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Climate Change Impacts on Hydrological Processes in Norway 2071-2100

Based on RegClim HIRHAM and Rossby Centre RCAO Regional Climate Model Results

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REPORT

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Stein Beldring, Lars A. Roald, Torill Engen-Skaugen, Eirik J. Førland

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Preface

Production of electricity in Norway is dependent on runoff, and possible changes in hydropower production capacity are therefore of large economical importance. Assessment of the future hydrological regime is a production chain where changes in external forcing caused by greenhouse gas emissions are introduced into general circulation models and regional climate models. The climate model results are used for driving hydrological models which determine time series of hydrological state variables and fluxes for present and future climate conditions. These time series and their statistics, e.g. annual or seasonal mean and extreme values, are a useful way of communicating the results from modelling hydrological impacts of climate change. The results presented in this report have been produced by the Norwegian Water Resources and Energy Directorate and the Norwegian Meteorological Institute. The study was funded by the Nordic Energy Research within the Nordic research project "Climate and Energy" (2004-2006), and by the Norwegian Electricity Industry Association within the project "Climate predictability 0-100 years" (2006-2007).

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Summary

Ensembles of climate change impact simulations for hydrological processes in Norway have been estimated through the 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 Rossby Centre RCAO and RegClim HIRHAM regional climate models. This procedure resulted in several scenarios of projected climate for the period 2071-2100. The regional climate model results were further downscaled to meteorological stations sites using two different approaches. These climate scenarios were used for driving a spatially distributed version of the HBV model, yielding an ensemble of hydrological climate change scenarios. Present conditions were determined through control runs with the hydrological model using observed meteorological data and climate model results for 1961-1990. The different hydrological scenarios are consistent regarding whether an increase or a decrease in streamflow and other hydrological variables occur, but the magnitudes of the changes differ between the scenarios.

Moderate changes in the annual streamflow are expected, with a decline in some basins for some scenarios. The increase is dependent on the spatial distribution of the pressure fields as modelled by the two global climate models. Significant changes in the seasonal distribution of streamflow are expected; increase everywhere in the winter, increase in mountainous basins in southern Norway and in basins in central and northern Norway in the spring, a moderate decline in coastal basins in southern Norway and a moderate increase in basins in south-eastern Norway in the spring. Decrease will occur everywhere in the summer, while autumn streamflow will increase in every basin.

The occurrence of large snowmelt floods is likely to become more seldom due to earlier snowmelt and reduced snow storage. The combined effect of increase 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.

1 Introduction

Global warming with approximately 0.6 °C increase of the surface temperature has been observed during the last 100 years. Different climate change scenarios project a further increase of the global temperature between 1 °C to 5 °C by the end of this century (Cubash et al., 2001). At the regional scale both increases and decreases in precipitation are projected, however, the projections of the development of precipitation are even more uncertain than for temperature (Benestad, 2002).

Production of electricity in Norway is dependent on runoff, and possible changes in hydropower production capacity caused by climate change are therefore of large economical importance. 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. General circulation model results are subsequently downscaled dynamically using regional climate models. Downscaled scenarios for temperature and precipitation are used for driving hydrological models which determine time series of hydrological state variables and fluxes for present and future climate conditions. These time series and their statistics, e.g. annual or seasonal mean and extreme values, are a useful way of communicating the results from modelling hydrological impacts of climate change. However, projecting the impacts of climate change on hydrological processes is a major challenge due to the complex nature of the interactions between oceans, atmosphere and land-surface. Climate scenarios differ substantially due to uncertainties with regard to climate forcing caused by greenhouse gas emissions, uncertainties caused by imperfect representation of processes in the models, and uncertainties with regard to initial conditions. Ensembles of climate change simulations from model runs using different approaches to predict the future represent one way of quantifying this uncertainty. The analyses in this report are based on two different emission scenarios combined with two different general circulation models (4 scenarios). These scenarios were downscaled using two regional climate models; the Rossby Centre Regional Atmosphere-Ocean (RCAO) model (Döscher et al., 2002); and the HIRHAM model applied in the Regional Climate Development Under Global Warming (RegClim) project (Bjørge et al., 2000). The first was used for downscaling all four scenarios, while the latter was used for downscaling three scenarios. The analyses have been performed for 20 catchments representing different runoff regimes in Norway.

The results presented in this report have been produced by Norwegian Water Resources and Energy Directorate and Norwegian Meteorological Institute. The study was funded by Nordic Energy Research within the research project “Climate and Energy” which has the objective of a assessing the impacts of climate change on renewable energy sources in the Nordic countries (2004-2006), and by Norwegian Electricity Industry Association within the project “Climate predictability 0-100 years” (2006-2007).

Within the Climate and Energy project a set of maps of water resources under present and future conditions based on climate scenarios and hydrological modelling have been produced. These maps were presented by Beldring et al. (2006) and may serve as a foundation for assessments of the future production potential of hydropower in the Nordic area. The maps are based on the same climate scenarios and hydrological model runs as the results presented in this report, and may be viewed as complementary information.

2 Study areas

This study examined possible climate change impacts on hydrological processes in 20 basins selected to represent hydrological regimes in different parts of Norway. The basins are listed in Table 2.1. Table 2.2 gives some characteristics of each catchment. The model was calibrated individually for all catchments for the period 1976-1990, and then evaluated for the period 1961-1990. The results for the Nash-Sutcliffe and bias statistics (Chapter 3) for the evaluation period are presented in Table 2.3. The location of the catchments is shown in Figure 2.1.

Table 2.1 Overview of basins

Station no.	Name	River	Basin area km^2	Observation period
311.6	Nybergsund	Trysilelv	4410	1908 -
2.142	Knappom	Flisa	1625	1916 -
2.111	Aursunden	Glomma	835	1923 -
2.13	Sjodalsvatn	Sjoa	474	1930 -
15.79	Orsjoren	Numedalslågen	1154	1982 -
16.19	Møsvatn	Måna	1506	1909 -
18.10	Gjerstad	Gjerstadelv	235	1980 -
20.3	Flaksvatn	Tovdalselv	1794	1899 -
26.20	Årdal	Sira	76	1970 -
26.21	Sandvatn	Sira	28	1970 -
27.26	Hetland	Bjerkreimselv	70	1915 -
41.1	Stordalsvatn	Etneelv	127	1912 -
48.5	Reinsnosvatn	Austdøla	118	1917 -
50.1	Hølen	Kinso	229	1923 -
83.2	Viksvatn	Gaular	505	1902 -
109.9	Risefoss	Driva	738	1933 -
123.20	Rathe	Nidelv	3061	1902 -
151.15	Nervoll	Vefsna	650	1968 -
167.3	Kobbvatn	Kobbelv	386	1916 -
212.10	Masi	Alta	5693	1966 -

Table 2.2 Selected characteristics of the basins

Station no.	Name	Elevations			Basin characteristics (%)				
		Bottom	Median	Top	Forest	Mountain	Lakes	Bogs	Glaciers
311.6	Nybergsund	353	783	1748	44.78	26.26	8.4	11.6	0
2.142	Knappom	170	411	808	77.96	0	1.4	16.48	0
2.111	Aursunden	685	847	1567	34.04	32.72	12.1	10.04	0
2.13	Sjodalsvatn	940	1467	2362	5.25	71.2	9.3	1.03	9.22
15.79	Orsjoren	951	1229	1539	1.55	79.59	12.9	4.6	0
16.19	Møsvatn	890	1256	1628	6	76	12.8	5	0.02
18.10	Gjerstad	49	315	658	81.25	2.8	3.4	5.05	0
20.3	Flaksvatn	19	358	1146	74.44	6.45	7.7	7.89	0
26.20	Årdal	113	479	750	38.16	24.68	9	2.25	0
26.21	Sandvatn	306	472	572	44.25	35.16	10	8.84	0
27.26	Hetland	23	188	555	12.58	60.52	6.1	3.32	0
41.1	Stordalsvatn	51	685	1297	24.95	58.5	10.7	0.96	0
48.5	Reinsnosvatn	595	1234	1637	9.42	76.34	6.6	0.54	1.18
50.1	Hølen	120	1276	1686	1.85	88.38	0	0.32	0.35
83.2	Viksvatn	145	841	1636	22.5	57.32	9.5	1.07	4.72
109.9	Risefoss	556	1347	2284	6.84	83.91	1.9	1.22	0.37
123.20	Rathe	13	679	1572	37.8	30.16	6.7	14.07	0
151.15	Nervoll	345	827	1692	25.86	55.16	0	4.93	1.78
167.3	Kobbvatn	8	680	1512	15.51	63.09	13.9	0.56	0
212.10	Masi	272	451	1085	35.75	1.51	7	16	0

Table 2.3 Model validation results for 1961-1990

Station no.	Name	River	Nash-Sutcliffe efficiency	Bias
311.6	Nybergsund	Trysilelv	0.91	-0.04
2.142	Knappom	Flisa	0.80	0.05
2.111	Aursunden	Glomma	0.90	-0.03
2.13	Sjodalsvatn	Sjoa	0.82	0.0
15.79	Orsjoren	Numedalslågen	0.84	0.0
16.19	Møsvatn	Måna	0.87	0.0
18.10	Gjerstad	Gjerstadelv	0.70	0.0
20.3	Flaksvatn	Tovdalselv	0.81	0.02
26.20	Årdal	Sira	0.79	0.02
26.21	Sandvatn	Sira	0.78	0.02
27.26	Hetland	Bjerkreimselv	0.70	0.02
41.1	Stordalsvatn	Etneelv	0.77	-0.01
48.5	Reinsnosvatn	Austdøla	0.89	-0.01
50.1	Hølen	Kinso	0.81	0.03
83.2	Viksvatn	Gaular	0.89	0.01
109.9	Risefoss	Driva	0.71	0.05
123.20	Rathe	Nidelv	0.80	-0.01
151.15	Nervoll	Vefsna	0.73	0.05
167.3	Kobbvatn	Kobbelv	0.84	-0.02
212.10	Masi	Alta	0.89	0.02

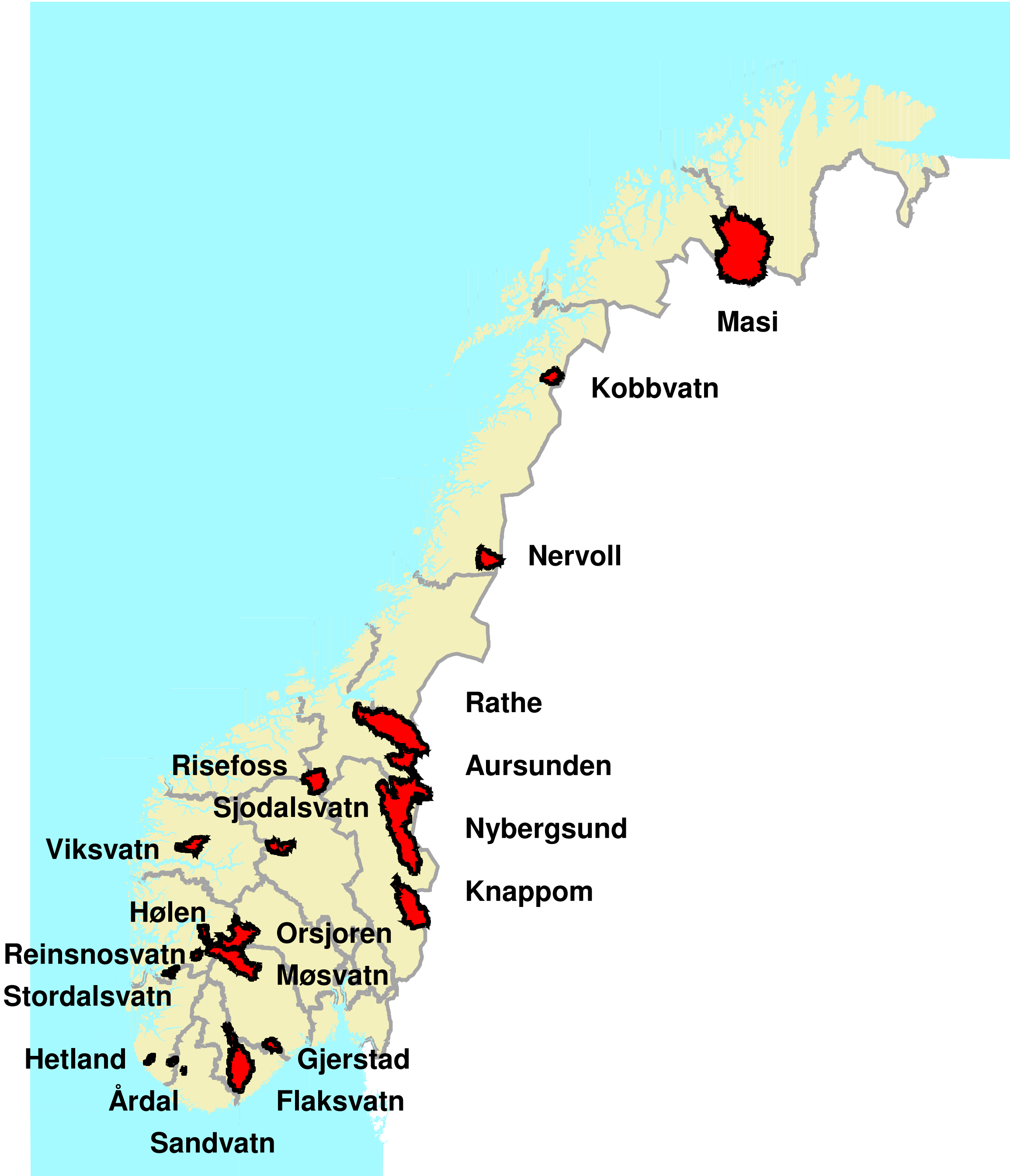

Fig 2.1 Location of the 20 catchments included in this study

3 Climate scenarios

3.1 Climate models

Results from the Max Planck Institute atmosphere-ocean general circulation model ECHAM4/OPYC3 (Roeckner et al., 1999), and from the general circulation model HadAM3H developed from the atmospheric component of the Hadley Centre atmosphere-ocean general circulation model HadCM3 (Gordon et al., 2000) have been used for assessment of climate change impacts on water resources in the Nordic countries. Observed fields of sea-surface temperature and sea-ice dataset were used as lower boundary conditions in the control simulation with HadAM3H (~1.875° by 1.25°, approximately 100 by 138 km^2 in the Nordic countries). In the climate change experiments, the sea-surface temperature anomaly described by HaDCM3 was added to the observed data to be used as the lower boundary forcing. Assumptions about future greenhouse gas emissions were based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 and B2 scenarios (Nakićenović et al., 2000). Up to 2100 B2 gives approximately 2.5 °C increase in global temperature while A2 is giving an increase of 3.5 °C.

