The four northernmost basins are of particular interest for the hydropower industry. The Suorva reservoir, located in the basin farthest to the north, has a storage capacity of 6 km^3 and is the most important reservoir in the Swedish hydropower system.

The HBV model was calibrated against an observed database of river discharge for the entire period 1967–1997, which is also the period used for the impact simulations. Split-sample tests have previously been carried out for the same basins, with satisfactory results (23). This, together with the long calibration period, reduces the risk for overparameterization.

Figure 4 summarizes results from eight different hydrological impact simulations from RCA1 (gray lines) and four simulations from RCAO. The plots illustrate the effects of the climate change scenarios on the seasonal variation of runoff. The total range of the plotted curves illustrates a span obtained by choosing between different scenarios, different modeling approaches and different interfacing techniques. A general tendency, which can be seen in all these simulations in northern Sweden, is the shift in the runoff regime towards decreasing spring flood peaks, and increasing autumn and winter flows. In the northernmost basin (Suorva) the magnitude of runoff in spring is less impacted as snow accumulation is less affected in this region. The timing of snowmelt is, however, affected in all the northern basins. Summer flows are severely reduced in the two southernmost basins (Blankaström and Torsebro). The RCAO scenario results, in both northern and southern Sweden, show higher runoff during wintertime and a lower spring flood than the results from the RCA1 scenarios. Generally, the span of the changed flows is larger towards the south of the country.

Table 3 shows a summary of mean annual change in runoff corresponding to the simulation results presented in Figure 4. There is generally an increasing annual runoff in the northern basins, whereas there is a decrease in the southern basins. Some observations can also be made here concerning different models and emission scenarios. For a majority of the basins, the RCA1-H simulations show greater impact on runoff than for the RCA1-E. For the RCAO simulations, the RCAO-E impacts are generally the greatest.

Table 4 shows the relative change of the 100-year spring and autumn floods in the future climate according to the different impact simulations. The changes are shown both as percent change and change in return period. For the change in return period, values exceeding 100 indicate less frequent events and values under 100 indicate more frequent events. With one exception, the Suorva basin, the analyses indicate decreasing spring floods in all basins with the RCA1-based simulations. This is not the case for the RCAO-based simulations, where spring floods increase for both Suorva and Torsebro basins, although this varies with the GCM boundary conditions. A general trend of increasing frequency for autumn floods can be seen. This type of analysis provides an easily accessible comparison of results from different simulations, although the results must be treated with caution due to the uncertainties in the methodology and the still small number of different scenarios and model configurations.

THE SWEDEN MODEL

The question of how to interpret climate change results from single test basins to other areas was often raised. Thus, there was a need for better spatial coverage in the collection of test catchments.

Table 4. Changes in the 100-year flood and return periods for the six test basins (cf Table 3).

Note: Hydrological simulations were not performed in all basins for all the model and scenario combinations shown in the table.
"–" indicate where hydrological simulations were not performed.

