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Climate change impacts on hydrological processes in Norway based on two methods for transferring regional climate model results to meteorological station sites

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ABSTRACT

Climate change impacts on hydrological processes in Norway have been estimated through combination of results from the IPCC SRES A2 and B2 emission scenarios, global climate models from the Hadley Centre and the Max-Planck Institute, and dynamical downscaling using the RegClim HIRHAM regional climate model. Temperature and precipitation simulations from the regional climate model were transferred to meteorological station sites using two different approaches, the delta change or perturbation method and an empirical adjustment procedure that reproduces observed monthly means and standard deviations for the control period. These climate scenarios were used for driving a spatially distributed version of the HBV hydrological model, yielding a set of simulations for the baseline period 1961–1990 and projections of climate change impacts on hydrological processes for the period 2071–2100. A comparison between the two methods used for transferring regional climate model results to meteorological station sites is provided by comparing the results from the hydrological model for basins located in different parts of Norway. Projected changes in runoff are linked to changes in the snow regime. Snow cover will be more unstable and the snowmelt flood will occur earlier in the year. Increased rainfall leads to higher runoff in the autumn and winter.

1. Introduction

Global warming of the surface temperature by approximately 0.75 °C has been observed over the last 100 yr (Trenberth et al., 2007). Different emission scenarios project a further increase of global temperature of 1–6 °C (Meehl et al., 2007). Globally averaged water vapour concentrations, evaporation and precipitation are projected to increase, with subsequent impacts on land surface hydrology. Water plays a significant role for important sectors in Norwegian society, for example, hydropower, water supply, tourism and transport. Furthermore, hydrological processes at the land surface influence the natural environment at a range of spatial and temporal scales through their impacts on biological activity and water chemistry. Water is also a primary weathering agent for rocks and soils, breaking them down, dissolving them, and transporting the resulting sediments and dissolved solids to the sea. Freshwater discharge and energy fluxes to the ocean, latent and sensible heat fluxes, glacier mass balance, snow cover and permafrost conditions influence the global climate through feedback effects involving atmospheric and ocean circulation (Peixoto and Oort, 1992). Climate change impact studies in natural and social sciences where land surface hydrological conditions exert a major control on the phenomena under consideration must consider changes in mean values, seasonal variability and extremes of water availability including snow, subsurface moisture conditions and runoff.

When focusing on the hydrological cycle, general circulation models are too coarse to provide regional and local details of the climate at a spatial scale suitable for climate change impact studies (Bronstert, 2004). Different downscaling methods have been developed to overcome this problem, dynamically, empirically or these two techniques in combination (e.g. Giorgi et al., 2001), in order to obtain higher spatial resolution. A regional pattern with focus on a shift in the future climate compared to present may be satisfactory for assessments on large spatial scales, but the uncertainty of regional climate model scenarios, especially the precipitation estimates, renders them useless for hydrological climate change impact studies. Daily values of at site measurements of temperature and precipitation are traditionally used as input to hydrological models. Estimates of temperature and precipitation must therefore be transferred from regional climate models to selected locations. Wood et al. (2004) stated that 'a

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minimum standard of any useful downscaling method for hydrological applications needs the historic (observed) conditions to be reproducible'. Different methods have been used to solve this problem; the delta change, or perturbation method has been widely used to adjust climate change scenarios to meteorological station sites (Lettenmaier et al., 1999; Middelkoop et al., 2001; Reynard et al., 2001). The delta change approach does not capture changes in the frequency of temperature and precipitation events, and it is therefore questionable whether hydrological model results for a future climate based on this method can be trusted, in particular for extreme events. An empirical adjustment method developed by Engen-Skaugen (2007) is used here for adjusting dynamically downscaled precipitation and temperature scenarios to meteorological station sites. The method reproduces mean monthly values and standard deviations based on daily observations. The trend obtained in the regional climate model both for temperature and precipitation is maintained, and the frequency of modelled and observed rainy days shows better agreement. Projections of climate change impacts on hydrological processes based on this method are compared to projections based on the delta change approach.

Although the level of simplification is higher in hydrological models than in atmospheric models, they describe the essential characteristics of the precipitation-runoff process, the volumes of water stored as snow and subsurface water are correctly reproduced, and they provide realistic simulations of streamflow, the only variable in the climate system which integrates processes at the basin scale. 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 basin characteristics occurs. In view of the natural variability of the landscape and the non-linearity of the processes involved, the parametrization procedure of hydrological models used for climate change impact studies must reflect the significant and systematic variations in the land surface properties, for example, by using representative parameter values for different soil types, vegetation types or geological layers. This implies repeated application of a hydrological model everywhere within a region using a global set of parameters (Gottschalk et al., 2001). The framework applied for assessment of climate change impacts on water resources in this study used a spatially distributed hydrological model which is based on integrating the contributions from several small scale elements. Similar parametrization procedures have been applied in order to determine model parameters for ungauged basins (e.g. Engeland and Gottschalk, 2002; Van der Linden and Woo, 2003).

2. Climate models

Results from the Max Planck Institute atmosphere-ocean general circulation model (AOGCM) ECHAM4/OPYC3 (Roeckner et al., 1999) with T106 ($\sim$125 $\times$ 125 km^2) resolution, and from the general circulation model HadAM3H developed from the atmospheric component of the Hadley Centre AOGCM HadCM3 (Gordon et al., 2000) have been used for assessment of climate change impacts on water resources in the Nordic countries. Assumptions about future greenhouse gas emissions are based on the IPCC Special Report on Emission Scenarios (SRES) A2 and B2 scenarios (Nakićenović et al., 2000). Up to 2100, scenario B2 gives approximately 2.5 °C increase in global temperature, while A2 gives an increase of approximately 3.5 °C.

