Climate change impacts on hydrological processes in headwater catchments

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Abstract

Climate scenarios from the RegClim project (http://regclim.met.no) have been used to study the impacts of climate change on hydrological processes in headwater catchments in Central-Norway and at the Hardangervidda plateau in South-Norway. Two models of land surface hydrological and thermal conditions have been applied. The COUP-model simulates exchanges of water and energy in a vertical profile from the atmosphere through the vegetation to the underlying soil. Although the COUP-model uses detailed process descriptions at the point scale, modelling of land surface hydrology at larger spatial scales should be performed by models which represent the significant and systematic variations in the properties of the land surface. A distributed version of the HBV-model was applied for modelling of hydrological processes at the catchment scale. This model is sensitive to changes in the properties of the land surface and the climatic input data. It describes interfaces between the land surface and the atmosphere, soil moisture and groundwater storage, groundwater flow and river flow, and it provides a realistic framework for regional hydrological modelling by integrating the contributions from several small scale elements. The climate change impact studies show moderate changes in annual streamflow, whereas the seasonal streamflow changes are larger. Annual mean values of snow storage, depth of frozen ground and depth to the groundwater table is expected to decrease.

Introduction

A large amount of observations give a picture of global warming and other changes in the climate system. Changes in the climate occur as a result both of internal variability within the climate system and external factors (both natural and anthropogenic). The major influence of external factors is related to the increasing concentrations of greenhouse gases which tend to warm the earth surface (Houghton et al. 2001). Water in mountainous regions plays a significant role for important sectors in the Norwegian society, e.g. hydropower industry, tourism and transport. Long term management within these sectors must consider the potential effects of climate change on seasonal variability, extremes and mean values of hydrological processes including snow, subsurface thermal and moisture conditions and runoff. Water storage as snow delays runoff relative to precipitation, and melting of the seasonal snow cover is the most significant hydrological event of the year in Norwegian mountains.

Furthermore, biological activity and water chemistry depend on the availability of water, and water is also a primary weathering agent for rocks and soils. Frost depth in the ground is influenced by the amount of subsurface water, while frozen ground on the other hand inhibits infiltration leading to higher snowmelt floods and reduced percolation to the groundwater table. Understanding and describing the water and energy balances is therefore a prerequisite for determining the consequences of possible climate change in a mountainous environment.

Research areas

Simulations have been performed for headwater catchments in Central-Norway and at the Hardangervidda plateau in South-Norway, representing different landscape types, including mountains and alpine terrain, subalpine and boreal forests, non-forested areas below the tree line, lakes, bogs and glaciers. The climate of the investigated area is continental, and the runoff regime is dominated by spring and summer high flows caused by snowmelt, and winter low flows. The continental parts of Central- and South-Norway are characterized by mean monthly winter temperatures below -15 °C, while mean monthly summer temperatures normally reach 6 to 8 °C in the high mountain areas (Tveito et al. 2000). Mean annual precipitation is largest (>2000 mm/year) in the western parts where the humid Atlantic low pressure air masses reaches the mountains. The precipitation amounts decrease further east depending on both distance from the coast and topography. The driest areas in Central- and South-Norway are the leeward side of the mountain ranges (<350 mm/year) (Tveito et al. 1997).

Special attention has been paid to the Groset (6.5 km^2) and Aursunden (835 km^2) catchments. Detailed measurements of snow water equivalent, snow depth, groundwater table depth, soil moisture content, soil frost depth and streamflow are available from two of the stations of the Norwegian soil moisture monitoring network. The other catchments studied have streamflow data, but no observations of other water balance components. These remaining catchments are Møsvatn (1510 km^2), Orsjoren (1178 km^2), Hølen (232 km^2) and Reinsnosvatn (121 km^2) at the Hardangervidda plateau, and Sjodalsvatn (480 km^2), Risefoss (744 km^2) and Nybergsund (4420 km^2) in the mountains of Central-Norway. Some characteristics of the investigated catchments are presented in Table 1.

