Vol. 16: 101–112, 2001

CLIMATE RESEARCH
Clim Res

Published January 18

Climate change impacts on runoff in Sweden — assessments by global climate models, dynamical downscaling and hydrological modelling

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ABSTRACT: The Swedish regional climate modelling programme, SWECLIM, started in 1997 with the main goal being to produce regional climate change scenarios over the Nordic area on a time scale of 50 to 100 yr. An additional goal is to produce water resources scenarios with a focus on hydropower production, dam safety, water supply and environmental aspects of water resources. The scenarios are produced by a combination of global climate models (GCMs), regional climate models and hydrological runoff models. The GCM simulations used thus far are 10 yr time slices from 2 different GCMs, UKMO HadCM2 from the Hadley Centre and the ECHAM4/OPYC3 of the Max Planck Institute for Meteorology. The regional climate model is a modified version of the international HIRLAM forecast model and the hydrological model is the HBV model developed at the Swedish Meteorological and Hydrological Institute. Scenarios of river runoff have been simulated for 6 selected basins covering the major climate regions in Sweden. Changes in runoff totals, runoff regimes and extreme values have been analysed with a focus on the uncertainties introduced by the choice of GCM and routines for estimation of evapotranspiration in the hydrological model. It is further shown how these choices affect the statistical return periods of future extremes in a design situation.

KEY WORDS: Climate change impact · Water resources · Regional climate model · Scenario · Hydrological model · HBV · Evapotranspiration · SWECLIM

1. INTRODUCTION

The issue of water resources and climate change impacts is not new. Examples of early work include Nemec & Schaake (1982), Gleick (1987), Bultot et al. (1988), Lettenmaier & Gan (1990), Nash & Gleick (1991), Cohen (1991) and Vehviläinen & Lohvansuu (1991), to mention just a few. The early studies were often based on the relatively straightforward use of climate scenarios and conceptual hydrological models developed for other purposes such as hydrological forecasting and design. It was, however, soon realised that some components of the hydrological models can be questioned, if a changed climate is assumed. The most critical of these is the parameterisation of evapotranspiration, which determines the response to increasing CO_2 concentrations and changed land-use (Martin et al. 1989, Lockwood 1999). Despite the limitations in hydrological models, the main source of uncertainty related to water resources scenarios lies in the climate scenarios. Hydrologists demand a lot from the climate modellers in this respect (Bergström 1998). Recent studies (e.g. Gellens & Roulin 1998) have tried to address the issue by using several climate scenarios.

Today the applied scientific literature on water resources is full of examples of climate change impact studies. Best known is the work by the Intergovernmental Panel on Climate Change and in particular by its Working Group II (IPCC 1996). Regional studies can be found, for example, in Jones et al. (1996) or in Lem-

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melä & Helenius (1998). The European and UK perspectives have been studied in depth by Arnell (1996, 1999), and a North American perspective can be found in the work by Loukas & Quick (1999). The latter work includes attempts to incorporate vegetation dynamics and CO_2 feedbacks on stomatal resistance in the modelling.

The Nordic perspective on climate change impacts on water resources has much in common with that of the rest of Europe, although with increased emphasis on hydropower production and less on water supply. Flooding, physical planning and dam safety are other issues of interest in the Nordic region, as are the water related problems of the environmental sector and the Baltic Sea. The Finnish SILMU project (Roos 1996) is probably the most comprehensive study on climate change impacts in the Nordic countries and the joint Nordic study on Climate Change and Energy Production (Saelthun et al. 1998) is the most complete one related to water resources. Graham (2000) modelled climate change impacts on the water balance of the entire Baltic drainage basin.

The Swedish regional climate modelling programme, SWECLIM, was initiated in 1997, with the main goal of producing regional climate change scenarios over the Nordic area on a time scale of 50 to 100 yr. The programme has its modelling centre, the Rossby Centre, at the Swedish Meteorological and Hydrological Institute (SMHI). Deriving water resources scenarios is an additional goal of SWECLIM, with implications for hydropower production, dam safety, water supply and environmental aspects of water resources.

2. STRATEGY AND METHODS

It is not trivial to derive water resources scenarios from climate scenarios. The hydrological components of current climate models are insufficient for direct use, as they usually lack the necessary details, such as proper representation of snow storage in mountainous terrain and river and lake routing functions. Therefore, scenarios from climate models must be interpreted with the help of hydrological models. These models have a long proven history of water balance modelling (Singh 1995). They predict that the impacts of climate change on river runoff can be quite pronounced in areas where snow accumulation and melt presently dominate the hydrological regime. The impacts on soil moisture content and groundwater recharge and storage are other important aspects addressed by a hydrological model.

A logical strategy would be to force the hydrological model with output from the climate model. This would, however, require a degree of precision as well as a spatial resolution of the climate model which have not yet been reached. There is, for example, a bias in both modelled temperatures and precipitation in most climate models which would lead to an unrealistic hydrological control run if direct input from a climate model were used (Graham 2000). Therefore a commonly used strategy is to simulate climate change impacts on water resources off-line, from differences between a climate model control run, which represents the climate of today, and a scenario run. This means that an interface is introduced where scenario changes to meteorological variables (i.e. temperature and precipitation) are superimposed upon a record of today's climate and fed into the hydrological model (Fig. 1). One potentially limiting simplification when manipulating the climate record in this way is that the same relative changes are assumed for all years and for extreme values as well as for average conditions. Only seasonal variations are accounted for. It is further assumed that the number of days with precipitation stays the same under a changing climate. Information on changed precipitation frequency can be extracted from climate models, but the figures are considered to be too uncertain to be quantified in the hydrological interpretation.