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 in Norway, downscaling is necessary. The general circulation model simulations were used as boundary conditions for dynamical downscaling with two regional climate models: the Rossby Centre Regional Atmosphere-Ocean (RCAO) model (Döscher et al., 2002), and the HIRHAM model applied in the Regional Climate Development Under Global Warming (RegClim) project (Bjørge et al., 2000). Both these regional climate models are based on the dynamics of the weather forecast model HIRLAM, which is operationally used at the Norwegian Meteorological Institute (met.no) and the physics of ECHAM4. RCAO and HIRHAM have a spatial resolution of 0.44° (~50 by 50 km^2) and 0.5° (~55 by 55 km^2) respectively. RCAO used the ECHAM4/OPYC3 run with T42 resolution (~280 by 280 km^2), while HIRHAM used the ECHAM4/OPYC3 run with T106 (~125 by 125 km^2) resolution. The ECHAM4/OPYC3 A2 scenario with T106 resolution has not been run, and has therefore not been downscaled by the RegClim HIRHAM model.

3.2 Interface between regional climate models 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 regional climate models to selected locations. However, there are large difficulties when using temperature and precipitation from regional climate models as meteorological station data representing at site locations. The station altitude is wrongly represented in the model, and the number of rainy days is typically estimated too large (Frei et al., 2003). Daily precipitation and temperature from the regional climate models were therefore downscaled to meteorological station sites using two different procedures as explained below.

The hydrological simulations used the time slice approach whereby model simulations representing a slice of time in present climate (control) and in a future climate (scenarios) were performed. The time slice for the control climate was 1961-1990 and for the future climate 2071-2100. The hydrological impact studies were done with off-line simulations with the hydrological model. Observed data from meteorological stations were used as a control climate for the Rossby Centre RCAO model runs, while observed data were replaced by HIRHAM model results downscaled to meteorological station sites for the RegClim model runs for the control period.

3.2.1 Rossby Centre RCAO model

The approach applied for hydrological modelling with Rossby Centre RCAO results as input transferred 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), and is a common method of transferring the signal of climate change from climate models to hydrological models. Monthly relative precipitation changes and absolute temperature changes predicted by the regional climate models were 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 for the hydrological impact simulations. The hydrological model calculates evapotranspiration using a temperature index approach for the control and scenario climates. The hydrological model parameter that controls the intensity of potential evapotranspiration was determined by calibration, however, this model parameter 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. Neither does transpiration depend linearly on temperature. Annual relative evapotranspiration changes predicted by the Rossby Centre RCAO model were therefore used to modify actual evapotranspiration calculated by the hydrological model in an iterative process. These results are termed Rossby or alternatively Rossby ΔPTE in the figure captions. The hydrological model was also run without consideration of the annual relative evapotranspiration changes predicted by the regional climate model, i.e. only monthly precipitation and temperature changes as predicted by the climate model were considered. These results are termed Rossby ΔPT in the figure captions.

3.2.2 RegClim HIRHAM model

The approach applied for hydrological modelling with RegClim HIRHAM results as input transferred precipitation and temperature from the regional climate model to meteorological station sites using an empirical adjustment technique which preserves the frequency of precipitation and temperature events as predicted by the climate models, aiming at reproducing observed monthly means and standard deviations for the control period (Engen-Skaugen, 2004). These results are termed RegClim in the figure captions. Evapotranspiration changes predicted by the regional climate model was not considered.

The hydrological impact simulations with RegClim HIRHAM model results were also performed using the delta change approach for modifying observed meteorological data driving the hydrological model for the baseline period 1961-1990. Monthly precipitation and temperature changes were applied in the same manner as was used for transferring the climate change signal from the Rossby Centre RCAO model. These results are termed RegClim ΔPT in the figure captions. Relative evapotranspiration changes predicted by the regional climate model was not considered.

HIRHAM was run with one control period and one scenario period for each global climate model. The control runs are realisations of today's climate, representing the present climate. The estimated day-to-day variability is thus not comparable with observed data, the monthly mean values and standard deviations based on daily model data should however be comparable.

4 Hydrological model

The observed meteorological data and the downscaled regional climate model results were used for driving a spatially distributed version of the hydrological HBV model (Beldring et al. 2003), yielding an ensemble of results for hydrological variables and fluxes for present and future conditions. The model performs water balance calculations for 1 by 1 km^2 grid cell landscape 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, sub-grid scale distribution and ablation of snow, interception storage, sub-grid scale distribution of soil moisture storage, evapotranspiration, groundwater storage and runoff response, lake evapotranspiration and glacier mass balance. Potential evapotranspiration is a function of air temperature, however, the effects of seasonally varying vegetation characteristics are considered. The water balance algorithms of the model were described by Bergström (1995) and Sælthun (1996). The model is spatially distributed since every model element has unique characteristics that determine its parameters, input data are distributed, water balance computations are performed separately for each model element, and finally, only those parts of the model structure which are necessary are used for each element.

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, evapotranspiration, 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, evapotranspiration processes, soil moisture storage, groundwater storage and runoff response. Lake evapotranspiration and glacier mass balance were controlled by parameters with the same values for all model elements within a catchment.

The model was calibrated using available information about climate and hydrological processes from the 20 gauged catchments analysed in this study. One model parameter set for each individual catchment 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. Individual model elements act as hydrological response units, i.e. patches in the landscape mosaic having a common climate, land use and pedological, topographical and geological conditions controlling their hydrological process dynamics (Gottschalk et al., 2001). 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 parameterisation of the processes that control runoff and evapotranspiration fluxes in the Norwegian landscape, and by application of this process-adequate spatial discretisation scheme. The nonlinear parameter estimation method PEST (Doherty et al., 1998) was used for automatic model calibration. PEST adjusts the parameters of a model between specified lower and upper bounds until the sum of squares of residuals between selected model outputs and a complementary set of observed data are reduced to a minimum. The parameter set determined for one specific catchment during this calibration procedure was applied for all hydrological model runs, regardless of which period or climate scenario that was considered. The same precipitation and temperature stations were applied in all model runs for one particular basin.

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. Precipitation and temperature values for the model grid cells were determined by inverse distance interpolation of observations from the three closest precipitation stations and the two closest temperature stations. Differences in precipitation and temperature caused by elevation were corrected by precipitation-altitude gradients and temperature lapse rates. There is considerable uncertainty with regard to the variations of precipitation with altitude in the mountainous terrain of Norway. Specific precipitation-altitude gradients and temperature lapse rates were therefore determined for each of the 20 basins, and these values were used for all grid cells within a basin. 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). The reduction of 50 % is arbitrarily chosen, however, the height of 1200 metres is not, as this is the approximate altitude of the coastal mountain ranges in western and northern Norway. These mountains ranges release most of the precipitation associated with the eastward-migrating extratropical storm tracks that dominate the weather in Norway. The temperature lapse rates for days with and without precipitation were also determined by calibration, however, the same values were used for all grid cells.

In order to have confidence in a hydrological model, its performance must be validated. Model performance is usually evaluated by considering one or more objective statistics or functions 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 (Węglarczyk, 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 model simulated values to be larger or smaller than their observed counterpart. Although the Nash-Sutcliffe efficiency criterion is frequently used for evaluating the performance of hydrological models, it favours a good match between observed and modelled high flows, while sacrificing to some extent matching of below-mean flows. It is for this reason that two different measures of model performance were considered. A test of model performance in an independent period was also performed (the normal period 1961-1990).

5 Results and discussion

Hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from the Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites are visualized in Appendices A-F:

- Appendix A presents hydrological model results for streamflow, precipitation and temperature for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and the scenario period 2071-2100.
- Appendix B presents hydrological model results for mean daily snow water equivalent for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and the scenario period 2071-2100.
- Appendix C presents estimated mean annual and 50-year floods for yearly maxima of daily streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and changes in the flood magnitudes from the control period 1961-1990 to the scenario period 2071-2100.
- Appendix D presents observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100 for all basins included in this study.
- Appendix E presents box-and-whisker plots summarising changes in streamflow from the control period 1961-1990 to the scenario period 2071-2100 for all basins included in this study.

- Appendix F presents model simulated mean weekly total discharge from the land surface of Norway for the control period 1961-1990 and projected mean weekly total discharge from the land surface of Norway for the scenario period 2071-2100.

5.1 Mean daily streamflow, precipitation and temperature

As stated by Wood et al. (2004); "A minimum standard of any useful downscaling method for hydrological applications needs the historic (observed) conditions to be reproducible". It is therefore imperative that the methods used for transferring climate model results to meteorological station sites generate precipitation and temperature time series that have the same statistical properties as the observed meteorological data that were used for calibrating the hydrological data. Furthermore, when used as input data 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 model. When using 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 (2004) this needs to be investigated.

Graphs presented on pages A2, A4, A6 and A8 show that mean daily streamflow based on the Rossby Centre RCAO control data set, i.e. observed meteorological data does not reproduce observed streamflow data. This is the normal case when running hydrological models, observed streamflow hydrographs are not modelled correctly due to errors in the input data, the observed streamflow data and the hydrological model structure. However, if the empirical adjustment procedure is able to reproduce the statistical properties of observed meteorological data, the hydrological model would 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. The graphs on pages A2, A4, A6 and A8 show that mean daily streamflow generated by using observed meteorological data (Rossby ctr.) as input to the hydrological model differ from mean daily streamflow generated by using RegClim HIRHAM results adjusted to represent meteorological station sites for the control period (RegClim Hadley ctr. and RegClim Echam ctr.). Model results for catchment average mean daily snow water equivalent in Appendix B and flood statistics in Appendix C confirm that the empirical adjustment procedures for precipitation and temperature does not reproduce the statistical properties of observed meteorological data with daily time resolution. However, monthly mean runoff simulations in Appendix D show that the empirical adjustment procedure is able to generate meteorological time series that reproduce monthly mean values of hydrological model results based on observed precipitation and temperature data. Although mean values and standard deviations of monthly meteorological data are reproduced, this is not sufficient for hydrological modelling due to the complex, non-lineare nature of geophysical processes. It is therefore questionable whether hydrological model results for a future climate based on the empirical adjustment procedure developed by Engen-Skaugen (2004) can be trusted for finer time resolution than monthly data. However, it may also be that 30 years is a too short period to obtain unbiased estimates for daily mean values of meteorological and hydrological variables.

The delta change approach which was applied for transferring Rossby Centre RCAO regional climate model results to meteorological station sites has the disadvantage that it does not alter the number of rainy days in the scenario climate, neither does it affect the frequency of precipitation events (Bergström et al., 2003). A particular problem for temperature is that temperature changes may be most pronounced at low temperatures (Andréasson et al., 2004). 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 (2004); although mean monthly values of precipitation and temperature are correctly described for the scenario climate, the day-to-day variability is not correctly transferred to meteorological station sites. The non-linear nature of hydrological processes will also in this case render daily data unreliable. This applies to both mean values and extremes. However, monthly and seasonal data are probably more trustworthy.