		Change of the 100 year flood (%)						Return period of present day 100 year flood under scenario conditions (years)					
		BaU RCA1-88 HBV-a	BaU RCA1-88 HBV-b	BaU RCA1-44 HBV-a	BaU RCA1-44 HBV-b	A2 RCAO HBV-d	B2 RCAO HBV-d	BaU RCA1-88 HBV-a	BaU RCA1-88 HBV-b	BaU RCA1-44 HBV-a	BaU RCA1-44 HBV-b	A2 RCAO HBV-d	B2 RCAO HBV-d
		Spring Season						Spring Season					
Suorva	H	0	0	2	2	-1	-5	100	100	80	80	100	166
	E	-1	-1	1	5	10	7	110	110	90	60	50	50
Kultsjön	H	-28	-25	-20	-17	–	–	>1000	>1000	710	500	–	–
	E	-24	-22	-15	-12	–	–	>1000	870	400	300	–	–
Torpshammar	H	-44	-37	-47	-37	-27	-24	>1000	>1000	>1000	>1000	>1000	1000
	E	-51	-46	-43	-36	-23	-24	>1000	>1000	>1000	>1000	1000	1000
Höljes	H	-48	-44	-42	-36	–	–	>1000	>1000	>1000	>1000	–	–
	E	-46	-43	-43	-31	–	–	>1000	>1000	>1000	>1000	–	–
Blankaström	H	-51	-35	-49	-28	–	–	>1000	>1000	>1000	>1000	–	–
	E	-46	-32	-48	-36	–	–	>1000	>1000	>1000	>1000	–	–
Torsebro	H	-21	-7	-29	-10	16	1	700	170	>1000	230	50	100
	E	-20	-8	-27	-13	29	23	640	190	>1000	320	20	30
		Autumn Season						Autumn Season					
Suorva	H	31	36	45	49	44	29	20	10	10	10	10	20
	E	27	32	23	42	77	46	20	20	30	10	5	10
Kultsjön	H	36	48	44	56	–	–	20	10	10	5	–	–
	E	13	28	17	31	–	–	50	20	40	20	–	–
Torpshammar	H	58	82	41	88	1	-4	10	5	20	5	100	166
	E	-12	7	0	41	32	21	240	70	100	10	20	30
Höljes	H	27	40	50	92	–	–	30	20	10	5	–	–
	E	21	35	29	74	–	–	30	20	20	5	–	–
Blankaström	H	-33	-5	-11	21	–	–	>1000	140	240	30	–	–
	E	-22	-2	-27	0	–	–	550	110	>1000	100	–	–
Torsebro	H	-23	-8	-21	1	5	4	600	170	570	90	70	70
	E	-24	-12	-27	-10	33	24	670	230	>1000	210	20	30

As a final contribution to SWECLIM, a high resolution hydrological modeling system covering all of Sweden was modified and used to produce runoff databases for present day conditions and future scenarios. A similar fine resolution hydrological model is used in Norway (41). The model, referred to as the *Sweden Model*, was originally set up to calculate runoff and the associated transport of nitrogen to the sea (42, 43). It simulates the hydrology of Sweden with more than 1000 subbasins, which makes it possible to generate detailed analysis at locations throughout the country. Due to the large number of subbasins, the Sweden Model was regionally calibrated. The time period 1985–1999 was used for calibration. The present climate in the hydrological change simulations was, however, represented by the time period 1961–1990. Impact simulations were done for the four RCAO regional climate scenarios (Table 1) using the model version HBV-c as this model version was the one used for the original calibration. Figure 5 shows the percentage difference in annual runoff between the climate change impact simulations and present climate (1961–1990). The regions used to summarize the climate change signal can be distinguished due to the crude regionalization in the interface between the climate model and the HBV application. This will be refined in future work.

As an average for the whole of Sweden, temperature increases by 2.5 to 4.6°C, precipitation increases by 7 to 23%, and mean annual runoff increases by 5 to 24%, according to the scenario simulations. The RCAO-E/A2 scenario produces the largest effect on all 3 variables and the RCAO-H/B2 scenario produces the weakest effect. The RCAO-E/B2 simulation shows larger impacts on both precipitation and runoff than the RCAO-H/A2, even though an emission scenario of higher concentration drove the latter. All four scenarios show increased total runoff for Sweden, but there are large regional differences. The common impact from all four scenarios is that the largest increase in runoff was found in the mountainous northwestern parts of Sweden. In southeastern Sweden, the impact is the opposite, with considerably drier conditions according to all scenario climates except from the RCAO-E/B2 simulation. There are large decreases in runoff from the three largest Swedish lakes, especially Lake Vättern and Lake Mälaren, but also for Lake Vänern.