2.1. The regional climate model

The regional climate model within SWECLIM, designated RCA, is based on the international HIRLAM forecast model (Källén 1996, Eerola et al. 1997). A number of HIRLAM parameterisations have been retained in RCA: the radiation scheme from Savijärvi (1990) and Sass et al. (1994), the convection scheme from Kuo (1965, 1974), the cloud and precipitation microphysics from Sundqvist et al. (1989) and Sundqvist (1993) and the vertical diffusion of Louis (1979). Compared to HIRLAM, RCA hosts a new surface/soil/

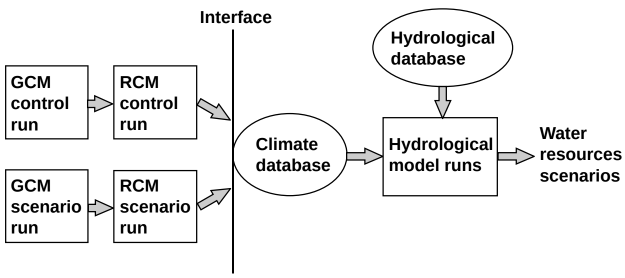

Fig. 1. Schematic presentation of the strategy for off-line simulations of water resources scenarios within SWECLIM. At the interface the differences between the regional climate scenarios and the control runs are calculated and these differences are superimposed upon the observed climate database. The hydrological database is used for calibration of the HBV model

snow scheme and an interactive treatment of regional water bodies, the Baltic Sea and the Nordic lakes.

The soil moisture scheme now consists of 2 prognostic layers, and runoff is generated in the same way as in the hydrological HBV model (Bergström 1995). Evapotranspiration causes a soil moisture loss, partitioned between the top soil layer and the layer immediately below according to transpiration by vegetation using features of the ISBA (Interactions between Soil, Biosphere and Atmosphere) model (Noilhan & Planton 1989). Heat, moisture and momentum fluxes between the atmosphere and the surface are calculated with bulk formulae, using vertical gradients, near-surface wind speed and drag coefficients that depend on the Richardson number and roughness lengths through analytical expressions. The soil temperature scheme includes soil freezing (Viterbo et al. 1999). The hydraulic and thermal diffusivities in the soil depend on soil texture and soil moisture (Clapp & Hornberger 1978, McCumber & Pielke 1981). In contrast to the free-running soil moisture, the deep soil temperature is relaxed against a field taken from the driving global climate model (GCM).

The surface water temperatures and ice in the Baltic Sea and the Nordic lakes are calculated prognostically, with the regional ocean model of PROBE-Baltic (Omstedt & Nyberg 1996), and the lake models of Ljungemyr et al. (1996) and Omstedt (1999). These are coupled interactively into the RCA. PROBE-Baltic divides the Baltic Sea into 13 sub-basins, with parameterised horizontal exchanges. The vertical dimension is resolved in the sub-basins with up to 100 layers. The prognostic variables are mean water level, ice thickness, ice compactness and vertical profiles of momentum, temperature, salinity and mixing. The lake modelling is done with a slab model for shallow lakes and a vertically resolved model for deep lakes. The water temperatures and ice cover are calculated for all lakes, and in the deep lakes even vertical mixing and ice drift are accounted for. The lake model is applied to the land area covering Norway, Sweden, Finland, the Baltic States and the Baltic Sea coasts of Poland and Germany.

In the regional model integrations used in this paper, the RCA model domain was set with a 0.8° (88 km) spherical, rotated latitude/longitude grid and 19 hybrid levels in the vertical (Simmons & Burridge 1981). The model domain covers an area encompassing the Nordic region, most of Europe and extends over the North Atlantic to the west. The prognostic model variables are atmospheric temperature, specific humidity, horizontal wind components, cloud water content, surface pressure, snow water content, soil temperature and soil moisture content. Parameters such as precipitation, evaporation, runoff, etc., are calculated diagnostically for every time step. A Davies-type lateral boundary relaxation is applied to temperature, specific humidity, wind, cloud water and surface pressure (Davies 1976). The lateral boundary relaxation zone is 8 grid boxes wide. The relaxation of the variables of the regional model is done to comparable variables taken from a GCM. The laterally applied large-scale forcing is thus an external drive behind the regional simulation.

2.2. The global climate models

To drive the regional climate model, time-dependent large-scale lateral boundary forcing is imposed from GCM simulations. These simulations are 10 yr time slices from the UKMO HadCM2 of the Hadley Centre in Reading (Johns et al. 1997) and the ECHAM4/OPYC3 GCM of the Max Planck Institute for Meteorology in Hamburg (Oberhuber 1993a,b, Roeckner et al. 1996). They both include fully 3-dimensional atmosphere and ocean components.

For both GCMs, two 10 yr time slices with different greenhouse gas concentrations are used to force the regional model, 1 for the control run and 1 for the scenario. Of the 2 time slices from HadCM2, the first is from its control simulation, with constant greenhouse gases (Johns et al. 1997), and the other is from its transient greenhouse gas run, described by Mitchell & Johns (1997). The atmospheric equivalent CO_2 concentration is about 150% higher in the latter than in the former. The 2 time slices from ECHAM4/OPY3 are both from its transient greenhouse gas simulation (Roeckner et al. 1998). One of the time slices corresponds to present-day conditions in the simulation and the other to a doubling of greenhouse gases (i.e. it has a 100% higher CO_2 concentration compared to the first time slice). Hence, the 2 GCMs differ with respect to the forcing, but the GCMs also differ in their climate sensitivity. Therefore, incidentally, the global mean warming between the control and scenario time slices is virtually the same (2.6°C) in both of these GCMs.

2.3. Downscaling

The downscaling of the HadCM2 and ECHAM4/OPYC3 simulations with the regional climate model is denoted RCA88-H and RCA88-E respectively. The '88' denotes the regional model resolution in km. A more detailed description of these RCA simulations is given in Rummukainen et al. (2000). The changes in the annual mean surface air temperature and in the annual total precipitation, taken as differences between the scenarios and control runs, are depicted in Figs. 2 & 3