Evapotranspiration is an important part of the hydrological cycle. On average, approximately 23 % of the precipitation falling in Norway is lost to the atmosphere as evapotranspiration, while the remaining part discharges to the ocean (Beldring et al., 2002). As mentioned above, the hydrological model parameter that controls the intensity of potential evapotranspiration 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. Neither does transpiration depend linearly on temperature. Annual relative evapotranspiration changes predicted by the Rossby Centre RCAO model were therefore used to modify actual evapotranspiration calculated by the hydrological model in an iterative process. The results presented in Appendix A show that changes in evapotranspiration are important for hydrological impact simulations. Streamflow was always higher when the annual evapotranspiration changes predicted by the Rossby Centre RCAO model was transferred to the hydrological model, compared to the case when evapotranspiration changes for the future climate was assumed to correspond to temperature changes. These results are termed respectively Rossby ΔPTE and Rossby ΔPT in the figure captions. The conclusion about which approach to apply for modelling evapotranspiration changes is further complicated by the fact that neither atmosphere models nor hydrological models simulate observed evapotranspiration 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 seasonal patterns between the two models. In the remaining part of this study presented in Appendices B-F relative evapotranspiration changes predicted by the Rossby Centre RCAO regional climate model was included in the delta change approach by correcting changes in evapotranspiration estimated by the hydrological model. Relative evapotranspiration changes predicted by the regional climate model was not considered when transferring RegClim HIRHAM regional climate model results to meteorological station sites, i.e. potential evapotranspiration was determined as a function of air temperature for both the control and the scenario climate.

A comparison between streamflow simulations based on Rossby Centre RCAO and RegClim HIRHAM regional climate model results is provided by Appendix A. The delta change approach without consideration of relative evapotranspiration changes predicted by the regional climate model is shown by the curves designated Rossby ΔPT and RegClim ΔPT. Monthly relative precipitation changes and absolute temperature changes predicted by the regional climate models were used to modify the observed daily meteorological data for the baseline period 1961-1990 in order to transfer the climate change signal to the meteorological station sites. A comparison of basin average precipitation and temperature based on one scenario for each catchment is also provided. In this case, Rossby ΔPTE and RegClim ΔPT simulations may be compared, as basin average precipitation and temperature simulations are not influenced by the algorithm used to determine evapotranspiration. The results, which are indicative of the differences between the two regional climate models, show that HadAM3H scenarios differ less between the regional climate models than ECHAM4/OPYC3 scenarios for basin Flaksvatn, Nybergsund and Viksvatn, while the results are less conclusive for the Masi basin. The results also show that differences in precipitation are larger than differences in temperature for all four basins. The different spatial resolution of the ECHAM4/OPYC3 runs used as input to the Rossby Centre RCAO and RegClim HIRHAM regional climate models will also influence hydrological model results.

Appendix A also provides a comparison between the delta change approach and the empirical adjustment procedure developed by Engen-Skaugen (2004), termed respectively RegClim ΔPT and RegClim in the figure captions. The accumulated differences between RegClim and RegClim ΔPT simulations for streamflow, precipitation and temperature are also shown. Differences in temperature are smaller than differences in precipitation and streamflow. There is a considerable bias in mean daily streamflow scenarios for all the catchments. Similar results were reached 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.

5.2 Mean daily snow water equivalent

Mean daily snow water equivalent for basins Flaksvatn, Nybergsund, Viksvatn and Masi presented in Appendix B is the average over all computational elements (grid cells) within each basin. RegClim Hadley and Echam control simulations deviate from Rossby control simulations, indicating that the empirical adjustment procedure (Engen-Skaugen, 2004) does not reproduce the statistical properties of observed precipitation and temperature time data on a daily time scale. The climate change impact simulations are all indicating that maximum snow water equivalent will be reduced in the future, the maxima occur earlier and the snow cover season will be shorter. No clear difference between the results based on different emission scenarios, general circulation model, regional climate model or approach applied for transferring the climate change signal to meteorological station sites can be seen, however, the ECHAM4/OPYC3 scenarios appear to give a large reduction in snow storage than the corresponding HadAM3H scenarios. This is least pronounced for the Masi basin. Vikhamar-Schuler and Førland (2006) showed that snow water equivalent simulated by the HIRHAM and HBV models differed due to different spatial resolution in the models, different land surface topography, and different algorithms for snow processes. 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. For glacier covered areas the snow water equivalent is reduced to zero at 1 September each year as part of the transformation of glacier ice to snow. This effect is seen for the control period simulations in the Viksvatn basin. 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 Norway was based on current conditions, therefore, climate change impact simulations may overestimate the increase in runoff, at least for glacier margins. A study by Lappegard et al. (2006) showed that changes in glacier covered area significantly influences climate change impacts on streamflow from catchments with a large proportion of the area covered by glaciers.

5.3 Flood statistics

Appendix C presents flood statistics estimated from hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Estimated mean annual and 50-year floods for yearly maxima of daily streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and changes in the flood magnitudes from the control period 1961-1990 to the scenario period 2071-2100 are presented. Flood quantiles were based on the General Extreme Value distribution and parameter estimation by the Probability Weighted Moments method (Hosking and Wallis, 1997). Flood statistics based on observed streamflow data were compared with similar values based on hydrological modelling. The results show that both Rossby control simulations which used observed meteorological data for driving the hydrological model and RegClim control simulations deviate somewhat from the statistics based on observed streamflow data for mean annual floods, whereas the deviations are much larger for 50-year floods. Changes in mean annual and 50-year floods for the Rossby Centre RCAO and RegClim HIRHAM regional climate model results were determined relative to the respective control periods. These changes depend on the choice of greenhouse gas emission scenario, global circulation model and regional climate model and the approach applied for transferring the climate change signal to meteorological station sites. In general, the delta change approach appears to give larger changes than the empirical adjustment procedure developed by Engen-Skaugen (2004). The changes for the basins Nybergsund and Masi that are dominated by snow melt floods in the control climate are negative, whereas the changes for the basins Flaksvatn and Viksvatn where rain floods are more important are positive. These results are caused by the combined effects of higher temperature and more precipitation in the winter in the scenario climate. Reduced snow cover leads to smaller snow melt floods, while increased precipitation where a larger proportion falls as rain will increase rain floods, and possibly also combined snow melt and rain floods.

5.4 Seasonal runoff

Appendix D presents observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100. Appendix E presents box-and-whisker plots summarising regional changes in runoff from the control period 1961-1990 to the scenario period 2071-2100. The regions represent south-eastern Norway, mountain areas in southern Norway, coastal areas in southern Norway and central and northern Norway.

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 the HadAM3H scenarios. With the topography of Norway, this results in different distributions of precipitation and the runoff (Tveito and Roald, 2005). The projected changes in the mean annual runoff are moderate, but the changes in the seasonal runoff are far larger.

The projected changes in the seasonal 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 accompanied by more winter precipitation in some regions. The spring flood, which now is mostly occurring in the early summer, will occur more frequently in the spring months, and this explains the increase in the spring in the mountainous basins in southern Norway and in basins in central and northern Norway.

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 evapotranspiration 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, in particular in basins in coastal areas in southern Norway and basins in other regions located close to the west coast.

A comparison of the projected changes in the seasonality of the mean monthly runoff between scenarios based on the Rossby Centre RCAO and RegClim HIRHAM regional climate models show fairly good agreement for most of the scenarios. The largest projected changes result from the Rossby Centre RCAO model with the ECHAM4/OPYC3 scenarios.

5.5 Total discharge from land surface of Norway

Appendix F presents model simulated mean weekly total discharge from the land surface of Norway for the control period 1961-1990 and projected mean weekly total discharge from the land surface of Norway for the scenario period 2071-2100. Annual values based on hydrological model results with observed meteorological data used for driving the model and annual total discharge from the land surface of Norway evaluated from observations (Pettersson, 2004) agree well. Furthermore, hydrological model results based on RegClim Hadley and Echam control simulations are also reasonable. The projections of future discharge confirm the overall pattern shown by the individual basins; snowmelt floods will occur earlier and autum, winter and autumn discharge will increase, while summer and spring discharge decrease. These projections of future streamflow result from changes in both precipitation and temperature, with temperature changes having a larger impact than precipitation changes (Roald et al., 2006). A2 scenarios lead to larger increase in the winter and also larger decrease in the summer for results from the same general circulation model and regional climate model. This is a consequence of the fact that the A2 scenario results in larger temperature increase than the B2 scenario. The differences between the results from the climate scenarios were confirmed by Rummukainen (2006) who showed that Rossby Centre Echam A2 and B2 scenarios resulted in large temperature changes for winter, spring and autumn in Northern Europe than the other combinations of regional climate models and emission scenarios.

6 Conclusions

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 of less importance than the uncertainties of the meteorological data driving the model. 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. The scenarios presented in this report are based on climate scenarios from two different global climate models, two regional climate models, two emission scenarios for greenhouse gases and two methods for transferring the climate change signal to meteorological station sites. This resulted in a large number of 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 regional climate models to meteorological station sites show large differences with few clear regional patterns in the biases.

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.

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 increase 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.

Moderate changes in the annual streamflow are expected, with a decline in some basins for some scenarios. The increase is dependent on the spatial distribution of the pressure fields as modelled by the two global climate models. Significant changes in the seasonal distribution of the streamflow; increase everywhere in the winter, increase in mountainous basins in southern Norway and in basins in central and northern Norway in the spring, a moderate decline in coastal basins in southern Norway and a moderate increase in basins in south-eastern Norway in the spring. Decrease will occur everywhere in the summer, while autumn streamflow will increase in every basin.

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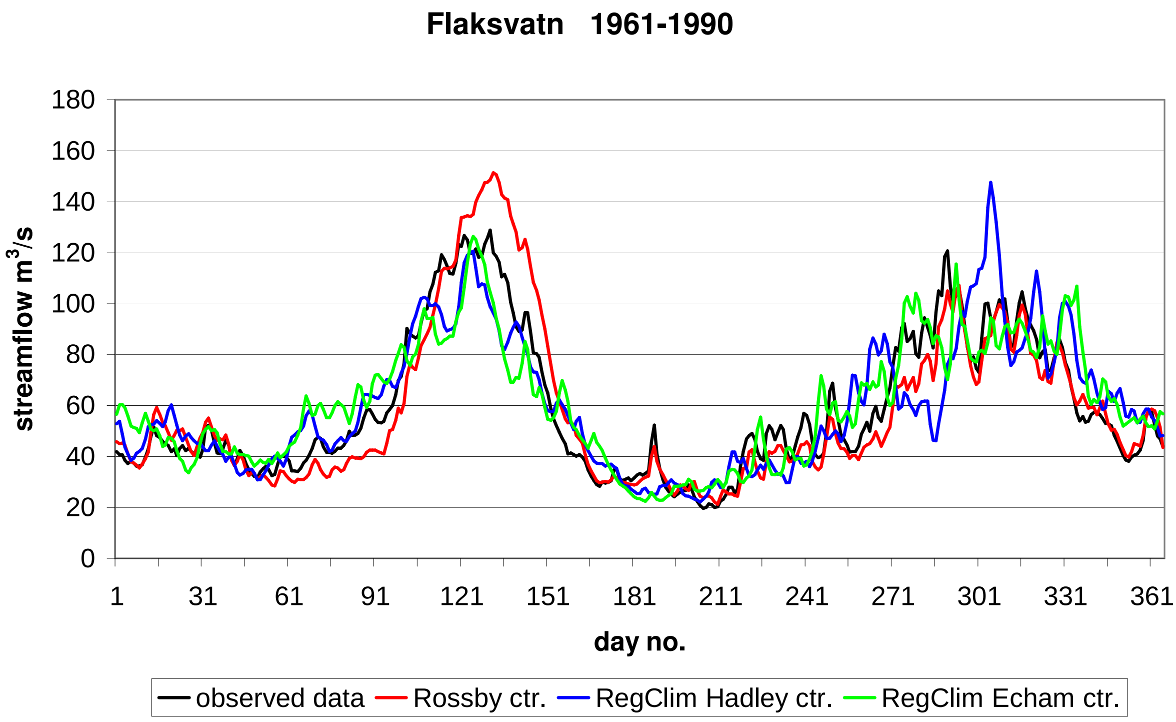
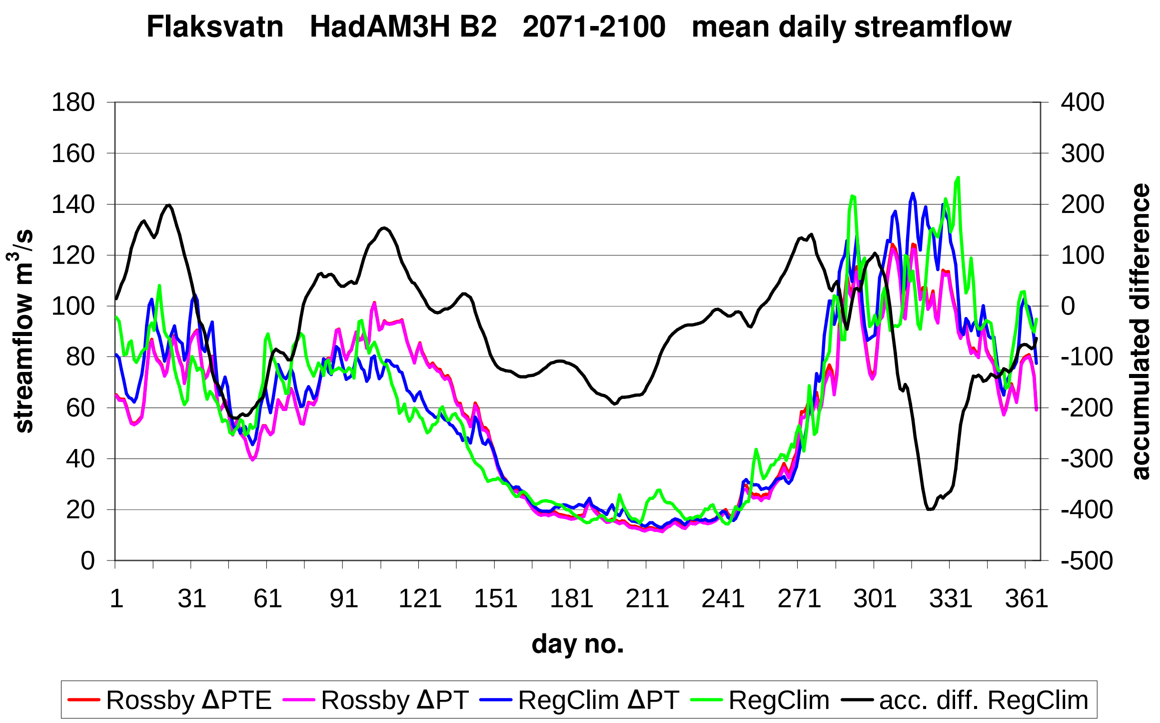
Appendix A

This appendix presents hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Streamflow, precipitation and temperature for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and the scenario period 2071-2100 are presented.