Assessment of the future hydrological regime is a production chain where scenarios for changes in external forcing caused by greenhouse gas emissions are introduced into general circulation models. The analyses presented in this study are based on two general circulation models forced with, respectively, one and two greenhouse gas emission scenarios. The spatial resolution of general circulation models is quite coarse, and the regional and local details of the climate at that scale are lost. Thus, to obtain reliable estimates of the climate at specific regions, downscaling is necessary. The HadAM3H A2 and B2, and ECHAM4/OPYC3 B2 scenarios were used as boundary conditions for dynamical downscaling with the HIRHAM regional climate model (RCM) applied in the Norwegian RegClim project (Bjørge et al., 2000). The HIRHAM model has a spatial resolution of 0.5° ($\sim$55 $\times$ 55 km^2). The analyses have been performed for basins representing different parts of Norway. These experiments and their results for temperature were described by Engen-Skaugen et al. (2007).

3. Interface between regional climate model and hydrological model

Daily values of at site measurement of temperature and precipitation are traditionally used as input to hydrological models. Estimates of temperature and precipitation must therefore be transferred from the 55 $\times$ 55 km^2 grid in the RCM to selected locations. However, there are large difficulties when using temperature and precipitation data from regional climate models as meteorological station data representing at site locations. The station altitude is wrongly represented in the regional climate model, and the number of rainy days is typically overestimated (Frei et al., 2003). Daily temperature and precipitation simulations from the regional climate model were therefore transferred to meteorological station sites using two different procedures as explained below.

The hydrological climate change impact simulations used the time slice approach whereby model simulations representing a slice of time in the baseline climate (control: 1961–1990) and in a future climate (scenario: 2071–2100) were performed. The hydrological impact studies were done using off-line simulations with the hydrological model, based on two different methods for transferring the signal of climate change from the regional climate model to the hydrological model. Both methods perform bilinear interpolation of daily temperature and precipitation

Fig. 1. Location of basins and meteorological stations.

Table 1. Estimates of 99th, 95th, 90th and 75th percentiles of daily precipitation for meteorological station Drevsjø for 1961–1990 based on observed meteorological data and HIRHAM simulations transferred to the station site using the empirical adjustment technique (Engen-Skaugen, 2007)

Percentiles	Observed	Hadley ctr.	Echam ctr.
(a) Winter			
99^{th}	9.9	8.4	8.4
95^{th}	4.8	5.1	4.9
90^{th}	3.0	3.4	3.3
75^{th}	1.0	1.1	1.1
(b) Spring			
99^{th}	12.4	12.8	11.0
95^{th}	6.0	6.3	6.2
90^{th}	3.4	3.9	3.7
75^{th}	0.8	0.6	0.7
(c) Summer			
99^{th}	23.9	24.8	25.0
95^{th}	12.9	13.7	12.0
90^{th}	8.2	8.5	7.5
75^{th}	2.7	2.5	2.7
(d) Autumn			
99^{th}	17.4	17.6	16.6
95^{th}	8.4	9.0	9.0
90^{th}	5.2	5.8	5.9
75^{th}	1.8	1.7	1.8

data from the RCM grid points to meteorological station sites for the time slice of each regional climate model run as a first adjustment.

3.1. *Empirical adjustment of regional climate model results*

An empirical adjustment technique developed by Engen-Skaugen (2007) was used for transferring temperature and precipitation simulations from the RCM to meteorological station sites. This method has previously been applied by Kaste et al. (2006) for analysing climate change impacts on water quality in a watershed in Norway. The empirical adjustment technique improves the statistical moments mean value and standard deviation from the RCM. Although the RCM simulates too many rainy days, the number of days with precipitation is reduced to a realistic level after the adjustment. The mean monthly change from the control to the scenario period predicted by the RCM is maintained both for precipitation and temperature. Extreme values are satisfactory reproduced with the method as well. Estimates of the 99th, 95th, 90th and 75th percentiles of daily precipitation for 1961–1990 for two meteorological stations, Drevsjø and Fjærland-Skarestad (Fig. 1), are presented in Tables 1 and 2, respectively. Since the climate change signal from the RCM is preserved and the adjusted precipitation and temperature data from the control period reproduce the frequency distribution of daily values for the observed climate, it should be possible to use the adjusted scenario data as input to precipitation-runoff models for studying climate change impacts on hydrological processes. A question still not answered when using the empirical adjustment method, however, is how the consistency between climate elements obtained by the regional climate model is altered. This is of great interest for several impact research areas.

HIRHAM was run with one control period and one scenario period for each AOGCM simulation. The estimated day-to-day variability in the control runs are not comparable with observed data, however, the monthly mean values and standard deviations based on daily model data are comparable to observations. The statistics of daily data for the entire control period of 30 yr should also be comparable to statistics estimated from observations. A comparison between observed temperature and precipitation data and results from the empirical adjustment procedure for the control period are presented in Engen-Skaugen (2007).

3.2. *Delta change approach*

A common method for determination of climate change input to hydrological models transfers changes in meteorological variables between the control and the scenario simulations from the regional climate model to a database of observed meteorological data. This can be referred to as the delta change approach (e.g. Hay et al. 2000; Reynard et al. 2001). Observed data from

Table 2. Estimates of 99th, 95th, 90th and 75th percentiles of daily precipitation for meteorological station Fjærland-Skarestad for 1961–1990 based on observed meteorological data and HIRHAM simulations transferred to the station site using the empirical adjustment technique (Engen-Skaugen, 2007)

Percentiles	Observed	Hadley ctr.	Echam ctr.
(a) Winter			
99th	45.5	46.7	43.3
95th	28.0	27.4	26.0
90th	20.5	19.2	19.4
75th	8.8	9.1	9.5
(b) Spring			
99th	33.7	29.0	31.4
95th	16.6	16.5	17.8
90th	10.8	11.6	11.5
75th	3.6	3.9	3.8
(c) Summer			
99th	30.2	29.3	26.9
95th	16.0	16.2	16.4
90th	10.6	11.7	11.5
75th	4.5	4.4	4.7
(d) Autumn			
99th	49.7	50.0	50.5
95th	33.6	31.3	32.2
90th	23.8	23.3	22.5
75th	10.4	11.4	11.4

meteorological stations were used as the control climate for the hydrological model runs. Monthly relative precipitation changes and absolute temperature changes predicted by the regional climate model were then used to modify the observed daily meteorological data driving the hydrological model for the baseline period 1961–1990. The same monthly precipitation changes were used for all years of the impact simulations and for extreme values as well as for average conditions. The number of precipitation days was not changed in the scenario climate. Constant monthly temperature changes for all temperature intervals were applied. The delta change approach reproduces the changes in monthly mean values from the control to the scenario period.