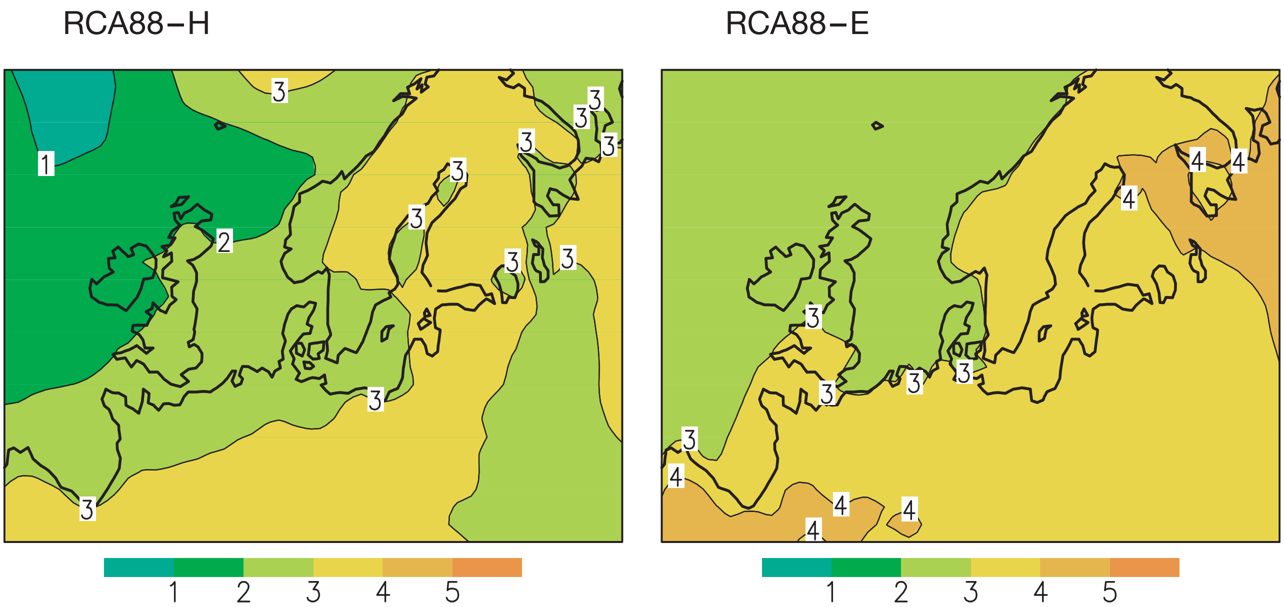

Fig. 2. Annual mean surface air temperature changes (°C) in the regional model domain, excluding lateral boundary zones, taken as the difference between the scenario and control runs

for the regional simulation domain, excluding the lateral boundary relaxation zones, for both RCA88-H and RCA88-E. The simulated mean annual warming is highly significant in the whole area. The precipitation changes are significant at the 90% level when they exceed about 10% of the annual mean and at the 99% level when they exceed about 20% of the annual mean.

2.4. The hydrological model

While the regional climate model is developed at the Rossby Centre, the choice of hydrological model fell upon the HBV model (Bergström 1995). One reason for this was the large amount of positive experience gained with this model at SMHI, but also the fact that it has previously been used in the Nordic countries for

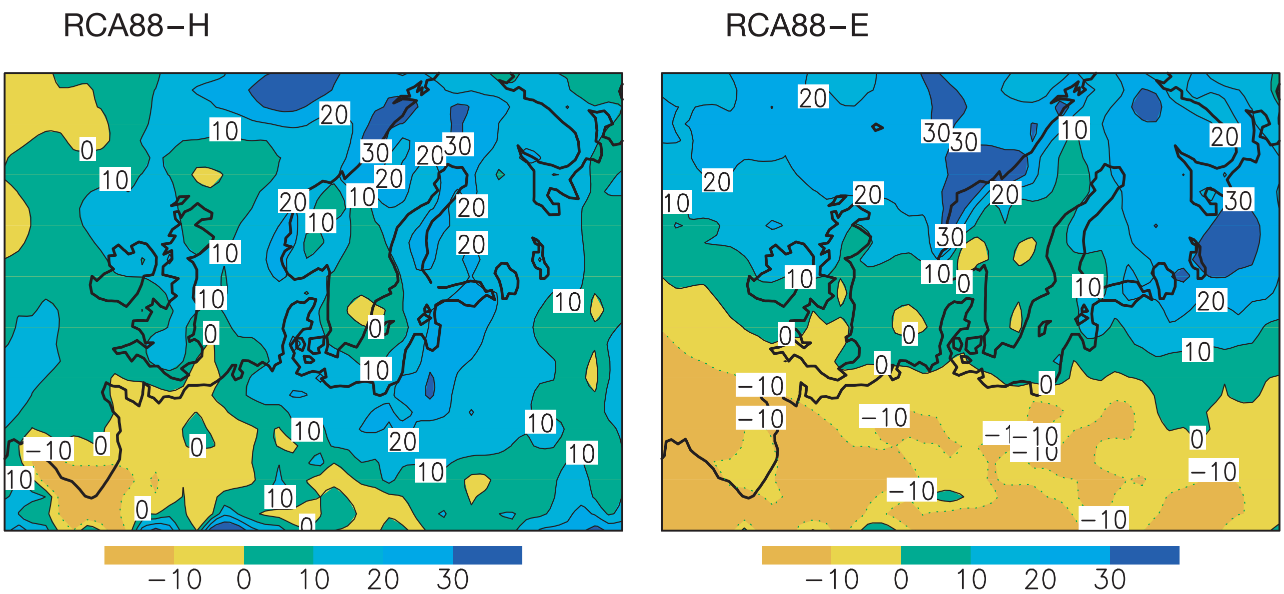

Fig. 3. Annual mean precipitation changes (%) in the regional model domain, excluding lateral boundary zones, taken as the difference between the scenario and control runs

similar tasks by Vehviläinen & Lohvansuu (1991) and by Saelthun et al. (1998), among others.

The HBV model started as a very simple lumped hydrological model and has gradually become more and more distributed. With the latest release, HBV-96 (Lindström et al. 1997), full distribution into sub-basins and statistical distribution of some properties within these have become the basic principle. So the HBV model is now a distributed hydrological model (Fig. 4). The snow routine is basically a degree-day approach with a liquid water holding capacity that delays runoff at the onset of melt. Sub-basin variability is provided for by elevation zones, vegetation zones and a statistical distribution of snow to account for patchiness and snowdrifts above the tree line.