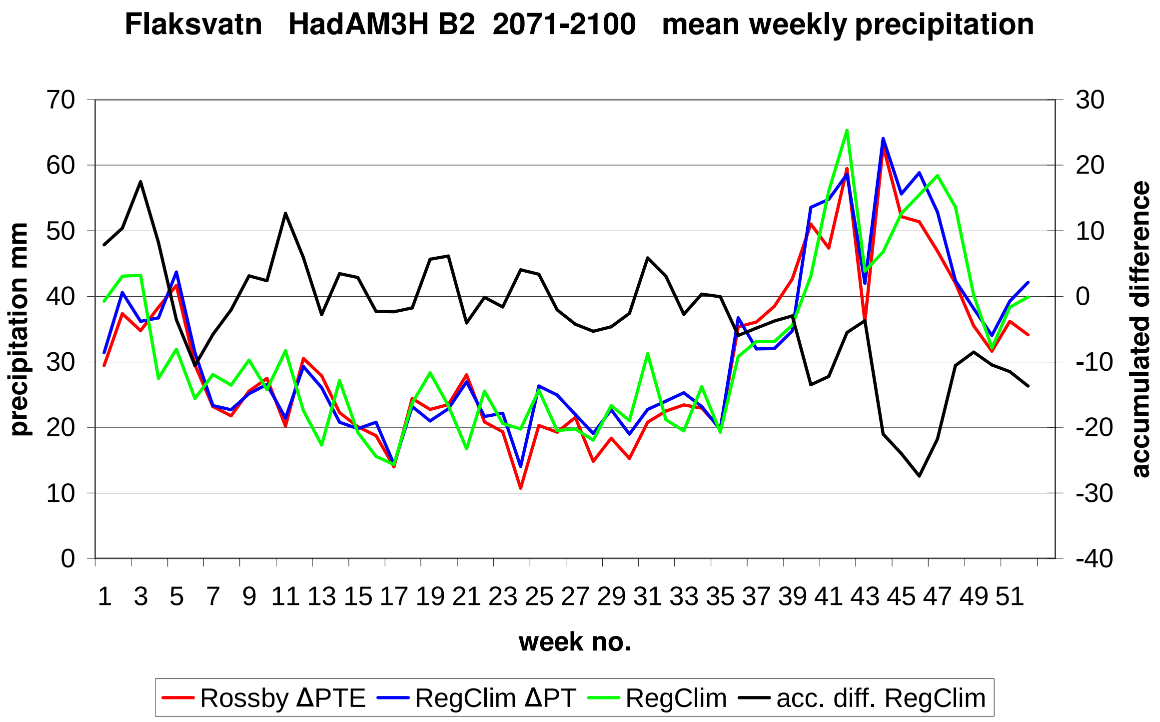


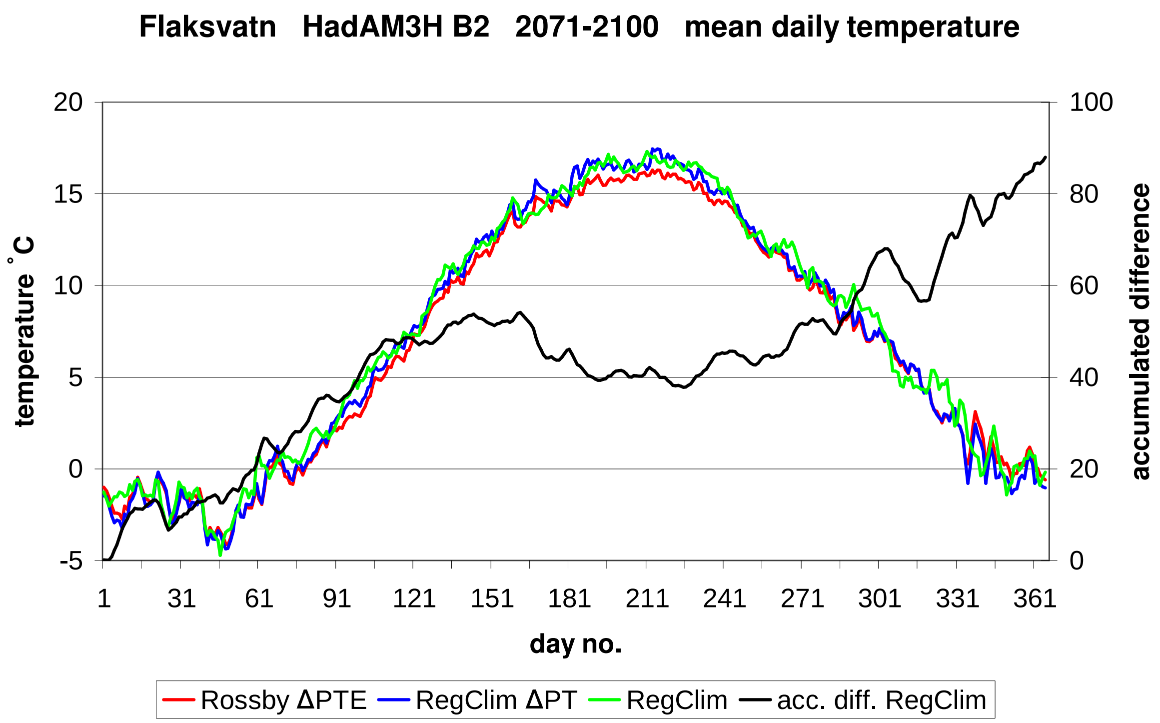
Top: Mean daily observed and simulated streamflow for Flaksvatn basin for 1961-1990.

Bottom: Projected mean daily streamflow for Flaksvatn basin for HadAM3H B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim HadAM3H B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



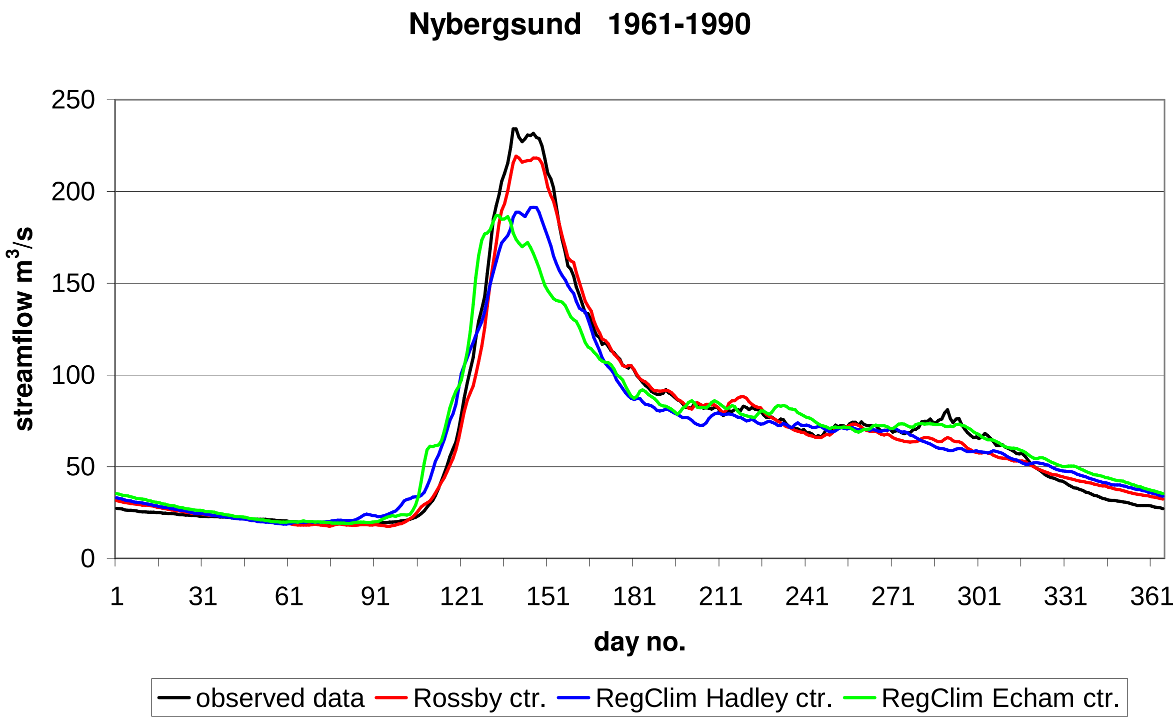


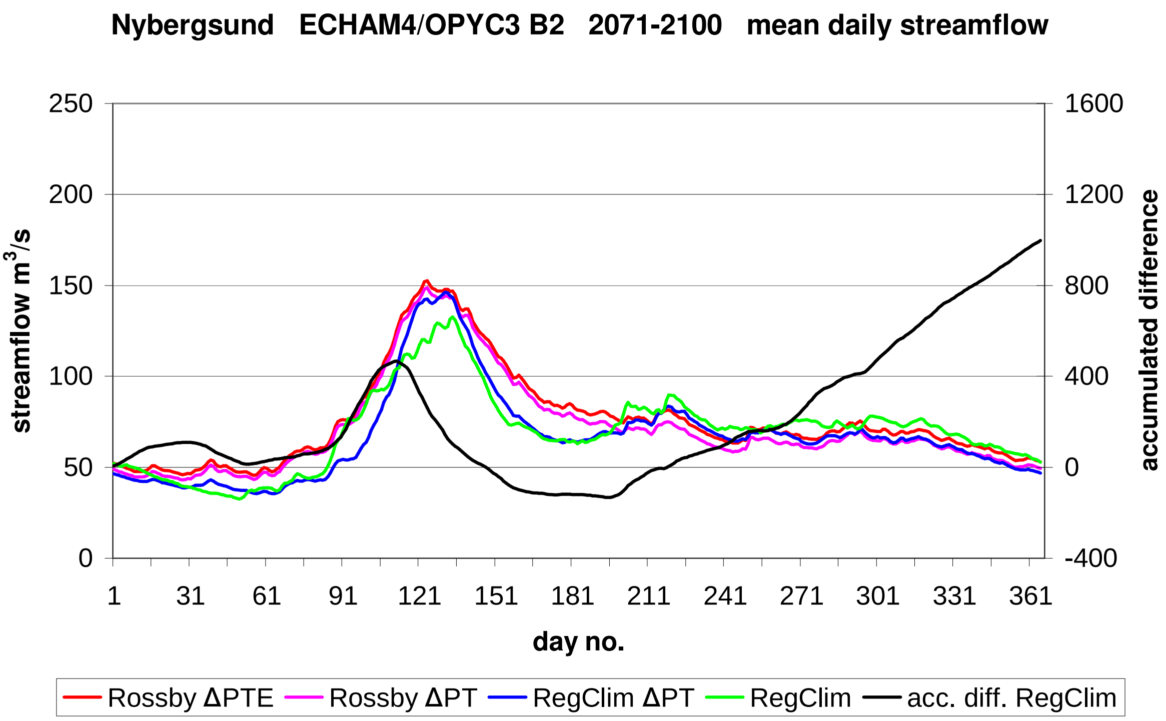
Top: Projected mean weekly precipitation for Flaksvatn basin for 2071-2100.