DISCUSSION AND CONCLUSIONS

The hydrological simulations within SWECLIM have confirmed that the production chain of water resources impact studies contains several sources of uncertainty, from emissions scenarios, through global models, *via* regional models, hydrological models and the possible interfaces between these families of models. According to the results from the Sweden Model, the weaker emission scenario, SRES B2, led to a larger regional impact on runoff when interpreted by the ECHAM4/OPYC3 model than did the stronger emission scenario, SRES A2, when interpreted by the HadAM3H model. This was due to the fact that changes in large-scale regional circulation patterns in the GCMs differ. ECHAM/OPYC3 shows a stronger increase in westerly winds and also a northward shift in the cyclonic activity, leading to a larger increase in precipitation, especially over northern Scandinavia. This rather dramatic

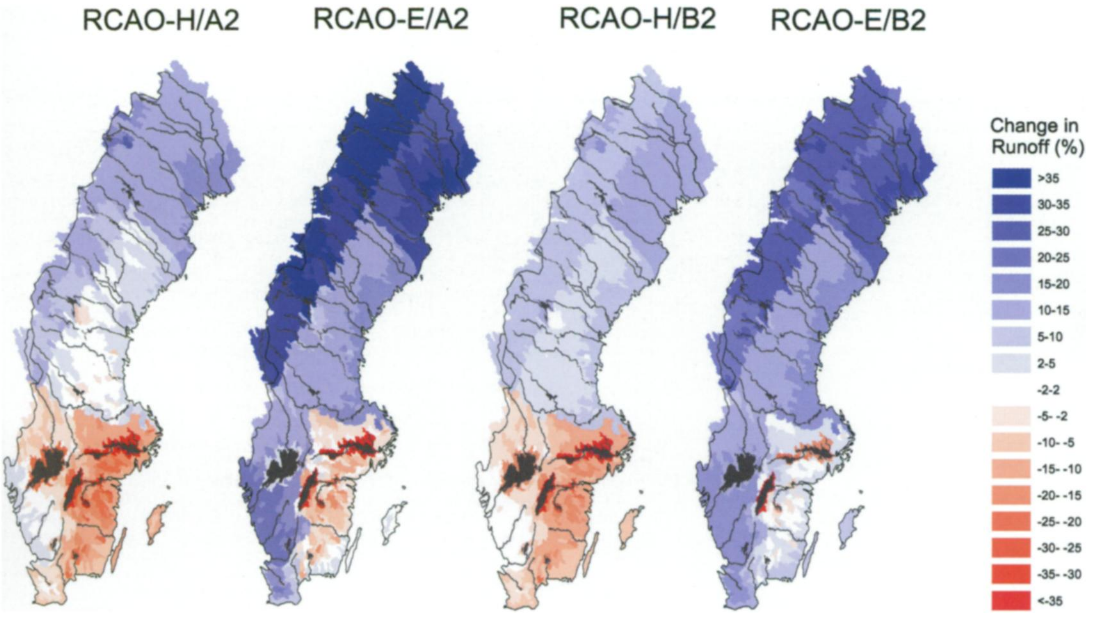

Figure 5. Percentage difference in annual mean runoff for the time period 2071–2100 compared to the time period 1961–1990 for the four RCAO-scenarios.

change in circulation did not appear in the HadAM3H simulations (44). This illustrates the importance of using more than one global model for regional impact studies. It may be argued that a conceptual hydrological model, which is based on empirical calibration, should not be used for simulations under conditions that are different from those under which it was calibrated (45). In this case, this means a different climate. There is, however, encouragement in the fact that the HBV model has been used worldwide over a variety of different climates with a surprisingly narrow range of optimum values for its empirical parameters. In Sweden alone, its applications range from north-central European to Arctic.

Principal Conclusions

There is a considerable range in the results of the hydrological impacts studies produced in SWECLIM. These originate from differences in the geographical location of the test basins, emission scenarios, global climate models, versions of the regional climate model, time periods used for the base climate and how the hydrological models are interfaced to the regional climate model results. There are, however, some common features from the ensemble of hydrological change studies that can be distinguished as follows:

- Decreased spring flood peaks.
- Decreased summer runoff in southern Sweden.
- Predominantly decreased annual runoff volumes in south-eastern Sweden.
- Decreased frequency of high flow events during spring.
- Increased autumn and winter runoff.
- Increased annual runoff volumes in northern Sweden.
- Increased frequency of high flow events during autumn.