Properly accounting for soil moisture is a key to successful hydrological modelling. The HBV model was one of the first hydrological models to adopt a variability parameter in the soil moisture procedure (Bergström & Forsman 1973). The technique has proven to be very useful and is relatively insensitive to scales (Bergström & Graham 1998). There are several routing options for water in the HBV model. For Scandinavian conditions it is usually sufficient to use the 2 reservoirs of the saturated zone, with a gradually increasing recession coefficient in the upper one, and to model major lakes explicitly by a storage-discharge relationship. Further smoothing of the runoff curve is obtained when the sub-basin option is used. This means that the catchment is modelled by several sub-models, which respond non-synchronously to input.

2.5. The evapotranspiration problem

Although hydrological models have become standard tools for hydrological interpretations of climate change scenarios, experience has shown that there are limitations which may make their use questionable. In the Nordic project on Climate Change and Energy Production (Saelthun et al. 1998) 2 main problems related to the hydrological HBV model were addressed, namely snow modelling and evapotranspiration. Snow modelling was soon realised to be a minor problem. It could be shown that the degree-day formulation used by most hydrological models is relatively stable over a range of climates even though the melt factor is strongly dependent on forest cover and exposure (Sand 1992).

More serious is the uncertainty in the modelling of evapotranspiration in a future climate. Most hydrological models of the HBV type use estimates of potential evapotranspiration, from which actual evapotranspiration is computed as a function of soil moisture deficit. Potential evapotranspiration can be calculated based on observations of wind speed, radiation, air temperatures and the humidity of the air. This technique requires an abundance of data, which are generally not available in Swedish catchments. For practical reasons temperature index methods are often used instead, although it is obvious that these can be questioned in a climate change simulation. The best known of these methods is the Thornthwaite formulation (Thornthwaite 1948). One of the 2 methods used in this study is a simple temperature index method of the Thornthwaite type, which relates potential evapotranspiration to air temperatures by a seasonally dependent coefficient (Saelthun et al. 1998).

Within SWECLIM it is attempted to narrow the gap between the climate models and hydrological models. Therefore it was decided to strive away from off-line evapotranspiration scenario simulations towards a more integrated approach, thereby making as much use of the evapotranspiration simulations of the climate model as possible. In analogy with the use of temperature and precipitation scenarios, it was decided to transfer relative changes in evapotranspiration from the climate scenarios into the hydrological model. The temperature index technique is used as a reference, which leads to the following 2 versions of the HBV model used so far: (1) HBV-a, a standard model with temperature index evapotranspiration formulation. The temperature anomalies affect evapotranspiration in the climate change mode on a degree-day basis. (2) HBV-b, a standard model based on climatological values of potential evapotranspiration, which are forced to give the same relative changes in actual evapotranspiration as the formulation in the regional climate model, when run in a climate change mode.

Note that possible feedbacks from increasing CO_2 concentrations in the atmosphere to plant use of water

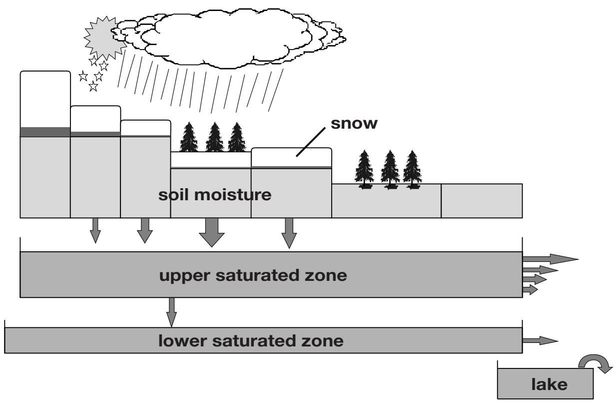

Fig. 4. Schematic picture of the HBV model as it is used in one sub-basin. Note the subdivision into elevation zones, forests and open areas and the statistical distribution of snow above the timber line. Major lakes are modelled explicitly while smaller ones are integrated into the lowest zone of the model

and thus evapotranspiration are not yet considered in these 2 model versions. We have concluded that this issue is not mature enough to be incorporated in a credible way in the modelling at present, although some experience has recently appeared (Loukas & Quick 1999).

3. DATABASE AND SIMULATIONS

3.1. Test catchments

Experience from previous climate change projects has shown that it is important to have an efficient modelling system if a large number of scenarios are planned. A standard set of 6 drainage basins was developed (Fig. 5). These basins are fairly representative of climate regions and of prime water related interests in the country. The 4 northernmost basins are of special interest to the hydropower industry, although there are power plants in all 6 rivers. The Suorva reservoir is the single most important one in the Swedish hydropower system, with an active storage capacity of 6 km^3. Complete hydrological and meteorological databases were set up, and the HBV model was calibrated automatically using the routine developed by Lindström (1997).

3.2. Water resources simulations

The use of 2 global climate models (H and E), 1 regional climate model (RCA88) and 2 hydrological model versions (HBV-a and HBV-b) resulted in the following ensemble of water resources scenarios: RCA88-H+HBV-a, RCA88-E+HBV-a, RCA88-H+HBV-b and RCA88-E+HBV-b. Differences between scenario runs and control runs were extracted for the meteorological variables for each test catchment. These were further processed before use in the hydrological model. Otherwise the variability in the climate change anomalies from one month to another would appear excessive. The monthly average changes in precipitation and temperature were extracted and smoothed to average running mean values over 3 mo. This procedure created standard sets of 12 monthly values used for all years in the hydrological simulations. These changes in temperature and the relative changes in precipitation were superimposed upon a 30 yr climate record and used as input to the hydrological scenario simulations. The original 30 yr climate record was used to produce the reference data for today's climate. An overview of temperature and precipitation changes for the test catchments is given in Tables 1 & 2.

It is important to realise that the technique used in the interface between the regional climate model and the off-line hydrological simulations is a considerable simplification. It does not account for changes in extreme values in the climate runs, alteration of the synchronisation of meteorological variables or changes of the number of precipitation events in a year. Furthermore it is assumed that the same anomalies persist every year, which might smooth interannual variability in an unrealistic manner.