Bottom: Projected mean daily temperature for Flaksvatn basin for HadAM3H B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim HadAM3H B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



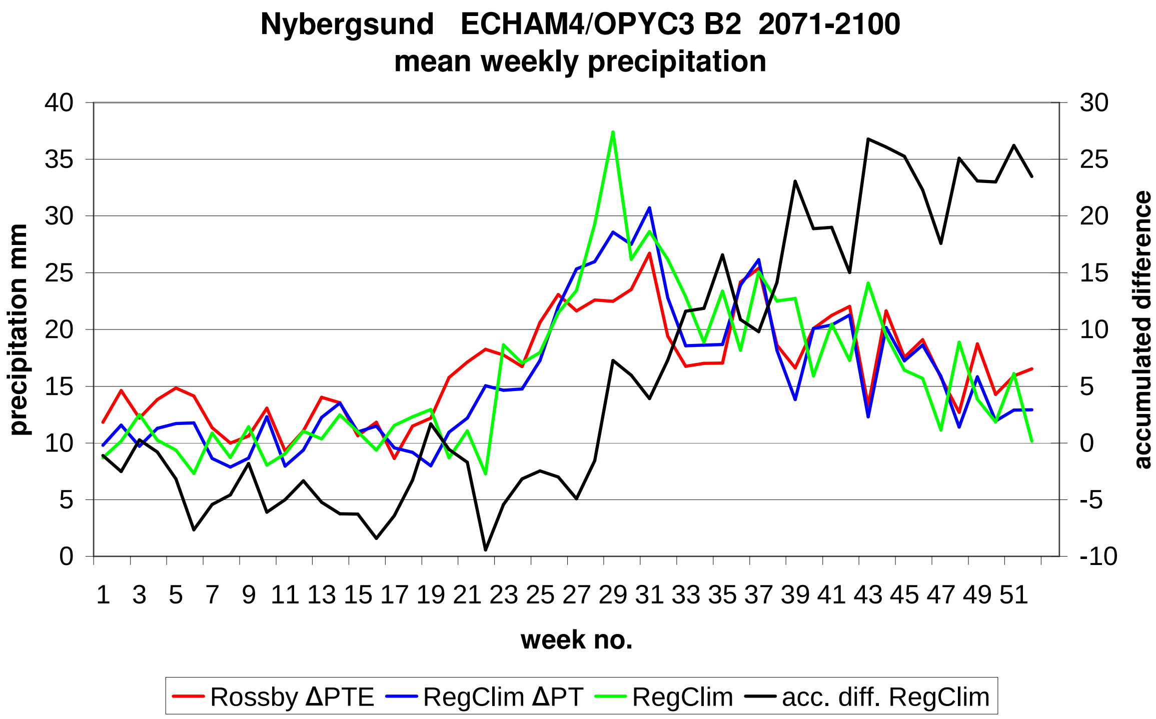


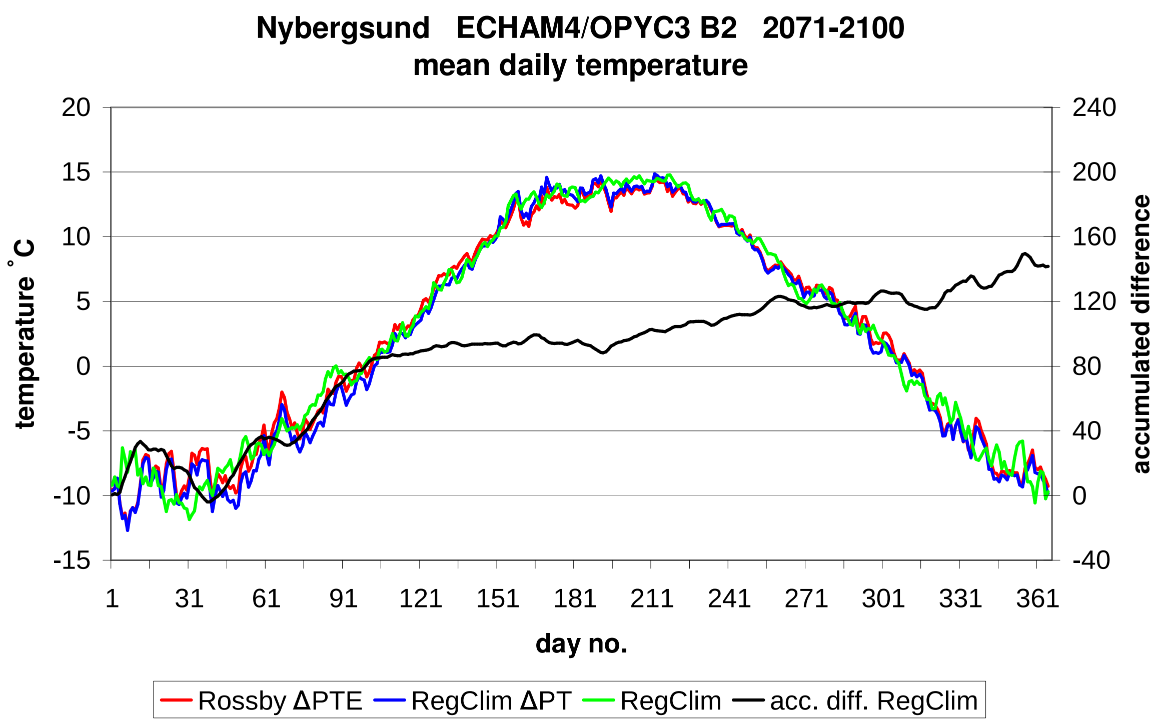
Top: Mean daily observed and simulated streamflow for Nybergsund basin for 1961-1990.

Bottom: Projected mean daily streamflow for Nybergsund basin for ECHAM4/OPYC3 B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim ECHAM4/OPYC3 B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



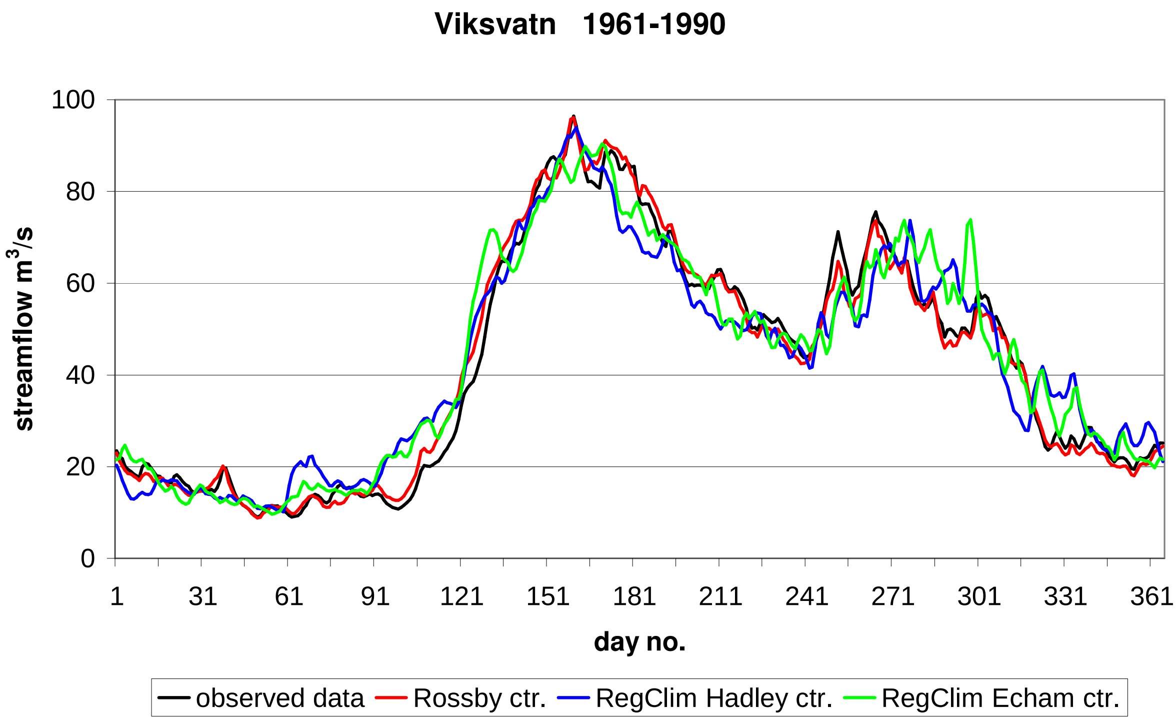


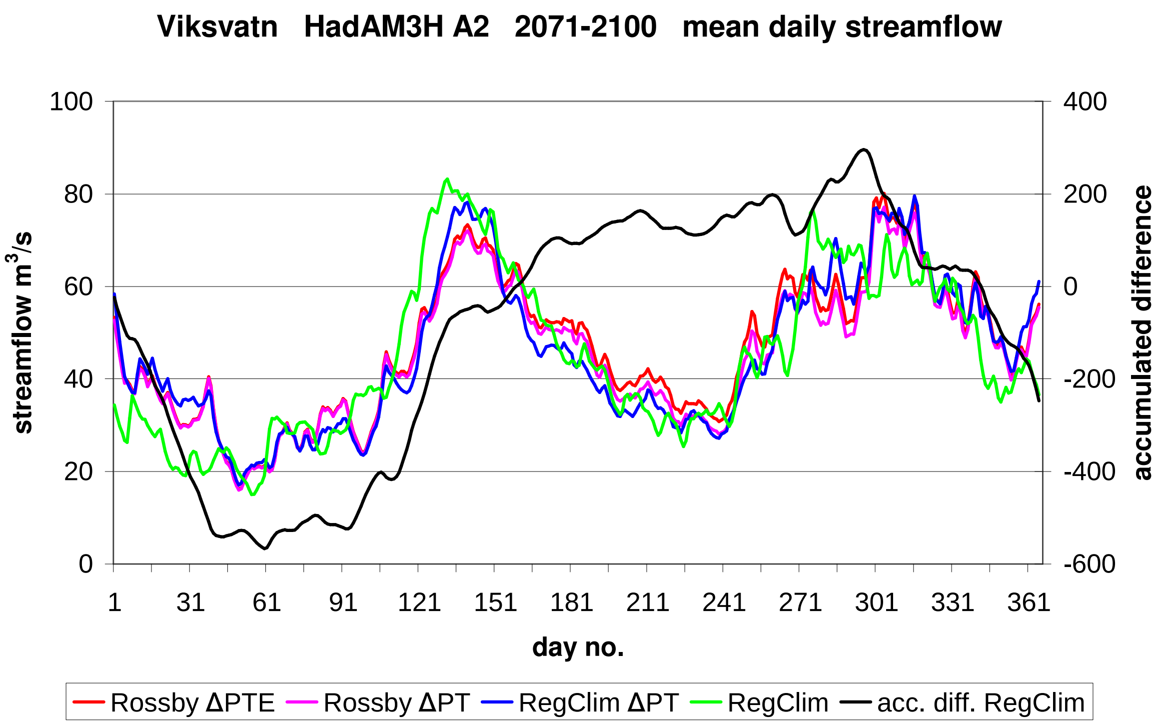
Top: Projected mean weekly precipitation for Nybergsund basin for 2071-2100.

Bottom: Projected mean daily temperature for Nybergsund basin for ECHAM4/OPYC3 B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim ECHAM4/OPYC3 B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