4. Hydrological model

The observed meteorological data and the regional climate model results transferred to meteorological station sites were used for driving a spatially distributed version of the HBV hydrological model (Beldring et al., 2003). The HBV model was developed at the Swedish Meteorological and Hydrological Institute as a conceptual, semi-distributed precipitation-runoff model (cf. Lindström et al., 1997). The HBV model exists in several versions and has been applied for a variety of purposes, including climate change impact studies (e.g. Andréasson et al., 2004). The spatially distributed HBV model that was applied in this study performs water balance calculations for 1×1 km^2 grid cell computational elements characterized by their altitude and land use. Each grid cell may be divided into a maximum of four land surface classes; two land use zones with different vegetations, a lake area and a glacier area. The model is run with daily time steps, using precipitation and air temperature data as input. It has components for accumulation, subgrid scale distribution and ablation of snow, glacier mass balance, interception storage, subgrid scale distribution of soil moisture storage capacity, groundwater storage and runoff response, evaporation including soil evaporation, evaporation of intercepted water, transpiration from vegetation and lake evaporation. A simplified form of the Thornthwaite method (Thornthwaite, 1948) is used to determine daily potential evaporation as a function of daily mean air temperature, with monthly coefficients of proportionality being used. Furthermore, the effects of seasonally varying vegetation characteristics are considered. The potential evaporation is reduced when water is present in the interception storage. In addition to grid cell computations, the model determines mean values for all water balance elements within the basins. Streamflow or discharge is the sum of values from all grid cells within a basin.

The parameter values assigned to the computational elements of the hydrological model should reflect that hydrological processes are sensitive to spatial variations in soil properties (e.g. Merz and Plate, 1997) and vegetation characteristics (e.g. Matheussen et al., 2000) through their control on storage of water, runoff events, evaporation, snow accumulation and snow melt. The following land use classes were therefore used for describing the properties of the landscape elements of the model: (i) areas above the tree line with extremely sparse vegetation, mostly lichens, mosses and grass; (ii) areas above the tree line with grass, heather, shrubs or dwarfed trees; (iii) areas below the tree line with subalpine forests; (iv) lowland areas with coniferous or deciduous forests and (v) non-forested areas below the tree line. The model was run with specific parameters for each land use class controlling snow processes, interception storage, evaporation processes, soil moisture storage, groundwater storage and runoff response. Lake evaporation and glacier mass balance were controlled by parameters with the same values for all model elements within a basin.

The model was calibrated using available information about climate and hydrological processes from the basins analysed in this study. One model parameter set for each individual basin was determined by calibrating the model with the restriction that the same parameter values are used for all computational elements of the model that fall into the same class for land surface properties. This calibration procedure rests on the hypothesis that model elements with identical landscape characteristics have similar hydrological behaviour, and should consequently be assigned the same parameter values. Beldring et al. (2003) showed that the hydrological model performs well under non-stationarity conditions through parametrization of the processes that control runoff and evaporation fluxes in the Norwegian landscape, and by

Table 3. Characteristics of the basins

Basin name	Area (km^2)	Elevations (m)			Basin land cover (%)				
		Low	Median	Top	Forest	Mountain	Lakes	Bogs	Glaciers
Flaksvatn	1794	19	358	1146	76.6	6.7	7.9	8.1	0
Nybergsund	4410	353	783	1748	48.7	28.6	9.1	12.6	0
Viksvatn	505	145	841	1636	23.5	59.7	9.9	1.1	4.9
Masi	5693	272	451	1085	37.6	38.3	7.3	16.8	0

application of this process-adequate spatial discretization scheme. The parameter set determined for one specific basin during this calibration procedure was applied for all hydrological model runs for that basin, regardless of which period or climate scenario that was considered.

The precipitation stations used in this study were classified in five exposure classes with fixed correction factors for rain, snow and mixed type precipitation according to a Nordic study (Førland et al., 1996). The precipitation data were accordingly given a simplified precipitation type classification that was used by the hydrological model for modifying all precipitation input, both observed data and downscaled climate model results. Temperature and precipitation values for the hydrological model grid cells were determined by inverse distance interpolation of observations from the three closest precipitation stations and the two closest temperature stations. The same temperature and precipitation stations were applied in all model runs for one particular basin. Differences in temperature and precipitation caused by elevation were corrected by precipitation-altitude gradients and temperature lapse rates. There is considerable uncertainty with regard to the variations in precipitation with altitude in the mountainous terrain of Norway. Specific precipitation-altitude gradients and temperature lapse rates were therefore determined for each of the basins, and these values were used for all grid cells within a basin. A few mountain stations necessitate use of these general gradients. The precipitation-altitude gradients were reduced by 50% for elevations above 1200 m a.s.l., as drying out of ascending air occurs in high mountain areas due to orographically induced precipitation (Daly et al., 1994).