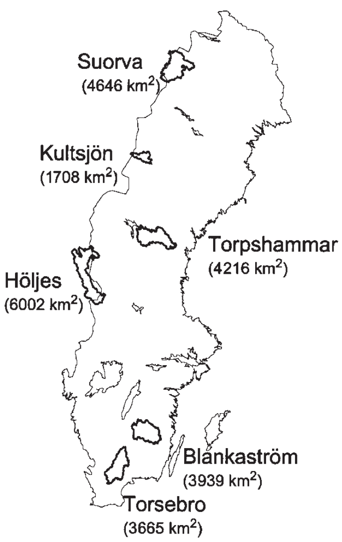

Fig. 5. Location and size of the selected test basins for water resources scenarios within SWECLIM

4. RESULTS

Table 3 shows the simulated average changes in runoff. The general pattern is fairly consistent for all runs with high increases in runoff in the north and a reduction in the south. However, there are also some remarkable individual deviations, such as between the results from the 2 global models for the Torpshammar basin. These deviations are related to differences in precipitation generated by the dynamic downscaling. There is also a considerable difference between HBV-a and HBV-b in that the temperature index method (HBV-a) is much more sensitive to warming than the regional climate model. Actually, as the regional climate model shows very little increase in evapotranspiration in the future climate as compared to today's climate, this will also be the case with HBV-b. This is reflected in the differences in the respective evapotranspiration simulations as shown in Fig. 6 and also in the arithmetic means of all simulations at the bottom of Table 3.

It is not surprising that a temperature index method leads to increased evapotranspiration if warming is assumed. The effect is amplified as snow melts earlier, and snow cover reduces evapotranspiration in the hy-

Table 1. Monthly temperature anomalies used in the water resources scenario simulations (°C)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Suorva RCA88-H	+4.7	+3.7	+2.8	+2.8	+2.9	+2.7	+2.7	+2.4	+2.7	+3.2	+4.5	+5.3	+3.4
Suorva RCA88-E	+4.2	+3.8	+3.0	+2.3	+2.2	+2.2	+2.3	+2.5	+3.7	+4.8	+5.1	+4.8	+3.4
Kultsjön RCA88-H	+4.4	+3.6	+2.9	+2.9	+2.8	+2.5	+2.3	+2.2	+2.7	+3.6	+4.7	+5.1	+3.3
Kultsjön RCA88-E	+4.2	+3.7	+2.9	+2.2	+2.4	+2.4	+2.6	+2.8	+3.8	+4.9	+5.0	+4.6	+3.4
Torpshammar RCA88-H	+4.2	+3.7	+3.3	+3.2	+2.8	+2.4	+2.1	+2.0	+2.6	+3.3	+4.3	+4.5	+3.2
Torpshammar RCA88-E	+4.3	+4.0	+3.2	+2.5	+2.8	+2.8	+2.9	+2.9	+3.7	+4.6	+4.6	+4.5	+3.6
Höljes RCA88-H	+4.0	+3.5	+3.2	+3.1	+2.7	+2.3	+1.9	+1.9	+2.6	+3.5	+4.4	+4.5	+3.1
Höljes RCA88-E	+3.4	+3.4	+3.0	+2.7	+3.0	+3.0	+3.0	+3.0	+3.8	+4.6	+4.3	+3.9	+3.4
Blankaström RCA88-H	+3.7	+4.0	+3.8	+3.3	+2.6	+2.0	+1.8	+1.9	+2.5	+2.9	+3.2	+3.4	+2.9
Blankaström RCA88-E	+3.4	+3.5	+3.4	+3.1	+3.2	+3.3	+3.3	+3.3	+3.6	+4.1	+3.9	+3.5	+3.5
Torsebro RCA88-H	+3.6	+3.9	+3.7	+3.2	+2.4	+1.8	+1.7	+1.8	+2.5	+2.9	+3.2	+3.4	+2.8
Torsebro RCA88-E	+3.1	+3.2	+3.1	+2.9	+3.1	+3.2	+3.2	+3.3	+3.7	+4.0	+3.6	+3.2	+3.3

Table 2. Monthly precipitation anomalies used in the water resources scenario simulations (%)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Suorva RCA88-H	+39	+24	+13	+7	+11	+16	+11	+24	+30	+36	+32	+32	+23
Suorva RCA88-E	+35	+29	+28	+25	+20	+2	–2	–3	+26	+29	+43	+32	+22
Kultsjön RCA88-H	+24	+13	+8	–1	+3	+14	+9	+28	+31	+37	+23	+16	+17
Kultsjön RCA88-E	+38	+36	+19	+16	+4	–13	–17	–2	+39	+39	+36	+30	+19
Torpshammar RCA88-H	0	0	+16	–2	+4	+12	+28	+35	+42	+44	+29	+4	+18
Torpshammar RCA88-E	+8	+17	+21	+10	–1	–5	–2	+5	+9	+12	+6	+6	+7
Höljes RCA88-H	+4	+6	+18	0	–1	+4	+10	+17	+16	+24	+16	+5	+10
Höljes RCA88-E	+11	+14	+10	+6	0	+2	+7	+19	+20	+19	+10	+11	+11
Blankaström RCA88-H	–3	+4	+8	0	–3	+5	+6	–1	–11	–6	–1	–4	0
Blankaström RCA88-E	–1	+9	+11	–5	–10	–22	–14	+7	+11	+19	–6	+2	0
Torsebro RCA88-H	+2	+15	+19	+16	+7	+7	+6	–1	–1	0	+3	0	+6
Torsebro RCA88-E	+1	+13	+14	+7	+3	–16	–19	–1	+12	+20	–4	+1	+3

Table 3. Average changes in runoff in the 6 test basins according to the regional climate scenarios and the 2 versions of the HBV model (%)

	HBV-a	HBV-b
Suorva RCA88-H	+25	+30
Suorva RCA88-E	+23	+28
Kultsjön RCA88-H	+13	+23
Kultsjön RCA88-E	+11	+22
Torpshammar RCA88-H	+10	+38
Torpshammar RCA88-E	–19	+2
Höljes RCA88-H	+0.8	+14
Höljes RCA88-E	–1	+12
Blankaström RCA88-H	–41	–10
Blankaström RCA88-E	–38	–21
Torsebro RCA88-H	–21	+3
Torsebro RCA88-E	–26	–11
Mean	–5	+11

drological model. It has to be noted that a simple degree-day method is very crude and disregards other important variables such as wind, solar radiation and humidity. This is why more emphasis will be put on the evapotranspiration from the climate model in the future.