Methods

The need for large scale mapping and management of water resources has been the driving force behind the frequent use of hydrological models in Norway. For more than three decades, models of hydrological processes have been applied for various purposes, e.g. for planning the operation of hydropower production systems, streamflow forecasting and in connection with water quality issues. Although observations networks are dense compared to most developing countries, the need for determination of water budgets at different spatial and temporal scales across large regions has frequently required use of hydrological models. A model is any method or algorithm that describes the processes of interest and their interactions. The simulations of present and possible future hydrological conditions have been performed with two hydrological models, the physically based COUP-model (Jansson and Karlberg 2004) and the conceptual HBV-model (Bergström 1995). Physically based and conceptual models describe the relationship between meteorological inputs or other boundary conditions and the hydrological system using process-based model equations derived from principles of thermodynamics and fluid mechanics, or from simplified, but plausible conceptual representations of the processes of interest.

A spatially distributed version of the HBV-model (Beldring et al. 2003) has been used. The model performs water balance calculations for square grid cell landscape elements. Each grid cell may be divided into a lake area, a glacier area and two land use zones with different vegetations and soils. Every model element therefore has unique characteristics, input data are distributed, and water balance computations are performed separately for every model element. The model is run with daily time step, using precipitation and air temperature data as input. It has components for accumulation, subgrid scale distribution and ablation of snow, interception storage, subgrid scale distribution of soil moisture storage, evapotranspiration, groundwater storage and runoff response, lake evaporation and glacier mass balance. Potential evapotranspiration is a function of air temperature, however, effects of seasonally varying vegetation characteristics are considered. An algorithm for calculation of soil frost depth based on results from Vehviläinen and Motovilov (1989) has been introduced. Groundwater levels are determined using a storage coefficient and the depth to an impermeable base. The model is calibrated with the restriction that model discretization units with identical landscape classification are assigned similar parameter values.

The COUP-model (Jansson and Karlberg 2004) simulates one-dimensional water and heat dynamics in a layered soil column covered by vegetation by solving numerically the relevant differential equations. The main equations include the laws of conservation of mass and energy together with flow equations for water (Darcy's law) and heat (Fourier's law). A detailed description of the model can be found at http://www.lwr.kth.se/Vara%20Datorprogram/CoupModel. Simulations with the COUP-model were performed only for the Groset catchment and for the plant (heather and grasses) and soil characteristics (silty sand) at the soil moisture monitoring station. The soil profile contains 4 master soil horizons witch are typical for spodosols (Organic (2-3 cm), Eluvial (5-10 cm), Illuvial (30 cm), and C horizon) developed on till deposits. The soil profile is divided into 15 layers in the COUP-model, each layer described by their soil hydraulic properties, i.e. soil moisture retention curve and hydraulic conductivity. The thickness of the soil profile in the COUP-model is 4 m.

The Groset catchment is situated at altitudes between 939 and 1058 m a.s.l. The distributed HBV-model simulates the water balance of 1 km^2 grid cells where the vegetation consists of subalpine forests and mountainous areas above the tree line with grass, heather or low shrubs. The soils are glacial tills, i.e. non-sorted bedrock fragments ranging in size from clay to boulders.

An overview of some important features of the COUP- and HBV-models are shown in Table 2.

Table 1. Characteristics of the investigated catchments.

	Area (km^2)	Altitude (m a.s.l.)	Proportion forest	Proportion mountain	Proportion lakes	Proportion bogs	Proportion glaciers
Groset	6.5	939-1058	59 %	14 %	7 %	20 %	0 %
Møsvatn	1510	890-1628	6 %	77 %	12 %	5 %	0 %
Orsjoren	1178	951-1539	2 %	79 %	14 %	5 %	0 %
Hølen	232	120-1686	4 %	85 %	10 %	1 %	0 %
Reinsnosvatn	121	595-1637	10 %	77 %	10 %	2 %	1 %
Sjodalsvatn	480	940-2362	6 %	72 %	10 %	2 %	10 %
Risefoss	744	556-2284	8 %	85 %	3 %	4 %	0 %
Nybergsund	4420	353-1748	45 %	31 %	11 %	13 %	0 %
Aursunden	835	690-1561	32 %	46 %	12 %	10 %	0 %

Table 2. Comparison of the distributed HBV-model and COUP-model used in this study.