Hydrological model performance is usually evaluated by considering one or more objective statistics of the residuals between model simulated output and observed watershed output. The objective functions used in this study were the Nash–Sutcliffe and bias statistics of the residuals, which have a low correlation (Wglarczyk, 1998). The Nash–Sutcliffe efficiency criterion ranges from minus infinity to 1.0 with higher values indicating better agreement. It measures the fraction of the variance of observed values explained by the model. Bias (relative volume error) measures the tendency of modelled values to be larger or smaller than their observed counterpart.

Table 4. Hydrological model validation results for 1961–1990

Basin name	River	Nash–Sutcliffe efficiency	Bias
Flaksvatn	Tovdalselv	0.81	0.02
Nybergsund	Trysilelv	0.91	–0.04
Viksvatn	Gaular	0.89	0.01
Masi	Alta	0.89	0.02

5. Study areas

This study examined projected climate change impacts on hydrological processes in four basins selected to represent different parts of Norway. The location of the basins and the station sites with observed meteorological data are shown in Fig. 1. Selected basin characteristics are listed in Table 3. The proportion used for agriculture is less than 1% in all basins. Nybergsund, Viksvatn and Masi are characterized by a mountain hydrological regime with low flows in the winter caused by snow accumulation and high flows during snowmelt in spring or early summer. Flaksvatn has an inland regime in which high flows are caused by both snowmelt in the spring and rain in the autumn, whereas low flows result from both snow accumulation in the winter and high evaporation and low precipitation in the summer. The hydrological model was calibrated individually for each basin for the period 1976–1990, and then evaluated for the period 1961–1990. The results for the Nash–Sutcliffe and bias statistics for the evaluation period presented in Table 4 demonstrate that the model performs well for the investigated catchments.

6. Results

It is imperative that the methods used for transferring RCM results to meteorological station sites generate temperature and precipitation time series that have the same statistical properties as the observed meteorological data used for calibrating the hydrological model. Furthermore, when these adjusted regional climate model results are used as input for hydrological modelling, the resulting time series must have the same statistical properties as the hydrological variables that would be generated using observed meteorological data for driving the hydrological

Table 5. Changes in mean values and standard deviations of daily temperature from 1961–1990 to 2071–2100

Basin name	Climate change scenario	Change in mean (°C)		Change in standard deviation (°C)	
		Empirical adjustment	Delta change	Empirical adjustment	Delta change
Flaksvatn	Hadley A2	3.5	3.5	0.0	0.1
Flaksvatn	Hadley B2	3.0	3.0	–0.1	0.0
Flaksvatn	Echam B2	3.0	3.0	0.1	0.1
Nybergsund	Hadley A2	3.5	3. 6	–0.7	–0.2
Nybergsund	Hadley B2	2.8	2.8	–0.8	–0.3
Nybergsund	Echam B2	3.0	3.1	–0.3	0.0
Viksvatn	Hadley A2	3.1	3.0	–0.2	0.0
Viksvatn	Hadley B2	2.5	2.5	–0.3	–0.1
Viksvatn	Echam B2	2.9	2.9	0.0	0.1
Masi	Hadley A2	4.0	3.9	–0.9	–0.3
Masi	Hadley B2	3.5	3.3	–1.1	–0.4
Masi	Echam B2	3.4	3.3	–0.8	–0.3

Table 6. Changes in mean values and standard deviations of daily precipitation from 1961–1990 to 2071–2100

Basin name	Climate change scenario	Change in mean (mm)		Change in standard deviation (mm)	
		Empirical adjustment	Delta change	Empirical adjustment	Delta change
Flaksvatn	Hadley A2	0.1	0.1	0.6	0.4
Flaksvatn	Hadley B2	0.4	0.4	1.0	0.9
Flaksvatn	Echam B2	0.4	0.4	1.2	0. 8
Nybergsund	Hadley A2	0.1	0.1	0.8	0.1
Nybergsund	Hadley B2	0.1	0.2	0.7	0.2
Nybergsund	Echam B2	0.3	0.3	0.9	0.5
Viksvatn	Hadley A2	0.4	0.4	0.8	0. 7
Viksvatn	Hadley B2	0.9	0.9	1.5	1.7
Viksvatn	Echam B2	1.8	1.8	3.2	3.4
Masi	Hadley A2	0.1	0.1	0.7	0.4
Masi	Hadley B2	0.1	0.1	0.9	0.4
Masi	Echam B2	0.2	0.2	0.5	0.2

model. With the delta change approach this is not a problem, as the control period climate time series are equal to observed meteorological data. However, for the empirical adjustment procedure developed by Engen-Skaugen (2007) this needs to be investigated.

The hydrological model modified temperature and precipitation data from the meteorological station sites according to the simplified precipitation type classification and the precipitation-altitude gradients and temperature lapse rates. The same procedure was used for each time step of all model runs for all basins. Time series of temperature and precipitation input averaged over all grid cells within a basin may therefore be used for comparing the two methods used for transferring temperature and precipitation data from the regional climate model to meteorological station sites. Changes in mean values for daily temperature and precipitation data differ somewhat (Tables 5 and 6), although the two methods in theory project the same changes. These differences are small compared to absolute values and can be attributed to the precision in the calculations leading to the final results. Standard deviations of temperature for the empirical adjustment procedure have a more pronounced tendency towards reduced variability in the scenario climate as compared to the delta change approach (Table 5), whereas standard deviations of daily precipitation increase most for the empirical adjustment procedure (Table 6).