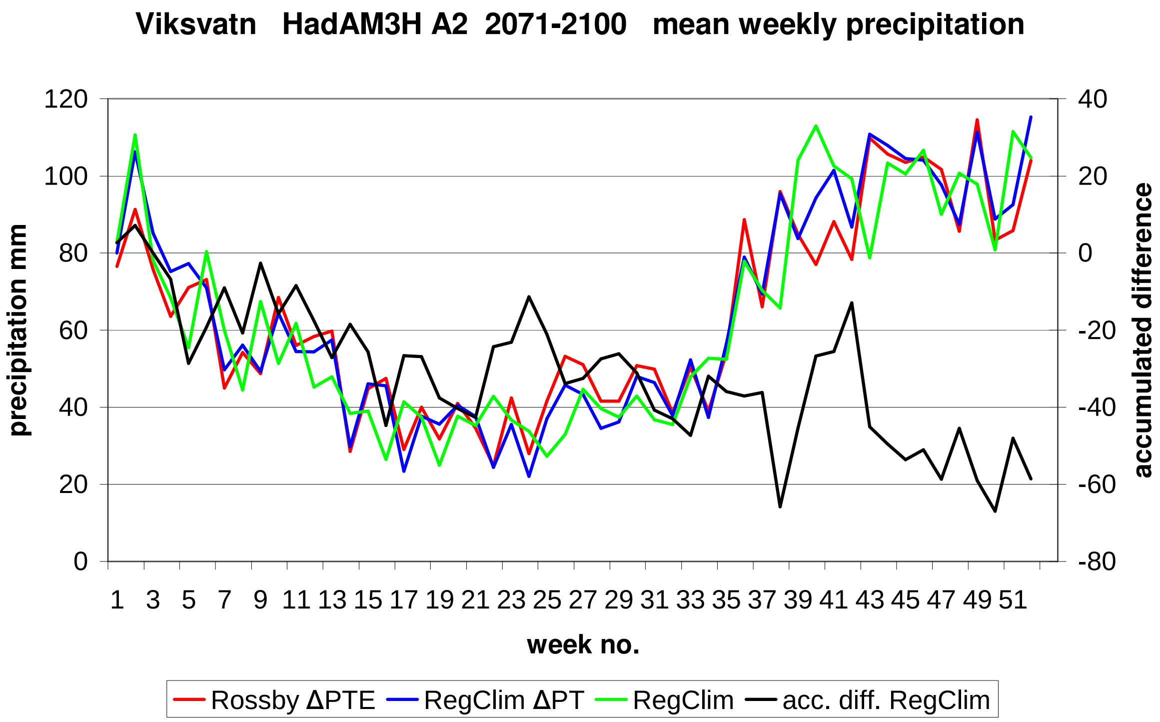


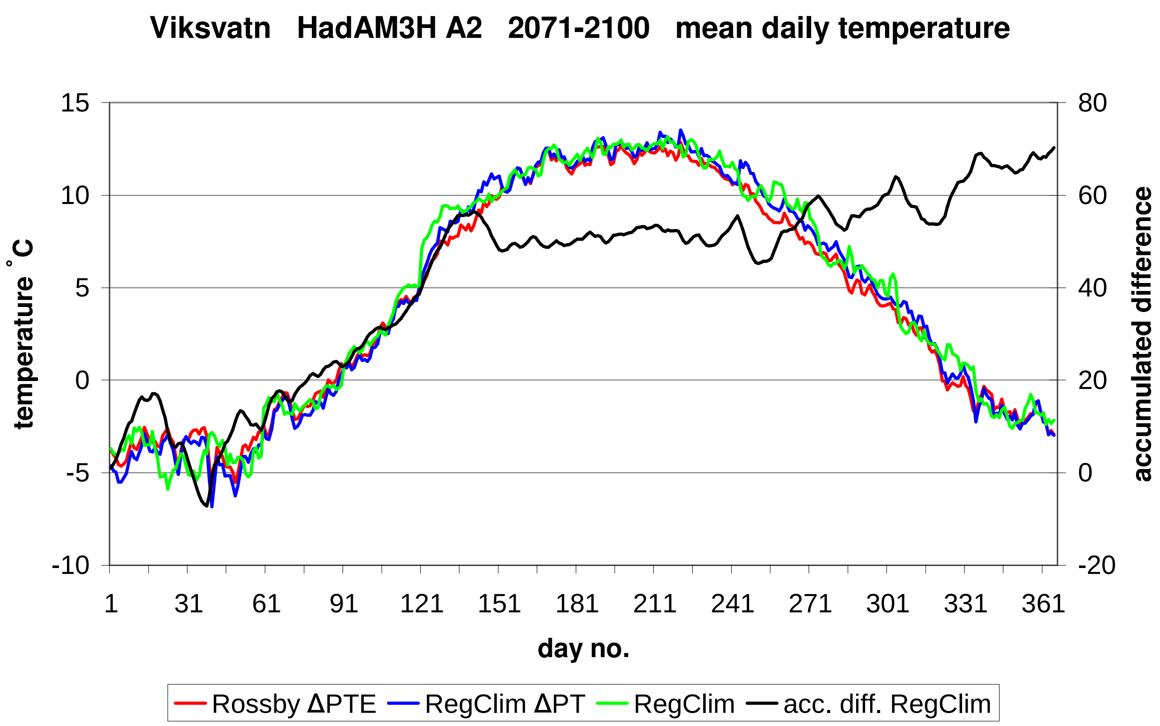
Top: Mean daily observed and simulated streamflow for Viksvatn basin for 1961-1990.

Bottom: Projected mean daily streamflow for Viksvatn basin for HadAM3H A2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim HadAM3H A2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



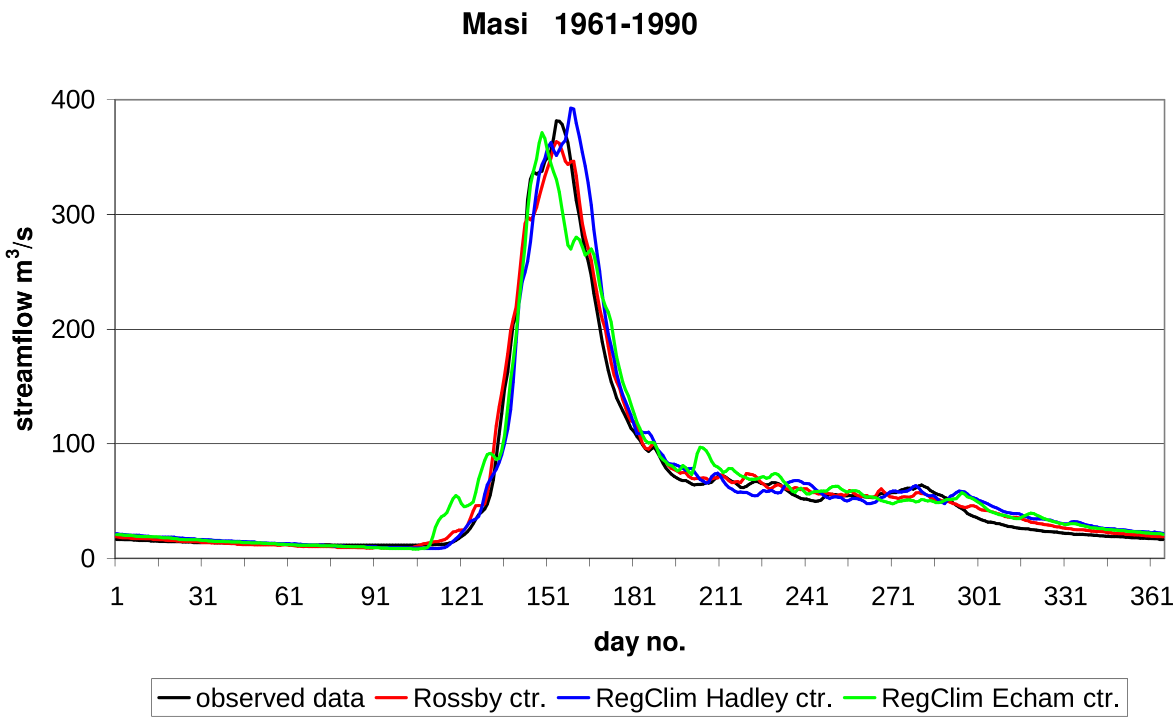


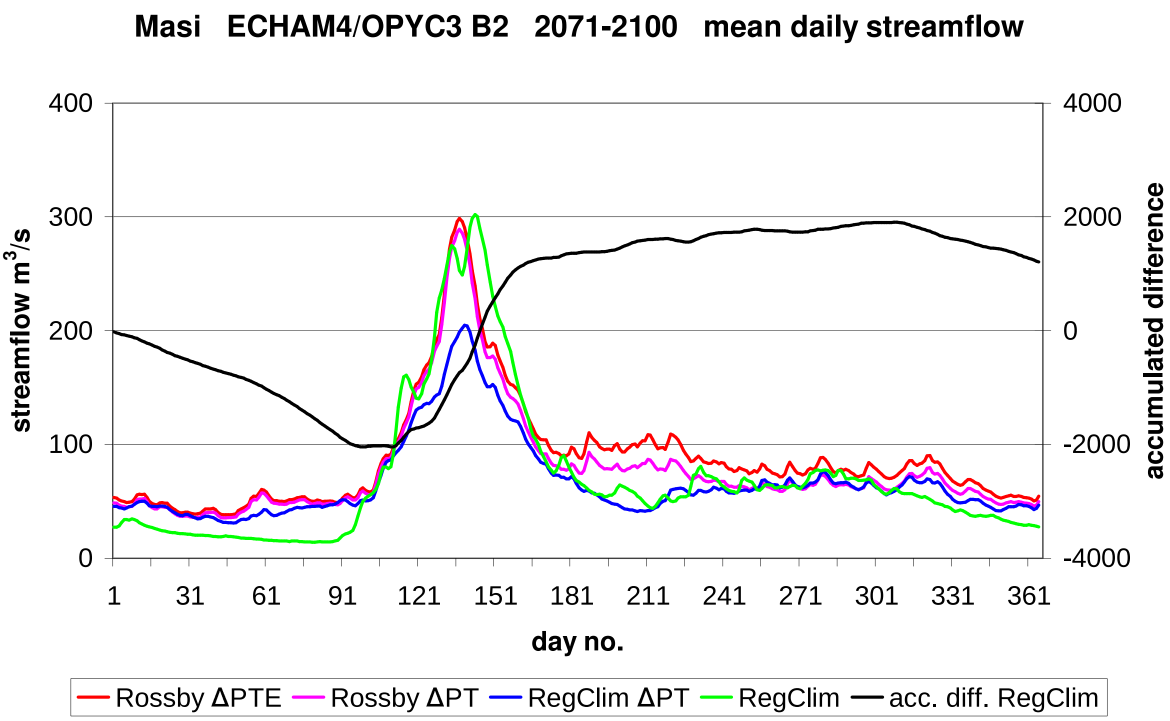
Top: Projected mean weekly precipitation for Viksvatn basin for 2071-2100.

Bottom: Projected mean daily temperature for Viksvatn basin for HadAM3H A2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim HadAM3H A2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



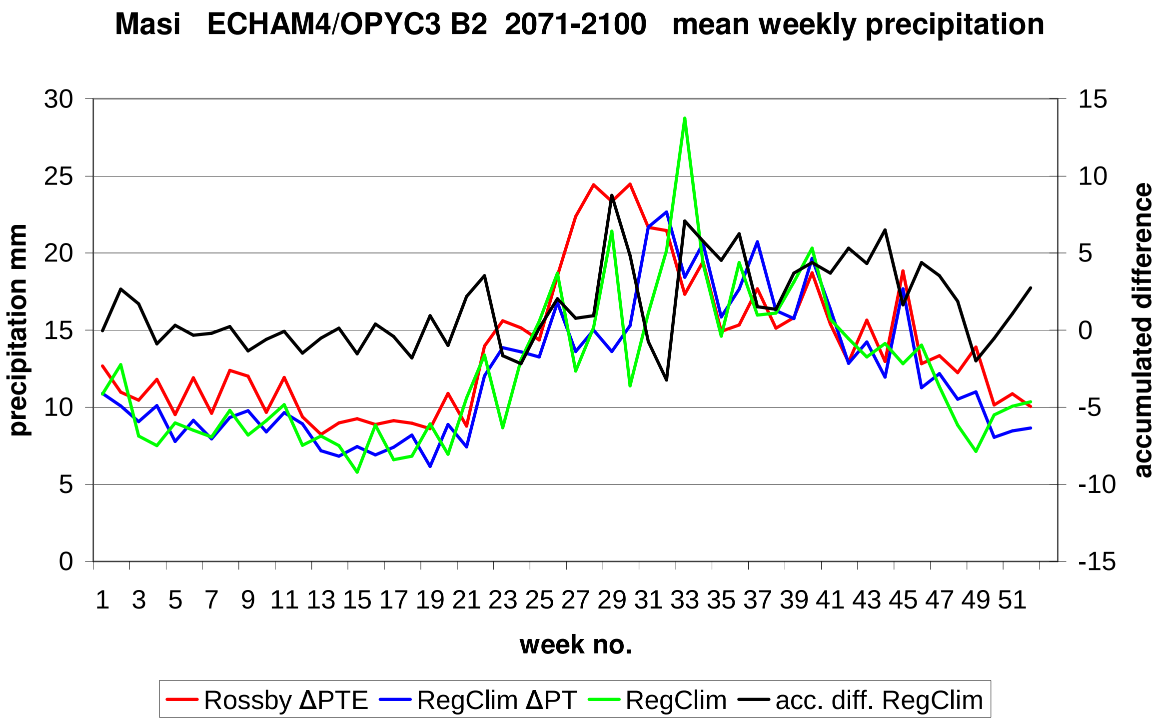


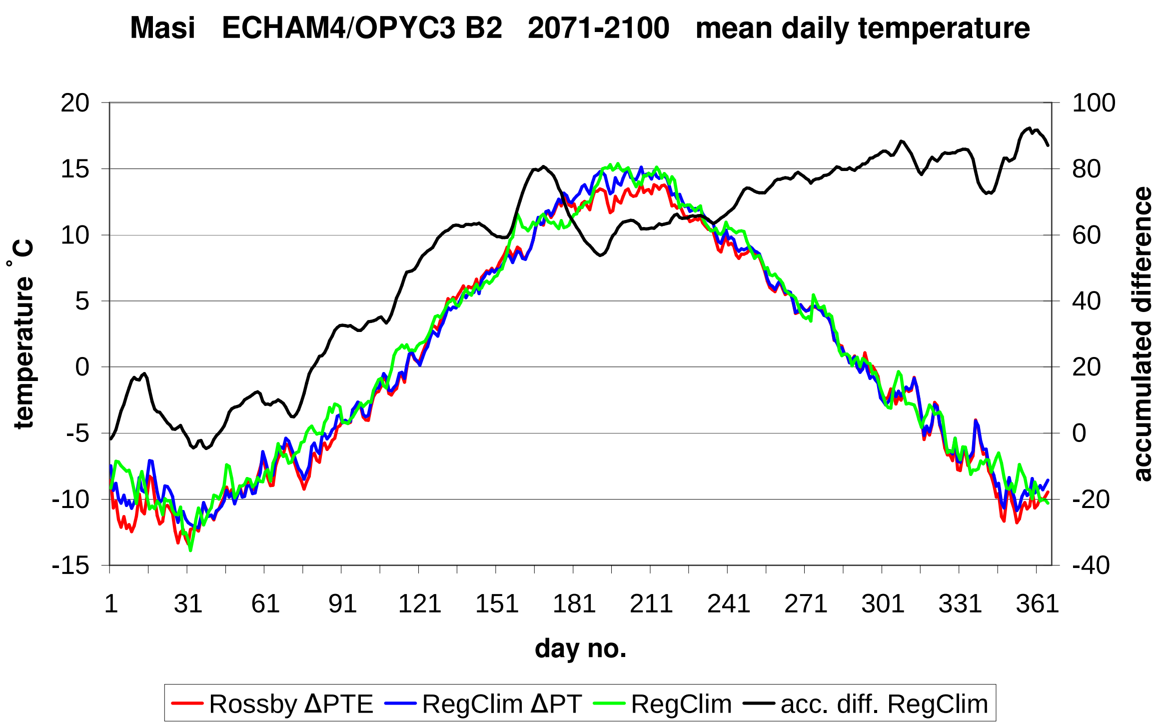
Top: Mean daily observed and simulated streamflow for Masi basin for 1961-1990.