	Distributed HBV-model	COUP-model
Time resolution	Daily	Daily
Spatial resolution	1 km^2	1-dimensional (~1m^2)
Driving variables	Air temperature, precipitation	Air temperature, precipitation, relative humidity, wind speed, global radiation
Soil frost	Simulated	Simulated
Interception	Yes	Yes
Infiltration	No restriction	Restricted by saturated hydraulic conductivity (soil frost or low-permeable soil)
Surface runoff	No	If rain intensity > Ksat → surface water created. Runoff from the surface water is described by 1st order kinetics
Evapotranspiration Potential Actual	 Thornthwaite-type Soil moisture deficit	 Penman-Monteith Soil moisture deficit
Soil moisture storage	Field capacity principle	According to the soil hydraulic properties (soil moisture characteristic, hydraulic conductivity)
Water transport in soil	Upwards and downwards (percolation and capillary rise)	Upwards and downwards (percolation and capillary rise)
Vertical discretization	1 root zone layer 2 ground water layers	Max 22 layers, 15 layers used for Groset
Output simulations Each soil layer Others	 Storage of water, vertical flow of water, discharge from groundwater layers Snow water equivalent and depth, soil frost depth, groundwater level, streamflow	 Temperature, water potential, vertical flow of heat and water, storage of water and heat, root water uptake Snow water equivalent and depth, soil frost depth, surface runoff, drainage flow, groundwater level

Hydrological models which are to be used for climate change impact studies must perform well under conditions of non-stationarity as defined by Klemeš (1986). Non-stationarity means that a significant change in climate, land use or other catchment characteristics occurs. Mroczkowski *et al.* (1997) argued that model validation using only streamflow data at the outlet of catchments is not an adequate test of model structure or the hypothesis upon which a model is built, while validation based on the model's ability to simulate several fluxes or state variables (e.g. runoff, evapotranspiration, groundwater levels, soil moisture content, snow water equivalent, soil thermal conditions) is a better test. Although the distributed HBV-model describes the most important physical characteristics of processes related to the water balance at the interface between the land surface and the atmosphere, it is important to evaluate its results using observed data and simulations with the physically more realistic COUP-model. If simulations of different water balance components compare fairly well with observations, climate change impact studies can be considered more trustworthy.

The climate scenarios used in this study were produced by the Atmosphere-Ocean General Circulation Model (AOGCM) HadAm3 developed at the Hadley centre in UK (Gordon et al. 2000). The spatial resolution of AOGCMs is typically ~300 * 300 km^2. Thus, to obtain reliable estimates of the climate at specific regions in Norway, downscaling is necessary. Results from HadAm3 were dynamically downscaled with the regional climate model HIRHAM (Bjørge et al. 2000) which has a spatial resolution of ~55 * 55 km^2. Daily values of measurements of temperature and precipitation are traditionally used as input to the hydrological model. Estimates of temperature and precipitation were interpolated from HIRHAM to locations of selected meteorological stations. However, the station altitude is wrongly represented in the model and the number of rainy days is typically estimated too high. The dynamically downscaled temperature and precipitation data were therefore empirically adjusted to be representative locally by Engen-Skaugen et al. (2005).

Results and discussion

The distributed HBV-model was calibrated against observed streamflow from all nine catchments for the period 1976-1990, and subsequently validated for the period 1961-1975. Model performance was good, meaning that simulations are trustworthy under current climate conditions. Fig. 1 presents results from streamflow simulations in the Groset and Aursunden catchments. The model was run with daily timestep, but the data have been aggregated to monthly values in Fig. 1. Simulations of snow water equivalent and soil frost depth for the Aursunden catchment are shown in Fig. 2. Results are mostly satisfactory, however, model simulations are averaged over the catchment area, while snow water equivalent and soil frost depth data are point measurements in the eastern and western parts of the Aursunden catchment, respectively. As all hydrological processes have a variability that depends on local meteorological, geological, topographical and vegetation characteristics, area averaged model simulations cannot be expected to conform to point measurements.