If the empirical adjustment procedure is able to reproduce the statistical properties of observed meteorological data, the hydrological model will generate times series that have the same statistical properties as the hydrological variables that are generated when using observed meteorological data for driving the hydrological model. Mean daily streamflow generated by using observed meteorological data as input to the hydro-

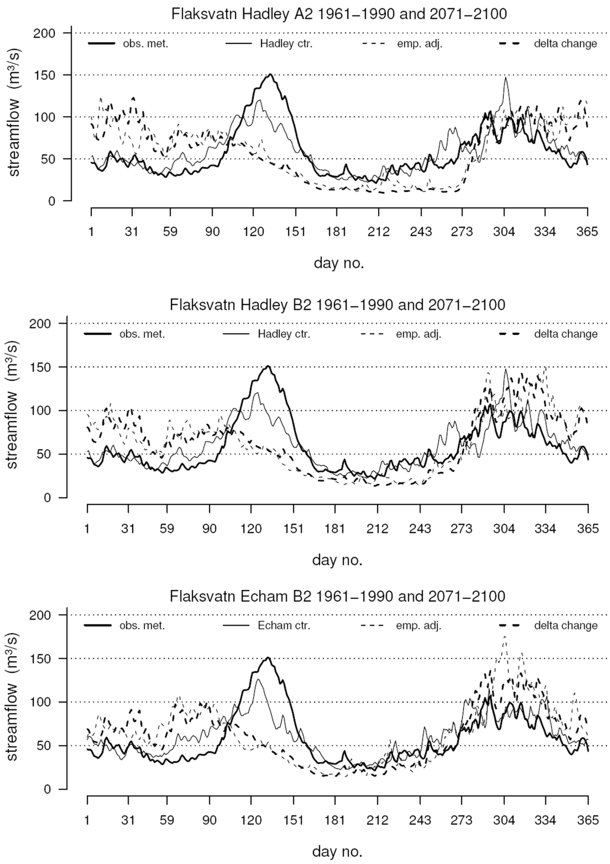

Fig. 2. Simulated mean daily streamflow for control period 1961–1990 and projected mean daily streamflow for scenario period 2071–2100 for basin Flaksvatn. HBV model input for 1961–1990 are observed meteorological data (obs. met.), and HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (Hadley ctr./Echam ctr.). HBV model input for 2071–2100 are HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (emp. adj.) and the delta change approach (delta change). Top: HadAM3H A2 scenario; Middle: HadAM3H B2 scenario; Bottom: ECHAM4/OPYC3 B2 scenario.

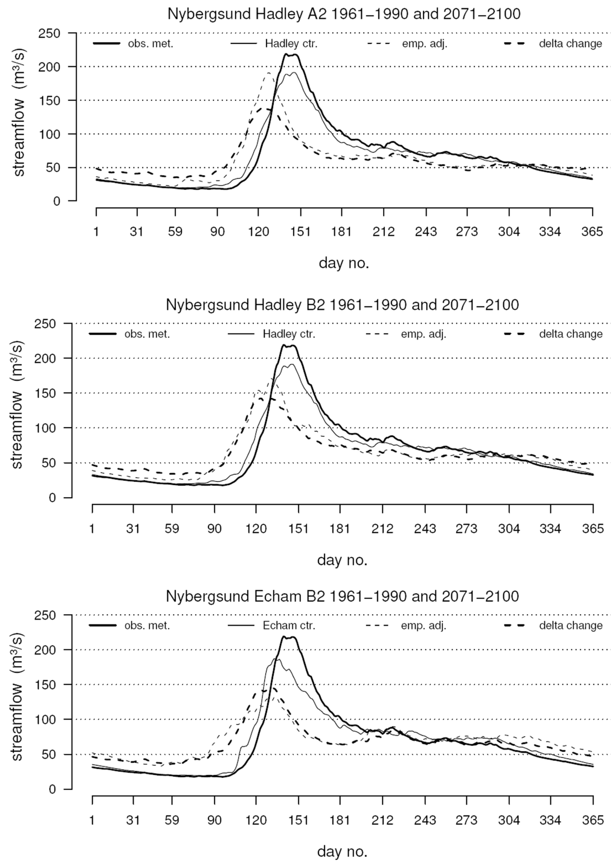

Fig. 3. Simulated mean daily streamflow for control period 1961–1990 and projected mean daily streamflow for scenario period 2071–2100 for basin Nybergsund. HBV model input for 1961–1990 are observed meteorological data (obs. met.), and HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (Hadley ctr./Echam ctr.). HBV model input for 2071–2100 are HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (emp. adj.) and the delta change approach (delta change). Top: HadAM3H A2 scenario; Middle: HadAM3H B2 scenario; Bottom: ECHAM4/OPYC3 B2 scenario.

logical model differ from mean daily streamflow generated by using HIRHAM results adjusted to represent meteorological station sites for the control period (Figs. 2–5). Similar results were reached for the control period for 20 Norwegian basins by Engen-Skaugen et al. (2005), who also concluded that the bias does not show any strong regional pattern and can be both positive and negative. Although mean values and standard deviations of monthly meteorological data are reproduced, this is not sufficient for hydrological modelling due to the complex, non-linear nature of geophysical processes.

The delta change approach which was applied for transferring HIRHAM regional climate model results to meteorological station sites has the disadvantage that it neither alters the number of rainy days in the scenario climate, nor does it affect the frequency of precipitation events (Bergström et al., 2003). This implies that the delta change method in the form applied in this study suffers from similar problems as the empirical adjustment procedure of Engen-Skaugen (2007); although mean monthly values of temperature and precipitation are correctly described for the scenario climate, the day-to-day variability is not correctly represented at the meteorological station sites. The non-linear nature of hydrological processes will also in this case render daily data unreliable.