4.1. The annual cycle

Figs. 7 & 8 picture the effects on the annual cycle of runoff for each of the 6 test basins. These results confirm the dramatic effects on the stability of Nordic winters that could be expected from a global warming, as also reported in the Nordic project on Climate Change and Energy Production (Saelthun et al. 1998). The spring floods tend to be less dominant and there will be several melt periods, which generate water that helps to keep up the low flows in winter. Worth noting

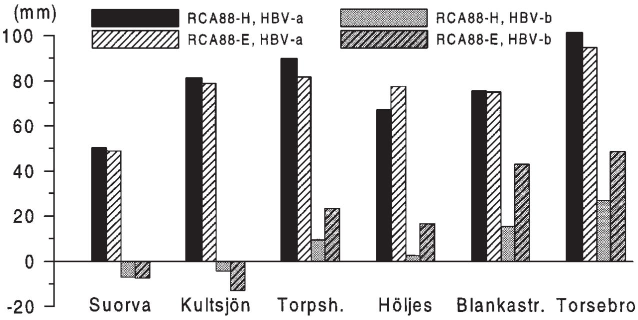

Fig. 6. Differences in yearly evapotranspiration between scenarios and control runs for the RCA88-H and RCA88-E regional climate scenarios and the 2 versions of the HBV model

is also the strong decline in low flows according to HBV-a in the southern basins.

4.2. Floods

Changes in extreme values of runoff can be more critical than mean values. For reservoirs and dams in northern Europe it is further necessary to analyse spring floods separately from summer and autumn floods as they belong to different statistical populations with quite different characteristics, in particular if the river is regulated. Spring floods are normally easier to manage as reservoirs tend to be low after winter, while summer or autumn floods often force the activation of spillways and create greater surprises for downstream developments (Bergström & Lindström 1999). In the following analysis it was assumed that floods occurring from August 1 until December 31 can be classified as summer or autumn floods, dominated by rain. Floods at any other time were assumed to be spring floods, dominated by snowmelt.

Frequency analyses, based on the Gumbel probability distribution function and the method of moments, were carried out for all scenarios. Tables 4 to 6 show the relative changes of the magnitudes of the 100 yr annual peak flows, spring floods, and autumn or summer floods, respectively, for the test catchments. They also show the new return periods which are obtained if a present-climate100 yr flood is analysed in the light of a changed climate according to the scenarios. Return

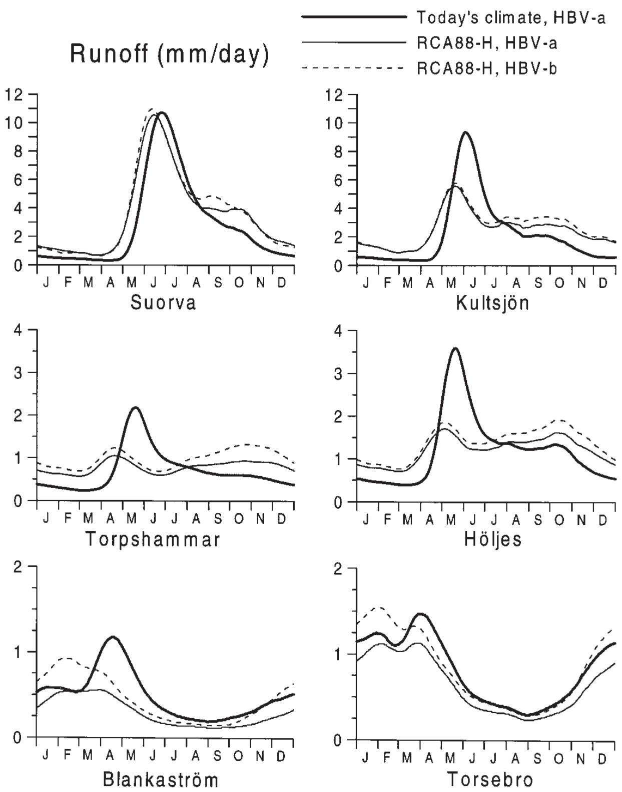

Fig. 7. Annual cycle of river runoff in 6 test basins today and according to the RCA88-H regional climate scenario and 2 versions of the HBV model. The curves have been smoothed

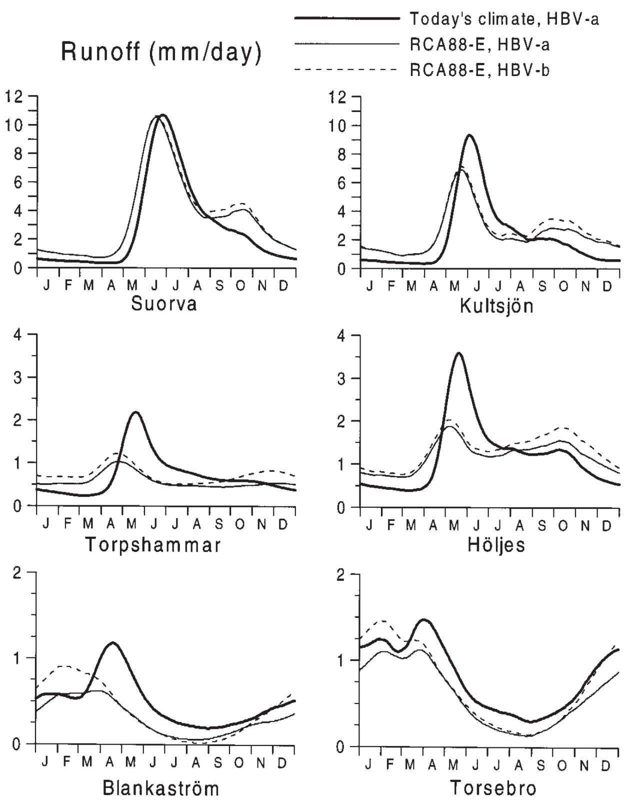

Fig. 8. Annual cycle of river runoff in 6 test basins today and according to the RCA88-E regional climate scenario and 2 versions of the HBV model. The curves have been smoothed

Table 4. Estimated change in the 100 yr annual peak flow according to the water resources scenarios