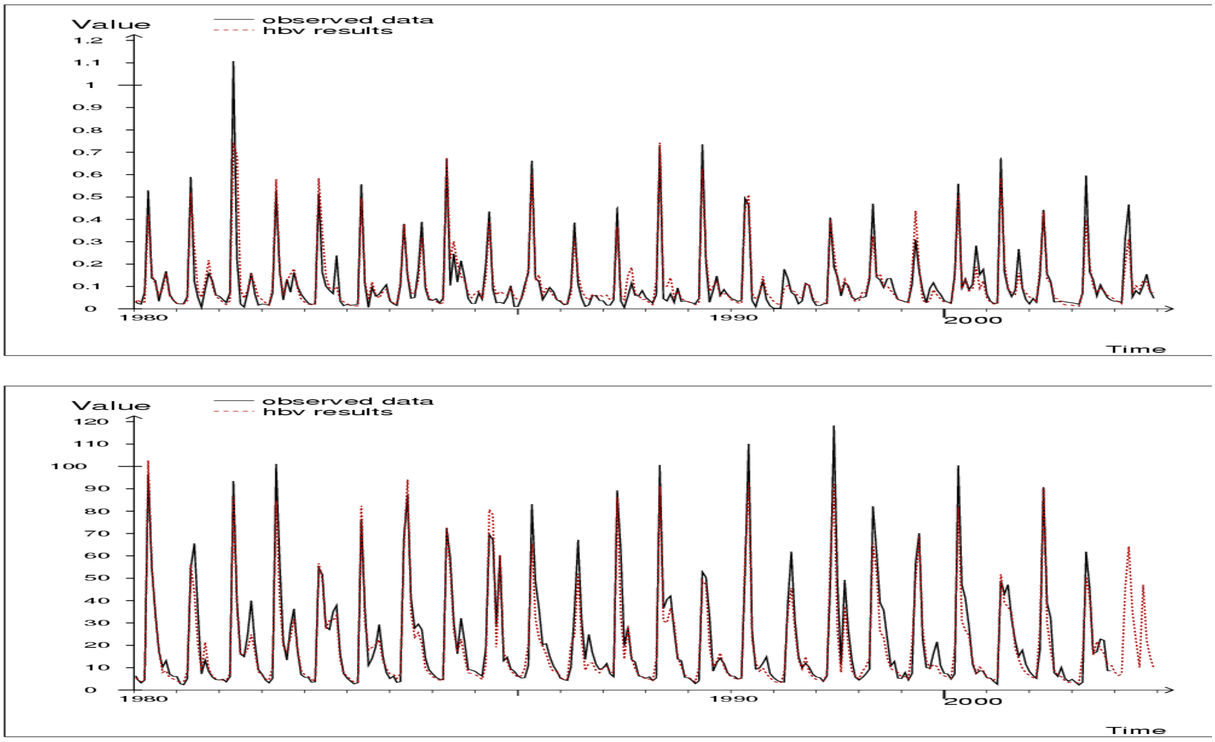


Figure 1. Observed and simulated (HBV) streamflow (m^3/s) from the Groset (top) and Aursunden (bottom) catchments. Data have been aggregated to monthly values.