Further Development

The climate change impact simulations with the Sweden Model revealed a deficiency that had previously been suspected regarding the regions used for summarizing climate model output. They are still too large and do not properly represent the geographical pattern of change in the climate change signal from the climate models, resulting in artificial discontinuities in the climate change signal between nearby basins in different regions. This can enhance or reduce the climate change signal for a specific basin, particularly if it lies near a border between regions. This needs to be refined for future applications to obtain more optimal regional division, yet still avoid unreasonable noise in analysis of climate variables.

Even though the delta-change approach, due to its simplicity, is a commonly used method to transfer the climate change signal from climate models to hydrological models it has several disadvantages. One is that it does not properly cover changes in extremes, nor does it consider changes in the number of wet days. As climate models get better at representing the present climate statistics, and also move towards finer horizontal resolution, more direct use of climate model output as input to hydrological models should be possible. In the meantime, there are other steps that could be taken to improve the representation of changes to extremes and the number of wet days. One alternative is to do sensitivity analysis using rainfall hyetographs corresponding to different return times from the climate model control and scenario simulation (46). Another would be the use of monthly patterns of change in ranked rainfall from climate models, instead of the average delta change, to scale the ranked point daily rainfall by this pattern of change (47). Such a method can be used to alter the number of rainy days and is sensitive to changes in extreme daily rainfalls. Therefore it could result in a more realistic sequence of climate change impacted rainfall, compared to the common delta change, even though it still relies upon observed climate data.

References and Notes

1. IPCC 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.
2. IPCC 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 1032 pp.
3. Rummukainen, M., Bergström, S., Persson, G., Rodhe, J. and Tjernström, M. 2004. The Swedish Regional Climate Modelling Programme, SWECLIM: A Review. *Ambio 33*, 176-182.
4. Rummukainen, M., Räisänen, J., Bringfelt, B., Ullerstig, A., Omstedt, A., Willén, U., Hansson, U. and Jones, C. 2001. A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations. *Climate Dynam. 17*, 339-359.
5. Räisänen, J. and Joelsson, R. 2001. Changes in average and extreme precipitation in two regional climate model experiments. *Tellus 53A*, 547-566.
6. Graham, L.P., Rummukainen, M., Gardelin, M. and Bergström, S. 2001. Modelling climate change impacts on water resources in the Swedish regional climate modelling programme. In: *Detecting and Modelling Regional Climate Change and Associated Impacts.* López D. (ed.). Springer-Verlag, Berlin Heidelberg New York, 567-580.
7. Bergström, S., Carlsson, B., Gardelin, M., Lindström, G., Pettersson, A. and Rummu-