Evaporation is an important part of the hydrological cycle. On average, approximately one quarter of the precipitation falling in Norway is lost to the atmosphere as evaporation, while the remaining fraction discharges to the ocean (Beldring et al., 2002). The hydrological model calculates potential evaporation using a temperature index approach for the control and scenario climates. Although this is a common parametrization procedure

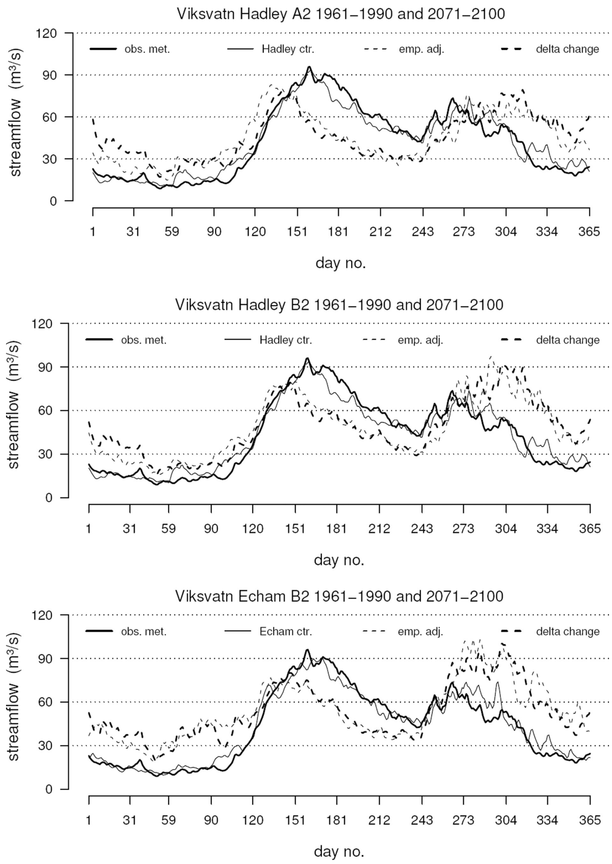

Fig. 4. Simulated mean daily streamflow for control period 1961–1990 and projected mean daily streamflow for scenario period 2071–2100 for basin Viksvatn. HBV model input for 1961–1990 are observed meteorological data (obs. met.), and HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (Hadley ctr./Echam ctr.). HBV model input for 2071–2100 are HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (emp. adj.) and the delta change approach (delta change). Top: HadAM3H A2 scenario; Middle: HadAM3H B2 scenario; Bottom: ECHAM4/OPYC3 B2 scenario.

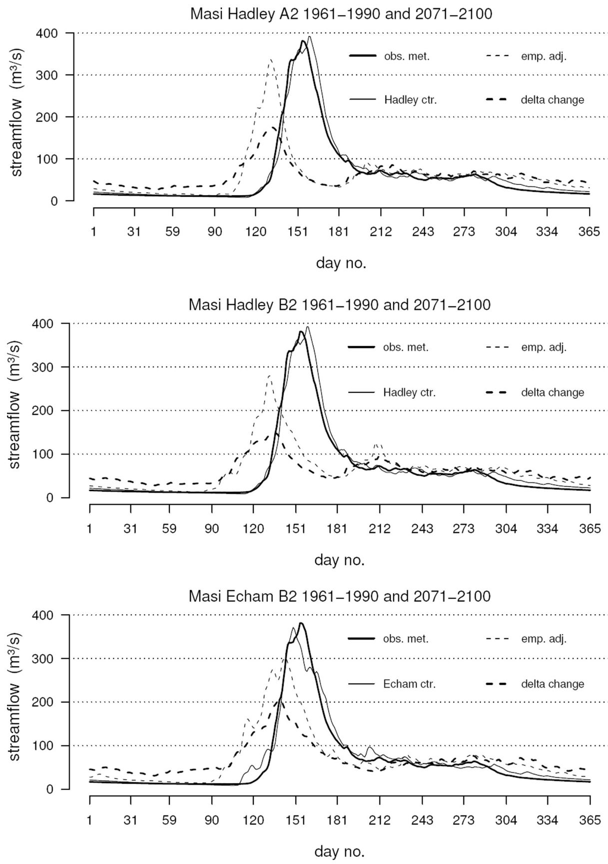

Fig. 5. Simulated mean daily streamflow for control period 1961–1990 and projected mean daily streamflow for scenario period 2071–2100 for basin Masi. HBV model input for 1961–1990 are observed meteorological data (obs. met.), and HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (Hadley ctr./Echam ctr.). HBV model input for 2071–2100 are HIRHAM simulations transferred to meteorological station sites using the empirical adjustment procedure (emp. adj.) and the delta change approach (delta change). Top: HadAM3H A2 scenario; Middle: HadAM3H B2 scenario; Bottom: ECHAM4/OPYC3 B2 scenario.

in hydrological models (e.g. Xu and Singh, 2001), it may not be valid under changed climate conditions as transpiration from plants depends on several factor like wind, humidity, radiation and ambient air CO_2 concentration which may influence the feedback between the land surface and the atmosphere. Neither does transpiration depend linearly on temperature. However, the effects of these changes are uncertain. For instance, Fowler (1999) argued that reduced transpiration from plants caused by higher CO_2 concentrations may be counterbalanced by several factors, including increased leaf area index and compensating increased evaporation from the soil surface. Andréasson et al. (2004) used annual relative evaporation changes predicted by a regional climate model to modify actual evaporation calculated by the HBV hydrological model in an iterative process. Their results showed that changes in evaporation are important for hydrological impact simulations. The conclusion about which approach to apply for modelling evaporation changes is further complicated by the fact that neither atmospheric models nor hydrological models simulate observed evaporation correctly under present climate conditions. A study by Engeland et al. (2004) showed that annual latent heat fluxes measured at three sites in Sweden and Finland were overestimated by the HIRHAM and HBV models. There were also large differences in the seasonal patterns between the two models.