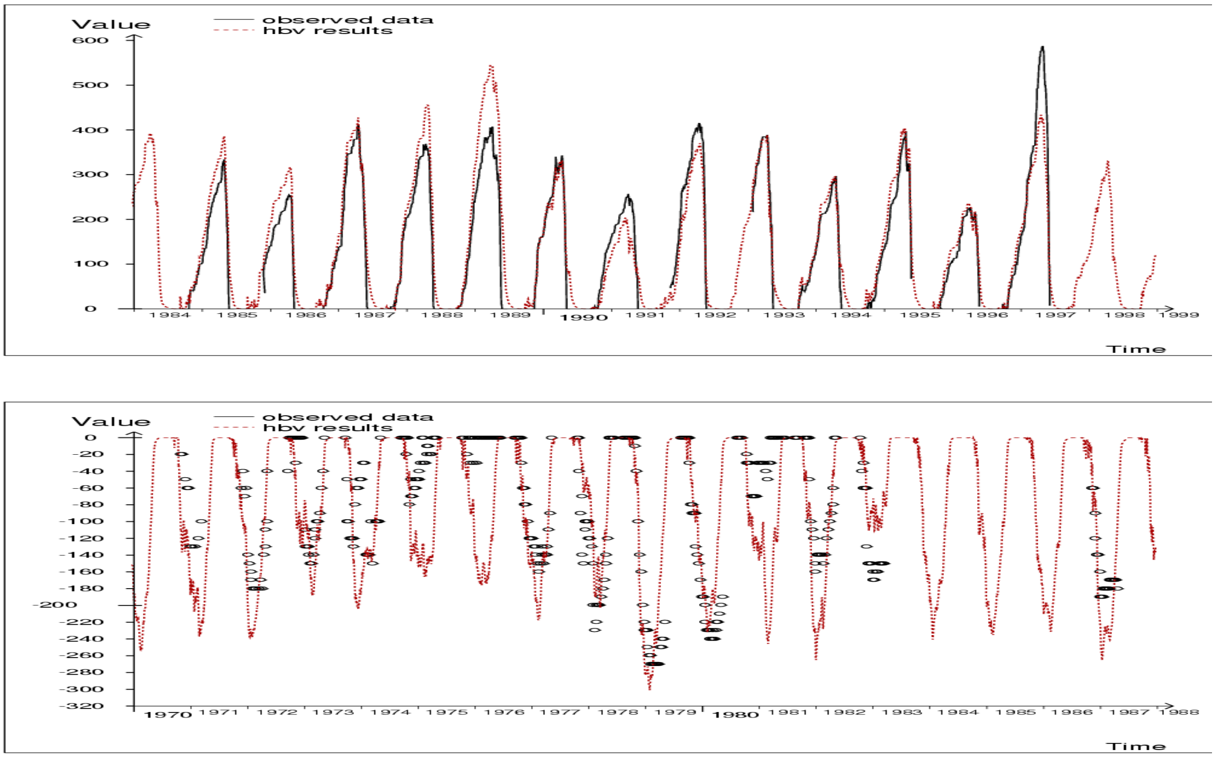


Figure 2. Observed and simulated (HBV) snow water equivalent (mm) (top) and soil frost depth (mm) (bottom) in the Aursunden catchment.