kainen, M. 2001. Climate change impacts on runoff in Sweden - assessments by global climate models, dynamical downscaling and hydrological modelling. *Climate Res. 16*, 101-112.
8. Graham, L.P. 2004. Climate change effects on river flow to the Baltic Sea. *Ambio 33*, 235-241.
9. Gardelin, M., Bergström, S., Carlsson, B., Graham, L.P. and Lindström, G. 2002. Climate change and water resources in Sweden - Analysis of uncertainties. In: *Climatic Change: Implications for the Hydrological Cycle and for Water Management.* Beniston M. (ed.). Advances in Global Change Research. Kluwer Academic Publishers, Dordrecht, 189-207.
10. Hay, L.E., Wilby, R.L. and Leavesley, G.H. 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. *J. Am. Water Resources Ass. 36*, 387-397.
11. Conway, D., Krol, M., Alcamo, J. and Hulme, M. 1996. Future availability of water in Egypt: the interaction of global, regional, and basin scale driving forces in the Nile basin. *Ambio 25,* 336-342.
12. Gellens, D. and Roulin, E. 1998. Streamflow response of Belgian catchments to IPCC climate change scenarios. *J. Hydrol. 210*, 242-258.
13. Hamlet, A.F and Lettenmaier, D.P. 1999. Effects of climate change on hydrology and water resources in the Columbia river basin. *Am. Water Resources Ass. 35,* 1597-1623.
14. Kavetski, D., Franks, S.W. and Kuczera, G. 2002. Confronting input uncertainty in environmental modelling. In: *AGU Water Science and Applications Series Volume 6*. Duan Q., Gupta H.V., Sorooshian S., Rousseau A.N. and Turcotte R. (eds). Calibration of Watershed Models, 49-68.
15. Beven, K. and Binley, A. 1992. The future of distributed model: models calibration and uncertainty prediction. *Hydrol. Processes 6,* 279-298.
16. Döscher, R., Willén, U., Jones, C., Rutgersson, A., Meier, H.E.M., Hansson, U. and Graham, L.P. 2002. The development of the regional coupled ocean-atmosphere model RCAO. *Boreal Environ. Res. 7*, 183-192.
17. Mitchell, J.F.B. and Johns, T.C. 1997. On modification of global warming by sulphate aerosols. *J. Climate 10*, 245-267.
18. Roeckner, E., Bengtsson, L., Feichter, J., Lelieveld, J. and Rodhe, H. 1999. Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *J. Climate 12,* 3004-3032.
19. IPCC 1992. *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment.* Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 198 pp.
20. Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L.P., Jones, C., Meier, H.E.M., Samuelsson, P. and Willén, U. 2004. European climate in the late 21st century: regional simulations with two driving global models and two forcing scenarios. *Climate Dynam. 22*, 13-31.
21. Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. and Dadi, Z. 2000. *IPCC Special Report on Emissions Scenarios.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 599 pp.
22. Bergström, S. 1995. The HBV Model. In: *Computer Models of Watershed Hydrology.* Singh V.P.(ed.). Water Resources Publications, Highlands Ranch, Colorado, 443-476.
23. Lindström, G., Johansson, B., Persson, M., Gardelin, M. and Bergström, S. 1997. Development and test of the distributed HBV-96 model. *J. Hydrol. 201*, 272-288.
24. Bergström, S., Andréasson, J., Beldring, S., Carlsson, B., Graham, L.P., Jónsdóttir, J.F., Engeland, K., Turunen, M.A., Vehviläinen, B. and Førland, E.J. 2003. *Climate Change Impacts on Hydropower in the Nordic Countries - State of the Art and Discussion of Principles.* CWE Report No. 1, CWE, Reykjavík, 40 pp. ISBN 9979-68-120-9.
25. Booij, M.J. 2002. *Appropriate Modelling of Climate Change Impacts on River Flooding.* Doctoral Thesis, Department of Civil Engineering, University of Twente, Enschede, The Netherlands. ISBN 90-365-1711-7.
26. Menzel, L. and Bürger, G. 2002. Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *J. Hydrol. 267*, 53-64.
27. Yu, P.-S., Yang, T.-C. and Wu, C.-K. 2002. Impact of climate change on water resources in southern Taiwan. *J. Hydrol. 260*, 161-175.
28. Penman, H.L., 1948. *Natural Evapotranspiration from Open Water, Bare Soil and Grass.* 193, Royal Society, London, 120-145 pp.
29. Lindström, G. 1997. A simple automatic calibration routine for the HBV model. *Nordic Hydrol. 28*, 153-168.
30. Lettenmaier, D.P., Wood, A.W., Palmer, R.N., Wood, E.F. and Stakhiv, E.Z. 1999. Water resources implications of global warming: A U.S. regional perspective. *Climatic Change 43*, 537-579.