Figure 6 shows that maximum snow water equivalent will be reduced in the future. The climate change impact simulations also indicate an earlier occurrence of the maxima and a shorter duration of the season with snow covered ground. No clear difference between the results based on different emission scenarios or general circulation models can be seen, however,

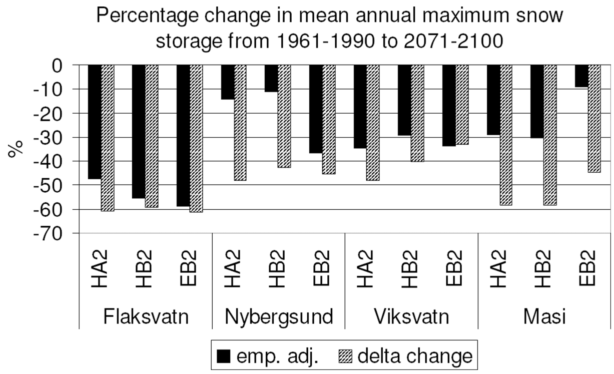

Fig. 6. Projected percentage change in mean of annual maxima of snow storage for basins Flaksvatn, Nybergsund, Viksvatn and Masi from control period 1961–1990 to scenario period 2071–2100 for scenarios HadAM3H A2 (HA2), HadAM3H B2 (HB2) and ECHAM4/OPYC3 B2 (EB2). HBV model results based on HIRHAM simulations were transferred to meteorological station sites using the empirical adjustment procedure (black) and the delta change approach (cross-hatched).

the delta change approach results in larger reduction in snow storage than the empirical adjustment procedure. Temperature changes in the HadAM3H and ECHAM4/OPYC3 model runs are strongest at low temperatures and less pronounced at high temperatures (Andréasson et al., 2004). The delta change approach applied the same monthly temperature changes to all temperature intervals, resulting in too high temperatures around 0 °C. Consequently, the snowmelt intensity which is based on a temperature-index approach is too large. It should also be noted that there is a large difference in snow water equivalent simulated by the HIRHAM and HBV models due to different spatial resolution in the models, different land surface topography, and different algorithms for snow processes (Vikhamar-Schuler and Førland, 2006). The hydrological model results are probably more reliable, as previous studies (e.g. Beldring et al., 2003) have shown that the water balance of the land surface is realistically described by the HBV model.

Glacier mass balance simulations were included in the hydrological model, but glacier dynamics were not considered. Although runoff from glaciers will increase due to higher temperatures, a decrease of glacier volumes in Norway will eventually reduce runoff from areas which are covered by glaciers today (Andreassen et al., 2006). The spatial extent of glaciers in basin Viksvatn is based on current conditions, therefore, climate change impact simulations may overestimate the increase in runoff, at least for glacier margins. Lappegard et al. (2006) showed that changes in glacier area influence climate change impacts on streamflow.

A comparison between the delta change approach and the empirical adjustment procedure for the scenario climates shows a considerable difference in mean daily streamflow for all four basins (Figs. 2–5). This bias may partly be caused by the fact that different realizations from an ensemble of 30 yr long climate change projections cannot be expected to provide identical results for mean daily values. However, it is obvious that the differences in daily temperature and precipitation data resulting from the two methods used for transferring regional climate model results to meteorological station sites is a source of this bias. Basins Nybergsund and Masi experience smaller mean daily streamflow during the snowmelt period for the delta change approach as a consequence of smaller snow storage. The snowmelt flood occurs earlier in all basins, but the time of occurrence of the peaks agrees well. Basins Flaksvatn and Viksvatn experience moderately larger mean daily streamflow in the autumn for some scenarios, in particular for ECHAM4/OPYC3 B2. This may be a result of higher frequencies of large precipitation events in the climate projections for the empirical adjustment procedure than for the delta change approach. The 90th percentile of daily precipitation was larger for all basins for the empirical adjustment procedure than for the delta change approach.

Figure 7 presents changes in flood statistics estimated from hydrological model results based on observed meteorological data and the two approaches for transferring the climate change signal from the HIRHAM regional climate model to meteorological station sites. Flood quantiles are based on the General Extreme Value distribution and parameter estimation by the Probability Weighted Moments method (Hosking and Wallis, 1997). Changes in the flood magnitudes from the control period 1961–1990 to the scenario period 2071–2100 depend on the greenhouse gas emission scenario, the global circulation model and the approach applied for transferring the climate change signal to meteorological station sites. The changes in flood magnitudes for the basins Nybergsund and Masi which are dominated by snow melt floods in the control climate are negative, whereas the changes for the basin Flaksvatn where rain floods are equally important are positive. Vikvatn basin is dominated by snow melt floods in the present climate, but rain floods which are also of significance in the present climate will increase. These results are caused by the combined effects of higher temperature and more precipitation during winter in the scenario climate. Reduced snow cover leads to smaller snow melt floods in basins Nybergsund and Masi, while increased precipitation where a larger proportion falls as rain will increase rain floods, and possibly also combined snow melt and rain floods, in basins Flaksvatn and Viksvatn. In general, the delta change approach results in larger changes than the empirical adjustment procedure. In basins Nybergsund and Masi this is in agreement with changes in maximum snow storage (Fig. 6). For basins Flaksvatn and Viksvatn, the delta change approach may result in more frequent episodes of snowmelt in combination with large precipitation events.