	Change in 100 yr annual peak flood (%)		Return period of today's 100 yr flood under the scenario conditions	
	HBV-a	HBV-b	HBV-a	HBV-b
Suorva RCA88-H	–0.5	–1	110	110
Suorva RCA88-E	–2	–2	120	130
Kultsjön RCA88-H	–13	–8	320	190
Kultsjön RCA88-E	–21	–16	900	490
Torpshammar RCA88-H	–27	–15	>1000	360
Torpshammar RCA88-E	–48	–43	>1000	>1000
Höljes RCA88-H	–27	–21	>1000	680
Höljes RCA88-E	–30	–24	>1000	960
Blankaström RCA88-H	–52	–35	>1000	>1000
Blankaström RCA88-E	–47	–32	>1000	>1000
Torsebro RCA88-H	–21	–9	740	220
Torsebro RCA88-E	–21	–11	750	260

Table 5. Estimated change in the 100 yr spring flood (January to July) according to the water resources scenarios

	Change in 100 yr spring flood (%)		Return period of today's 100 yr spring flood under the scenario conditions	
	HBV-a	HBV-b	HBV-a	HBV-b
Suorva RCA88-H	+0.5	+0.4	100	100
Suorva RCA88-E	–0.5	–1	110	110
Kultsjön RCA88-H	–28	–25	>1000	>1000
Kultsjön RCA88-E	–24	–22	>1000	870
Torpshammar RCA88-H	–44	–37	>1000	>1000
Torpshammar RCA88-E	–51	–46	>1000	>1000
Höljes RCA88-H	–48	–44	>1000	>1000
Höljes RCA88-E	–46	–43	>1000	>1000
Blankaström RCA88-H	–51	–35	>1000	>1000
Blankaström RCA88-E	–46	–32	>1000	>1000
Torsebro RCA88-H	–21	–7	700	170
Torsebro RCA88-E	–20	–8	640	190

Table 6. Estimated change in the 100 yr summer or autumn flood (August to December) according to the water resources scenarios

	Change in 100 yr summer or autumn flood (%)		Return period of today's 100 yr summer or autumn flood under the scenario conditions	
	HBV-a	HBV-b	HBV-a	HBV-b
Suorva RCA88-H	+31	+36	20	10
Suorva RCA88-E	+27	+32	20	20
Kultsjön RCA88-H	+36	+48	20	10
Kultsjön RCA88-E	+13	+28	50	20
Torpshammar RCA88-H	+58	+82	10	5
Torpshammar RCA88-E	–12	+7	240	70
Höljes RCA88-H	+27	+40	30	20
Höljes RCA88-E	+21	+35	30	20
Blankaström RCA88-H	–33	–5	>1000	140
Blankaström RCA88-E	–22	–2	550	110
Torsebro RCA88-H	–23	–8	600	170
Torsebro RCA88-E	–24	–12	670	230

periods exceeding 1000 yr have not been quantified, because such a long extrapolation of the frequency curve has very large uncertainty. It is important to bear in mind that this analysis is based on very short records of simulated climate change (10 yr), interpreted via a 30 yr hydrological simulation.

The frequency analyses indicate decreasing annual flood risks, which mostly are related to decreasing spring floods. Only in the northernmost Sourva catchment, with an arctic climate, would the winters remain stable, as would the 100 yr floods. The timing of extreme values shows a general tendency to shift from spring to other seasons in the north, where return periods related to rain floods in summer and winter decrease. If this becomes reality, it will have a significant impact on the number of times that spillways have to be activated. In the south there is a general decrease in flood risks according to these simulations.

The climate change impact on the annual cycle of flood risks is further illustrated in Figs. 9 & 10, where the shift towards more frequent winter floods in the north is clearly seen in all model runs. The differences in summer precipitation anomalies between the 2 climate simulations result in large differences in the summer flows. This is particularly marked for Torpshammar and Torsebro.

4.3. Low flows

Water shortage is normally not a major problem in Sweden but temporarily low flows may affect water quality and supply, in particular in the southeastern parts of the country. Table 7 shows how the lowest flow in the 30 yr of the test record would change according to the scenarios. The general pattern is higher low flows in the north, due to shorter and less stable winters, and decrease of the low flows in the south, due to changes in precipitation and evapotranspiration. The latter may influence water supply and water quality negatively. Some simulations even indicate zero flow (–100%), which means that there will be no net inflow to the lakes during the most extreme dry periods.

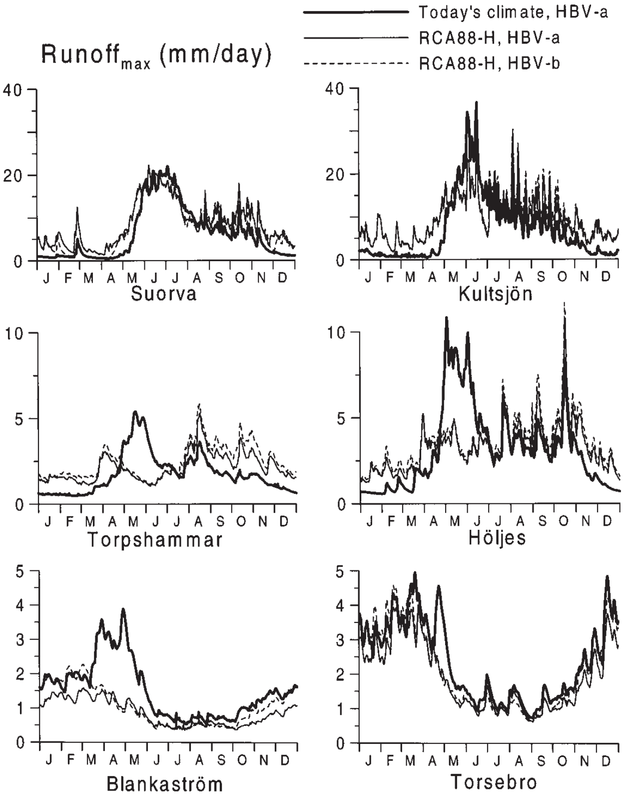

Fig. 9. Annual cycle of extreme daily runoff in 6 test basins today and according to the RCA88-H regional climate scenario and 2 versions of the HBV model