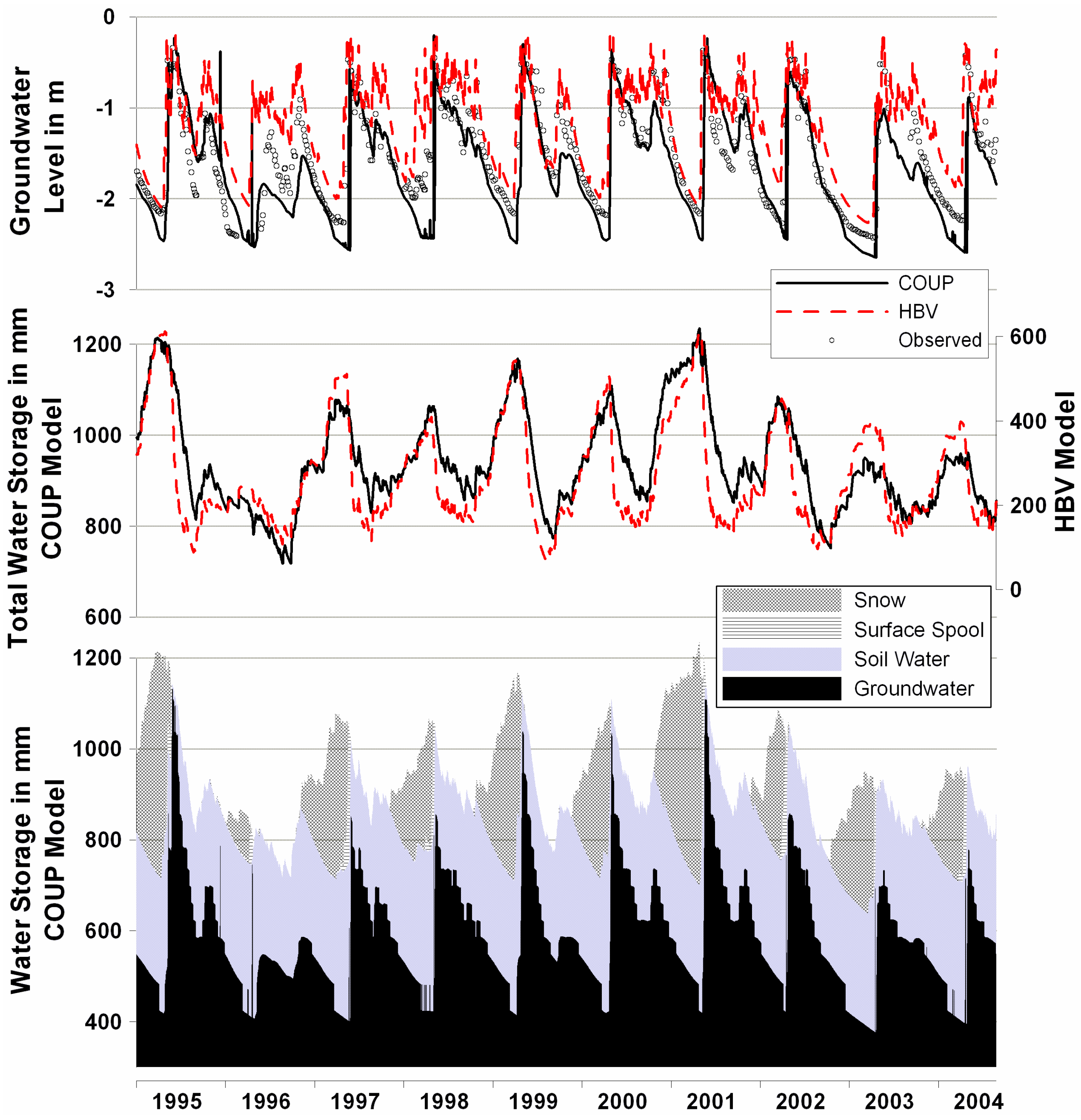
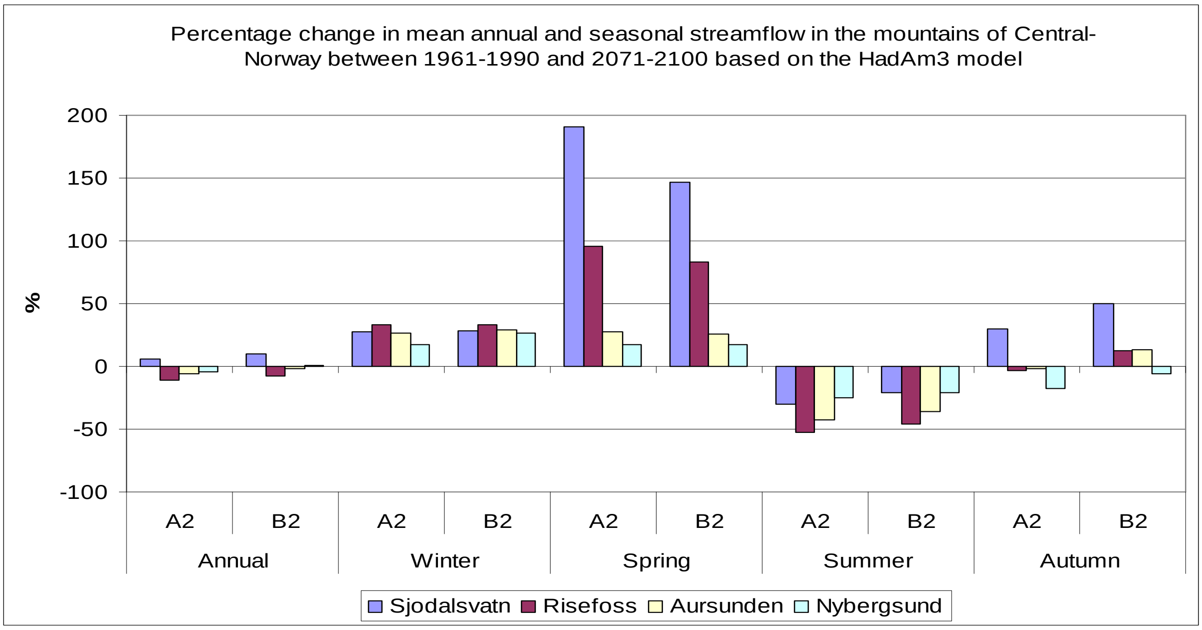