The projected changes in the seasonal streamflow or runoff are strongly linked to changes in the snow regime. The snow cover will be more unstable in the winter season and more mild periods will cause occasional winter floods. The milder winters are also

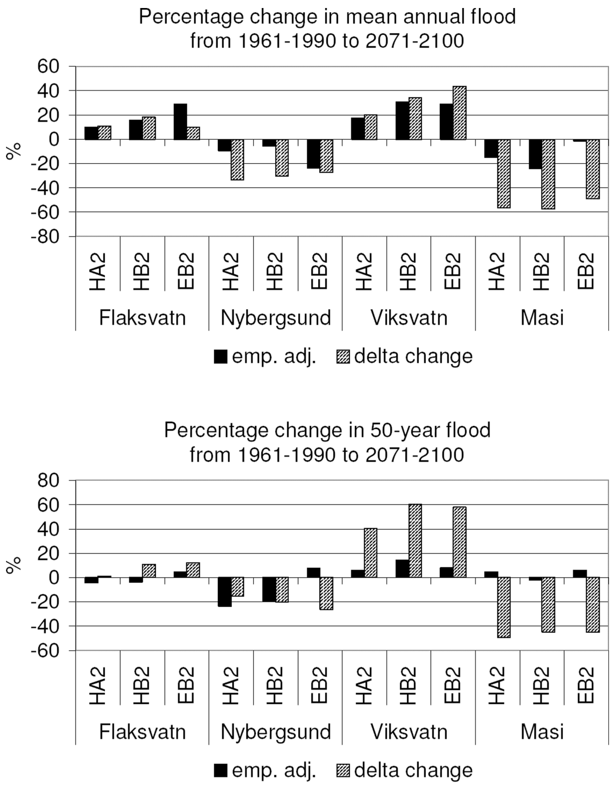

Fig. 7. Projected percentage change in magnitudes of mean annual (top) and 50-yr floods (bottom) for yearly maxima of daily streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi from control period 1961–1990 to scenario period 2071–2100 for scenarios HadAM3H A2 (HA2), HadAM3H B2 (HB2) and ECHAM4/OPYC3 B2 (EB2). HBV model results based on HIRHAM simulations were transferred to meteorological station sites using the empirical adjustment procedure (black) and the delta change approach (cross-hatched).

accompanied by more winter precipitation in some regions. The snowmelt flood, which now is mostly occurring in the spring and early summer, will occur more frequently in the late winter and spring months. The summers will be drier, and summer droughts may become more severe. This is partly caused by the shift in the time of the peak snow melt flood in mountainous basins, but also by an increased evaporation in a warmer climate. The A2 scenarios project a moderately larger reduction in the runoff than the B2 scenarios in the summer and autumn, which is as expected since the temperatures are projected to be higher in the A2 scenario. Increased rainfall in the autumn lead to higher autumn runoff.

The projected changes in runoff differ between the various scenarios based on the HadAM3H and ECHAM4/OPYC3 models. Because of natural climate variability, these two models result in two different dominating circulation patterns, with increasing dominance from the west in ECHAM4/OPYC3 and a more easterly pattern in some seasonal HadAM3H scenarios. Due to the topography of Norway, this results in different distributions of precipitation and runoff (Tveito and Roald, 2005).

There are many sources of uncertainties in the hydrological impact scenarios; in the climate modelling, the method used for transferring the climate change signal to meteorological station sites and in the hydrological modelling. The uncertainty caused by the hydrological model is also of importance. The projection of water balance elements in a warmer climate is based on the assumption that hydrological model parameters used under the present climate is still valid during a changed climate, however this assumption is not necessarily valid. Jiang et al. (2007) demonstrated that different hydrological models calibrated for present climate conditions resulted in different projections of future runoff for identical climate change scenarios.

The model simulations have not considered land use or vegetation changes caused by climate change or human transformation of the land surface. However, it is likely that changes in land cover may interact with climate, leading to different projections of future hydrological conditions due to feedback effects involving the land surface and the atmosphere (Bronstert, 2004). The uncertainty of hydrological climate change impact simulations increases due to the lack of consideration of possible land use and vegetation changes.

7. Conclusions

The projections of climate change impacts on hydrological processes presented in this study are based on scenarios from two global climate models, one regional climate model, two emission scenarios for greenhouse gases and two methods for transferring the climate change signal to meteorological station sites. This resulted in six different scenarios for the future climate at the meteorological station sites, and subsequently different projections for hydrological processes. Although a comparison between the annual and seasonal hydrological projections based on the different scenarios show general similarities, the different methods used for transferring the climate change signal from the regional climate model to meteorological station sites show large differences.

The delta change approach has the advantage that the control period climate is described by observed meteorological data. The drawback of the method is that it is unable to describe changes in the frequency of temperature and precipitation events, and it is therefore questionable whether hydrological model results for a future climate based on the delta change approach can be trusted. The empirical adjustment procedure developed by Engen-Skaugen (2007) is more appealing and probably more trustworthy as changes in the frequency of temperature and precipitation events and trend in the climate scenarios are preserved in the series adjusted to represent meteorological station sites. However, this method also has its deficiencies. This is evident from the bias between mean daily streamflow for the control period based on observed meteorological data and regional climate model simulations corrected by the empirical adjustment method. Another source of error is that regional climate model results for the control climate may be unreliable.

Research on climate change impacts on hydrological processes must be conducted with an awareness of how scenario data are obtained. There are uncertainties in every step of the process of downscaling the climate change signal, including how it is transferred to the hydrological model, leading to, as shown here, rather large differences in the results. This is particularly important when the results are to be subject to further analyses (e.g. changes in frequencies of floods or droughts) or used as input for climate change impact studies in other areas of research.

The projections of future discharge from the individual basins show a general pattern; snowmelt floods will occur earlier and winter and autumn discharge will increase, while summer and spring discharge will decrease. These projections of future streamflow result from changes in both temperature and precipitation, with temperature changes having a larger impact than precipitation changes (Roald et al., 2006). The A2 scenario leads to a larger streamflow increase in winter and also a larger decrease in summer. This is a consequence of the fact that the A2 scenario results in a larger temperature increase than the B2 scenario.

Given earlier snowmelt and reduced snow storage, the occurrence of large snowmelt floods is likely to become more seldom. Intensive local rainfall floods can become more severe because of increasing rainfall intensities in a warmer climate. These floods are potentially more dangerous in steep terrain, because they can cause landslides. The combined effect of increases in the rainfall intensities, number of rainfall events and total rainfall volume will most likely provide conditions that may be expected to yield larger rain floods.

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