31. Sælthun, N.R., Bergström, S., Einarsson, K., Jóhannesson, T., Lindström, G., Thomsen, T. and Vehviläinen, B. 1999. Potential impacts of climate change on floods in Nordic hydrological regimes. In: *Proceedings from Ribamod - River Basin Modelling, Management and Flood Mitigation Concerted Action - Final Workshop.* Balabanis P., Bronstert A., Casale R. and Samuels P. (eds). Wallingford, UK, 26-27 February 1998. Office for Official Publications of the European Communities, 103-115.
32. Reynard, N.S., Prudhomme, C. and Crooks, S.M. 2001. The flood characteristics of large U.K. Rivers: Potential effects of changing climate and land use. *Climatic Change 48*, 343-359.
33. Neff, R., Chang, H., Knight, C.G., Najjar, R.G., Yarnal, B. and Walker, H.A. 2000. Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources. *Climate Res. 14*, 207-218.
34. Miles, E.M., Snower, A.K., Hamlet, A.F., Callahan, B. and Fluharty, D. 2000. Pacific northwest regional assessment: The impacts of climate variability and climate change on the water resources of the Columbia river basin. *J. Am. Water Resources Ass. 36*, 399-420.
35. Loukas, A., Vasiliades, L. and Dalezios, N.R. 2002. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. *J. Hydrol. 259*, 163-188.
36. Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J. and Wilke, K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change 49*, 105-128.
37. Arnell, N.W. 1998. The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environ. Change 9*, 5-23.
38. Carlsson, B., Gardelin, M., Lindström, G. and Bergström, S. 2001. Climate change and hydropower production in northern Sweden. In: *Proc. Northern Research Basins 13th International Symposium and Workshop.* Kuusisto E. (ed.). Northern Research Basins, Saariselkä, Finland and Murmansk, Russia, August 19-21, 2001. Published by Finnish Environmental Institute, Helsinki, pp 31-40.
39. Andréasson, J., Gardelin, M. and Bergström, S. 2002. Modelling hydrological impacts of climate change in the Lake Vänern Region in Sweden. *Vatten 58*, 25-32.
40. Carlsson, B., Andréasson, J., Gardelin, M. and Lindström, G., 2002. HBV model simulations based on climate change scenarios for Sweden. In: *Proc. XXII Nordic Hydrological Conference.* Killingtveit Å. (ed.). Røros, Norway, 4-7 August 2002. Tapir Trykkeri, 545-554.
41. Roald, A.R., Beldring, S., Væringstad, T., Engeset, R., Skaugen, T.E. and Førland, E.J. 2003. *Scenarios of Annual and Seasonal Runoff for Norway Based on Climate Scenarios for 2030-49.* met.no Report 19/02 KLIMA, Norwegian Water Resources and Energy Directorate, Oslo, 57 pp.
42. Brandt, M. and Ejhed, H. 2002. *TRK (Transport, Retention, Källfördelning) - Belastning på Havet (Transport, Retention and Source Apportionment - Loads to the Sea).* Rapport nr. 5247, Naturvårdsverket, Stockholm, 117 pp. (In Swedish).
43. Grahn, G., Gyllander, A., Johansson, B. and Svensson, P. 2002. Runoff map of Sweden - a method for continuous production. In: *Proc. XXII Nordic Hydrological Conference.* Killingtveit, Å. (ed.). Røros, Norway, 4-7 August 2002. Tapir Trykkeri, 491-496.
44. Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L.P., Jones, C., Meier, M., Samuelsson, P. and Willén, U. 2003. *GCM Driven Simulations of Recent and Future Climate with the Rossby Centre Coupled Atmosphere - Baltic Sea Regional Climate Model RCAO.* SMHI Reports RMK, No. 101, Swedish Meteorological and Hydrological Institute, Norrköping, 60 pp.
45. Uhlenbrook, S., Seibert, J., Leibundgut, C. and Rodhe, A. 1999. Prediction uncertainty of conceptual rainfall-runoff models caused by problems in identifying model parameters and structure. *Hydrol. Sci. J. 44*, 779-797.
46. Roy, L., Leconte, R., Brissette, F.P. and Marche, C. 2001. The impact of climate change on seasonal floods of a southern Quebec River Basin. *Hydrol. Processes 15*, 3167-3179.
47. Harrold, T.I. and Jones, R.N. 2003. Generation of rainfall scenarios using daily patterns of change from GCMs. In: *Proc. Coupled Climate-Land Surface Modelling Approaches, Symposium HS02a of the XXIII Genaral Assembly of the International Union of Geodesy and Geophysics.* Rosbjerg D. (ed.). Sapporo, Japan, June 30-July 11. IAHS Publication no. 280, 165-172.
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