Figure 3. COUP- and HBV-model results from the Groset catchment. Top: Observed and simulated groundwater levels. Middle: Total water storage. Bottom: Snow, surface water, soil moisture and groundwater storage in the COUP-model.

Groundwater levels, soil moisture storage and snow water equivalent from simulations with the COUP- and HBV-models in the Groset catchment are presented in Fig. 3. Note the dry periodes in 1996 and 2002/2003 characterized by a deficit in soil moisture and low groundwater levels. The groundwater levels are well described by both models, although there are discrepancies between observations and model results. There are also differences between the two models, which can be attributed to differences in simulated actual evapotranspiration. The water storage of the two models agree to some extent, but the total volumes differ due to different representation of the hydrological processes. The HBV-model needs only consider the volume of water which is active in the precipitation-runoff process and deep immobile groundwater is not necessarily included. It is also a problem that model simulations represent different areas. The COUP-model simulates processes for one specific location within the catchment, while HBV-model results are averaged over the entire catchment area. Convergence and divergence of subsurface flow paths caused by the influence of bedrock and surface topography can significantly affect moisture conditions.



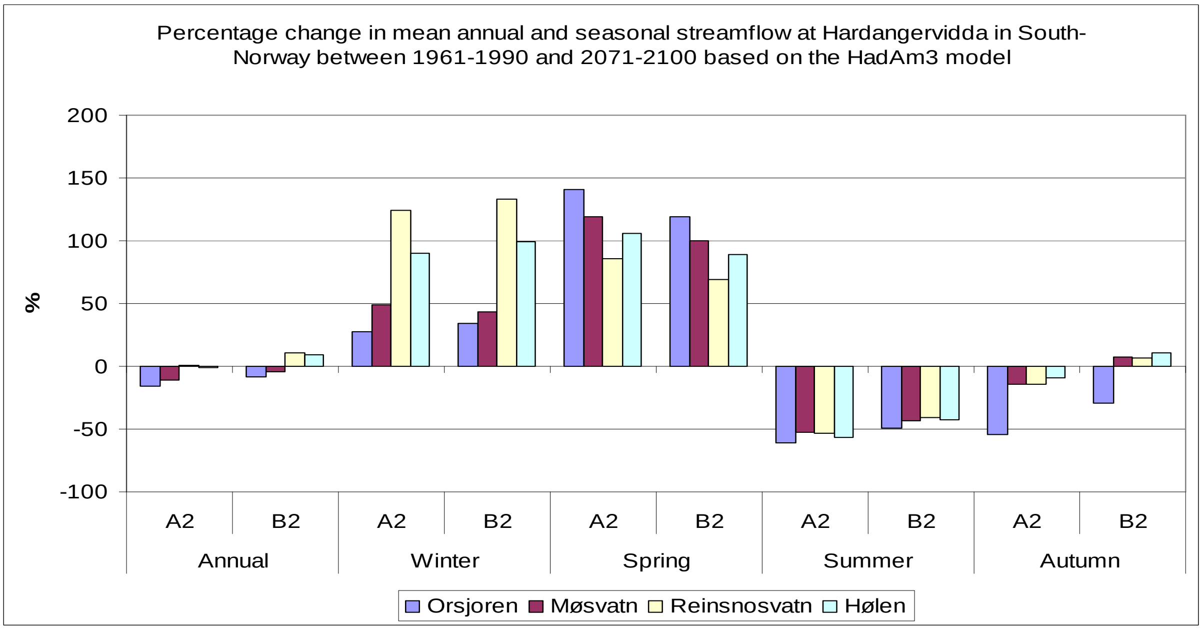


Figure 4. Climate change impact simulations based on the Atmosphere-Ocean General Circulation Model HadAm3 for annual and seasonal streamflow from catchments located in Central-Norway (top) and at the Hardangervidda plateau (bottom) in South-Norway.

The climate change impact simulations for annual and seasonal streamflow from catchments located in Central-Norway and at the Hardangervidda plateau in South-Norway are presented in Fig. 4. Two emission scenarios for greenhouse gases have been applied; a moderate (B2) and a high (A2). Climate model results for the scenario period 2071-2100 were compare to the control period 1961-1990 (present climate). Up to 2100 B2 gives approximately 2.5 °C increase in global mean temperature while A2 is giving an increase of 3.5 °C (Houghton et al. 2001). The annual streamflow will remain mostly unchanged, whereas the picture varies for seasonal streamflow. The winter streamflow will generally increase and the spring streamflow will increase substantially, in particular in high mountain areas. The summer streamflow will decrease, whereas the changes in autumn streamflow varies from moderate decrease to moderate increase. Calculated changes in the annual maximum water equivalent of snow for the Aursunden and Møsvatn catchments summarized in Table 3 show a decline, which is also the case for the number of days with snow cover. The maximum snow storage will occur two to three weeks earlier. The mean soil frost depth decreases and maximum frost depth occurs earlier. Mean depth to the groundwater table decreases, the maximum value occurs earlier for the A2 scenario and later for the B2 scenario.