Bottom: Projected mean daily streamflow for Masi basin for ECHAM4/OPYC3 B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim ECHAM4/OPYC3 B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).





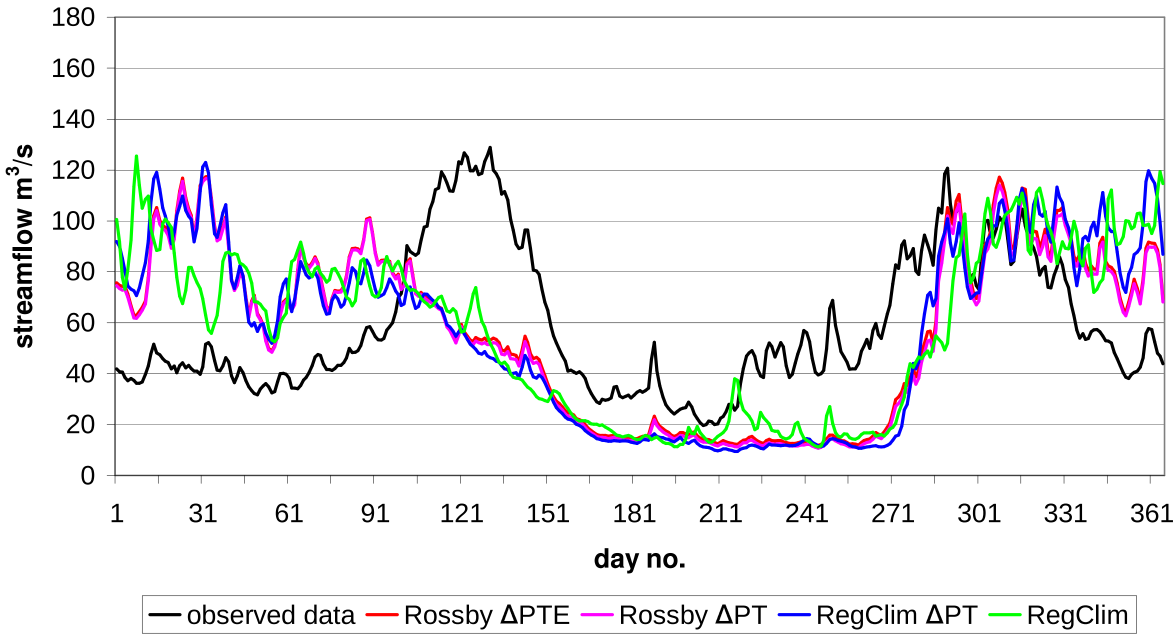
Top: Projected mean weekly precipitation for Masi basin for 2071-2100.

Bottom: Projected mean daily temperature for Masi basin for ECHAM4/OPYC3 B2 scenario 2071-2100. Accumulated difference between RegClim and RegClim ΔPT simulations.

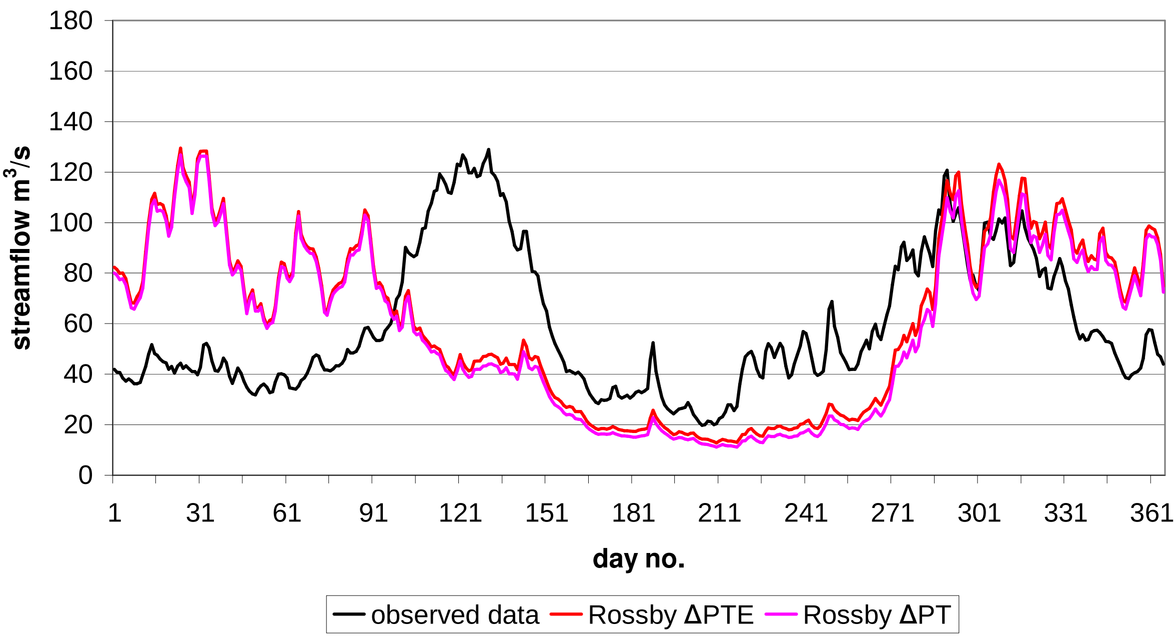
Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim ECHAM4/OPYC3 B2 simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

Flaksvatn HadAM3H A2 2071-2100 mean daily streamflow



Flaksvatn ECHAM4/OPYC3 A2 2071-2100 mean daily streamflow

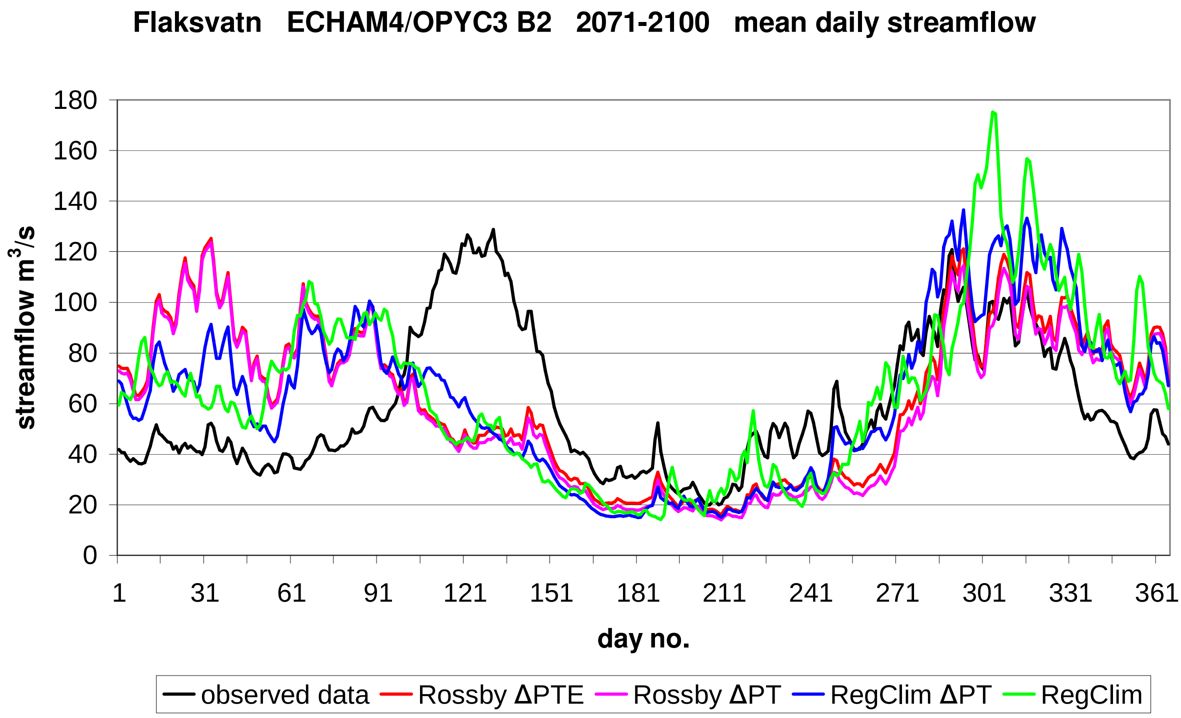


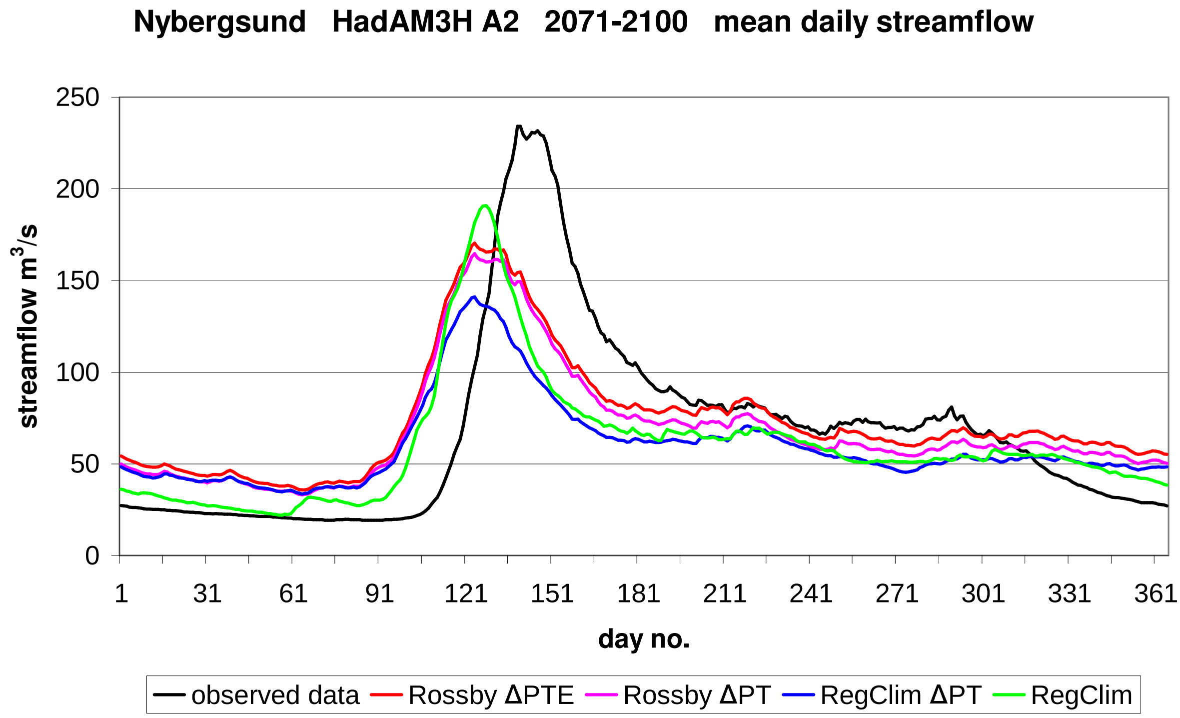
Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H A2 scenario 2071-2100 for Flaksvatn basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 A2 scenario 2071-2100 for Flaksvatn basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