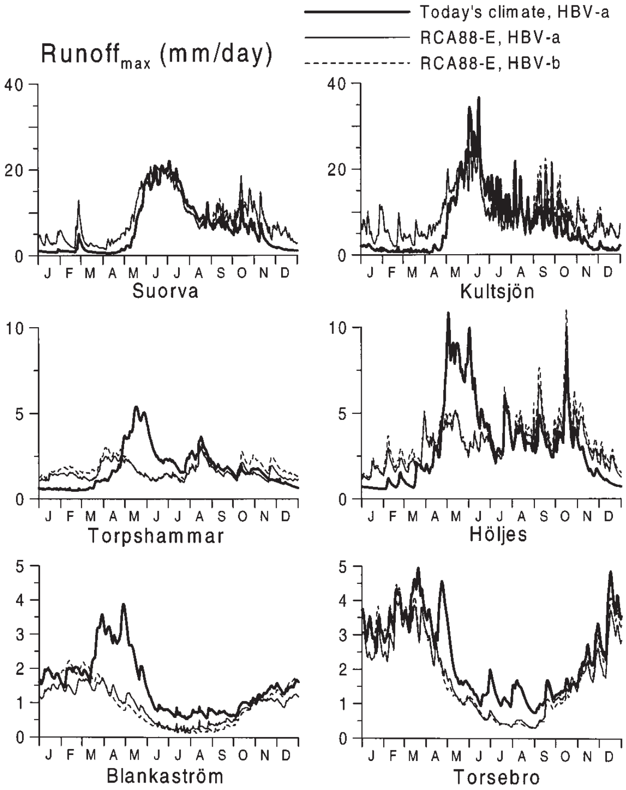

Fig. 10. Annual cycle of extreme daily runoff in 6 test basins today and according to the RCA88-E regional climate scenario and 2 versions of the HBV model

5. DISCUSSION AND CONCLUSIONS

The results from SWECLIM agree well with earlier studies in the Nordic countries in that water would be more abundant in the north and that drastic effects can be seen in the annual cycle of river flow, mostly because of less stable winter conditions, if the climate scenarios are correct. Some of the simulations indicate risks for water shortage in dryer parts of Sweden.

Table 7. Estimated change in the lowest flows in the 30 yr test record according to the water resources scenarios (%)

	HBV-a	HBV-b
Suorva RCA88-H	+44	+33
Suorva RCA88-E	+44	+33
Kultsjön RCA88-H	+76	+48
Kultsjön RCA88-E	+71	+43
Torpshammar RCA88-H	+13	+38
Torpshammar RCA88-E	0	+25
Höljes RCA88-H	+56	+50
Höljes RCA88-E	+44	+43
Blankaström RCA88-H	–100	–100
Blankaström RCA88-E	–100	–100
Torsebro RCA88-H	–43	0
Torsebro RCA88-E	–86	–38

In general, the timing of flood risks tends to shift from snowmelt in spring to summer, autumn or even wintertime. The impacts on design floods can be considerable. Decreasing 100 yr annual floods and spring floods is a general trend, but intense rain floods may be more frequent in the north. This may have implications for some reservoirs and put more stress on the spillways.

The use of 2 GCMs and 2 versions of the HBV model have given some insight into the generation of uncertainty in the water resources scenarios, although the sample is small. First of all it is quite evident that the general shift in the runoff regime, which is related to a general warming, is a consistent result shown by many studies. Uncertainties generally grow with an increasing role of local precipitation and evapotranspiration in runoff generation. Consequently the greatest relative uncertainties are found in the south, where the evapotranspiration is high and the runoff coefficient is low.

Several questions remain to be solved before climate impact scenarios on water resources can be used with full confidence for assessment of the future status of water resources in Sweden. Most critical are the global climate scenario itself and uncertainties in the local-scale patterns in downscaling of temperatures, precipitation and evapotranspiration to a specific drainage basin. Although this is a general problem, it is probably more serious in mountainous basins than in areas with more homogeneous climates.

The presently used technique in the interface between the regional climate model and the off-line hydrological simulations is a great simplification, which involves the risk of smoothing variability in an unrealistic manner. The consistent way to overcome these interface problems would be to fully integrate the hydrological model into the climate model. This would, however, require a precision in the climate models which has not yet been reached. For the time being, off-line hydrological simulations seem to be a practical way to investigate water resources scenarios. This means that we have to pay more attention to the interface between the climate models and the hydrological models even in the future and make sure that variability and extremes are not lost in the interface. An observation which has not been accounted for in the present study is that warming in the regional climate model tends to be stronger for low temperatures in winter and consequently less pronounced for days when melting occurs. This means that impacts on snowmelt, which is not affected by the lowest temperatures, might be overestimated. This effect will be analysed more closely in scenarios to come.

The basic hydrological tool in this study is a conceptual model with parameters which have to be calibrated before use of the model. The prediction uncertainty due to parameter identification of this type of model has been discussed by, for example, Uhlenbrook et al. (1999). This uncertainty may not be so large as long as the model is run within its range of calibration. However, uncertainties grow if the simulations are extrapolated outside this range, which may be the case in impact simulations. This problem is hard to overcome in the absence of hydrological models that are so exact that they perform well without any calibration or tuning.

Although considerable efforts have been dedicated to the evapotranspiration problem, some unsolved questions remain. The present results only represent 2 crude approaches and neither of these accounts for possible feedbacks from changing land-use or increasing CO_2 concentrations in the atmosphere to plant use of water. Nevertheless, the differences between the simulations created by the 2 versions of the HBV model confirm that climate change impacts on evapotranspiration are an important issue for assessments of future water availability as well as hydrological extremes even in northern Europe.

Acknowledgements. A great number of people have contributed to this paper. The global climate simulations were generously provided by the Hadley Centre and the Max Planck Institute for Meteorology. Staff at the Rossby Centre carried out the regional climate simulations. SWECLIM is funded jointly by the Swedish Foundation for Strategic Environmental Research (MISTRA) and the Swedish Meteorological and Hydrological Institute.

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Editorial responsibility: Hans von Storch, Geesthacht, Germany

Submitted: January 3, 2000; Accepted: June 11, 2000
Proofs received from author(s): December 4, 2000