Table 3. Changes in maximum water equivalent of snow for the Aursunden and Møsvatn catchments.

	Mean of annual maxima (mm)	Change of annual maximum	Mean day no. of annual maximum
Aursunden control	372		112
Aursunden A2	304	-18.3 %	98
Aursunden B2	313	-15.9 %	93
Møsvatn control	632		120
Møsvatn A2	543	-14.1 %	104
Møsvatn B2	558	-11.7 %	106

Conclusions

Comparing observed data and results from the HBV- and COUP-models confirms that model simulations are realistic. The theoretical basis of the two models is firmly grounded in experimental results, but the models represent real world processes differently. The COUP-model uses equations based on the governing laws of mathematical physics, the geometry of the system, sources and sinks and initial and boundary conditions. Although the level of simplification is higher in the HBV-model, it describes the essential characteristics of the precipitation-runoff process, the volumes of water stored as snow and subsurface water are correctly reproduced, and it provides correct simulations of streamflow, the only variable in the climate system which integrates processes at the catchment scale. Validation of the two models based on the their ability to simulate several hydrological processes is a good strategy in the respect that model results can be considered more realistic, even in the case of a shift in climate (Mroczkowski et al. 1997). The model discretization units of the spatially distributed

HBV-model represent the significant and systematic variations in the properties of the land surface, and representative parameter values are applied for different classes of soil and vegetation types, lakes and glaciers. According to Becker and Braun (1999), this process-adequate areal discretization scheme is a requirement for reliable modelling of large scale hydrological process dynamics, an essential requirement for studying climate change impacts on hydrological processes.

Climate change impact simulations show moderate changes in annual streamflow, whereas the seasonal streamflow changes are larger, in particular during spring when streamflow will increase substantially indicating earlier snowmelt floods. Mean values of snow storage, depth of frozen ground and depth to the groundwater table is expected to decrease.

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