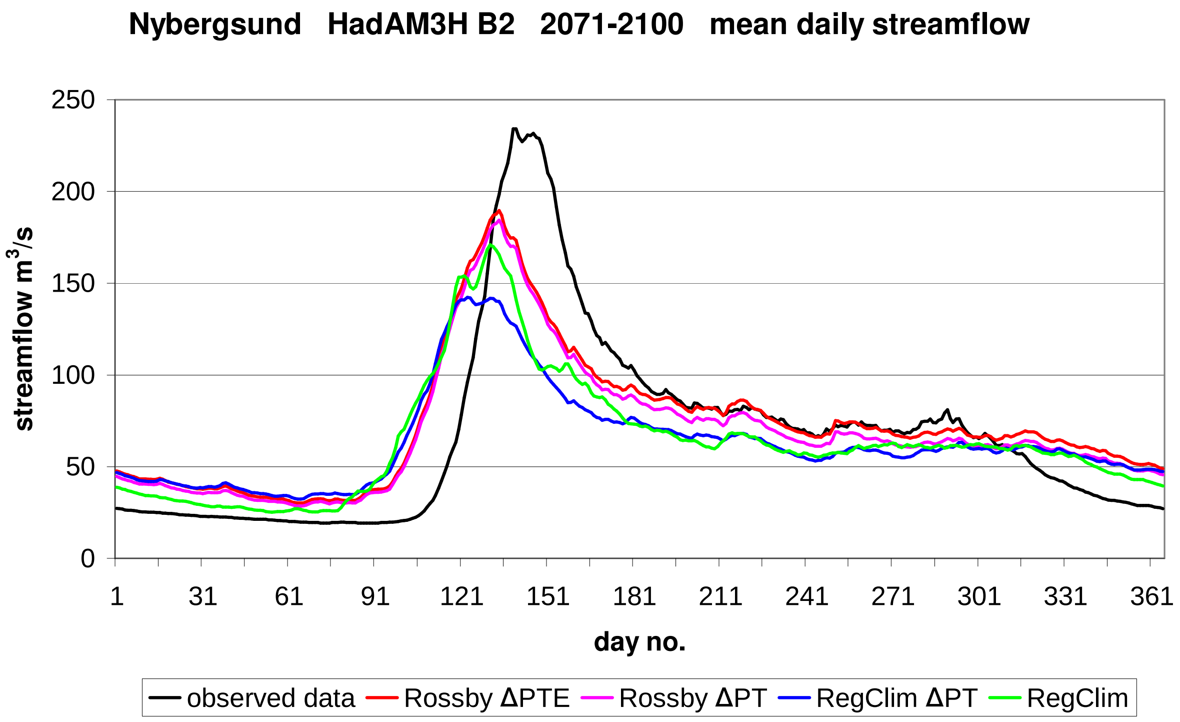


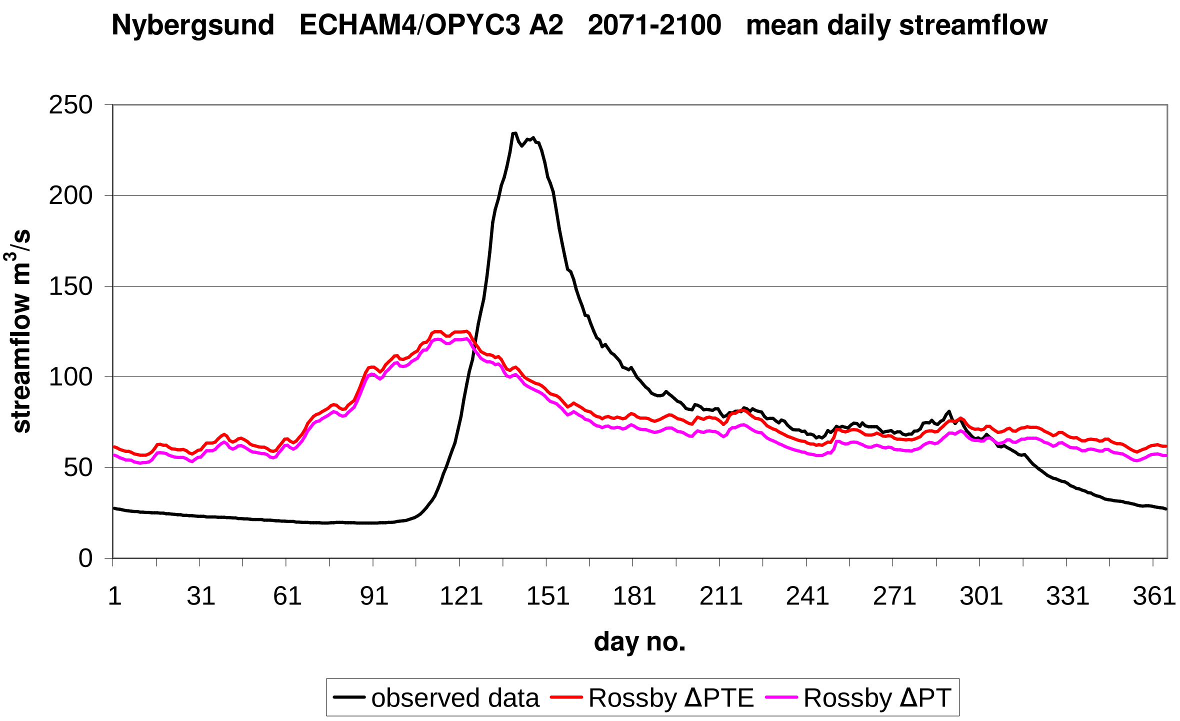
Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 B2 scenario 2071-2100 for Flaksvatn basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H A2 scenario 2071-2100 for Nybergsund basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



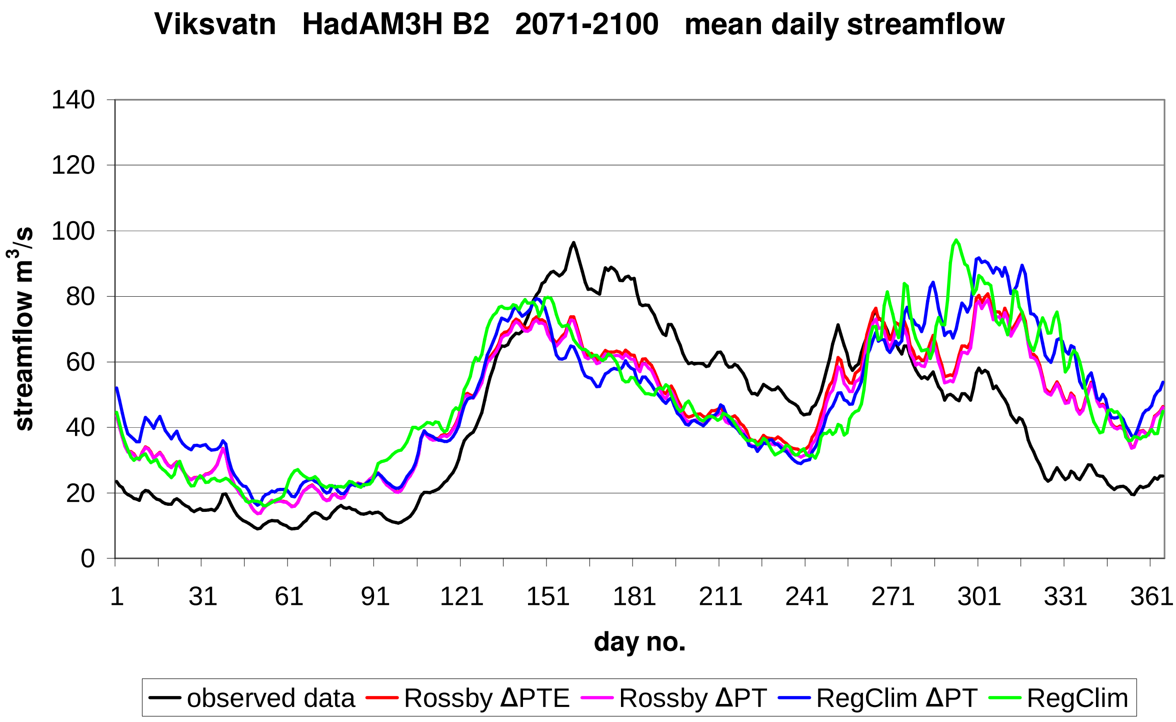


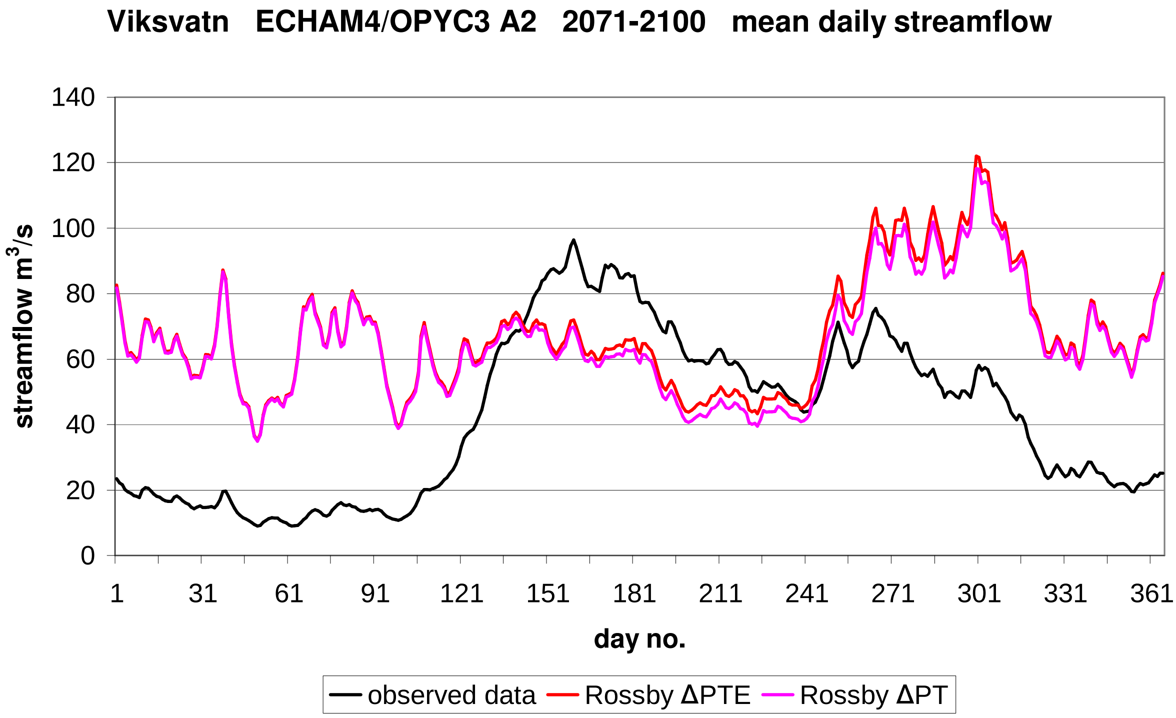
Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H B2 scenario 2071-2100 for Nybergsund basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 A2 scenario 2071-2100 for Nybergsund basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



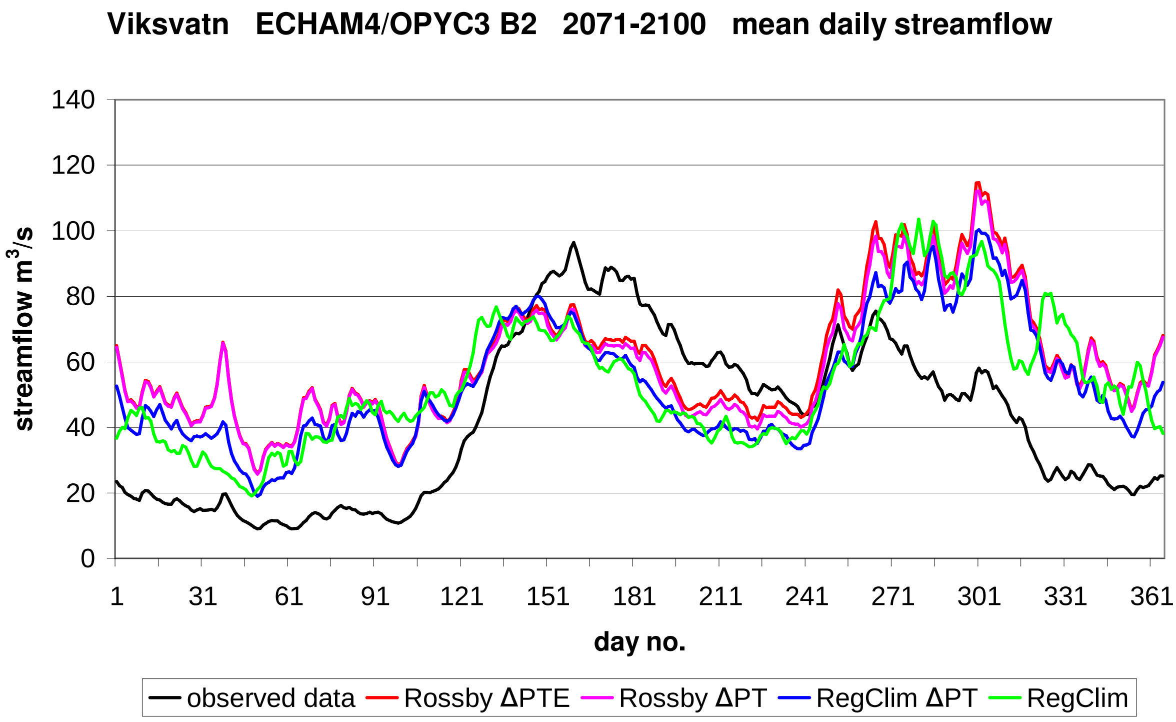


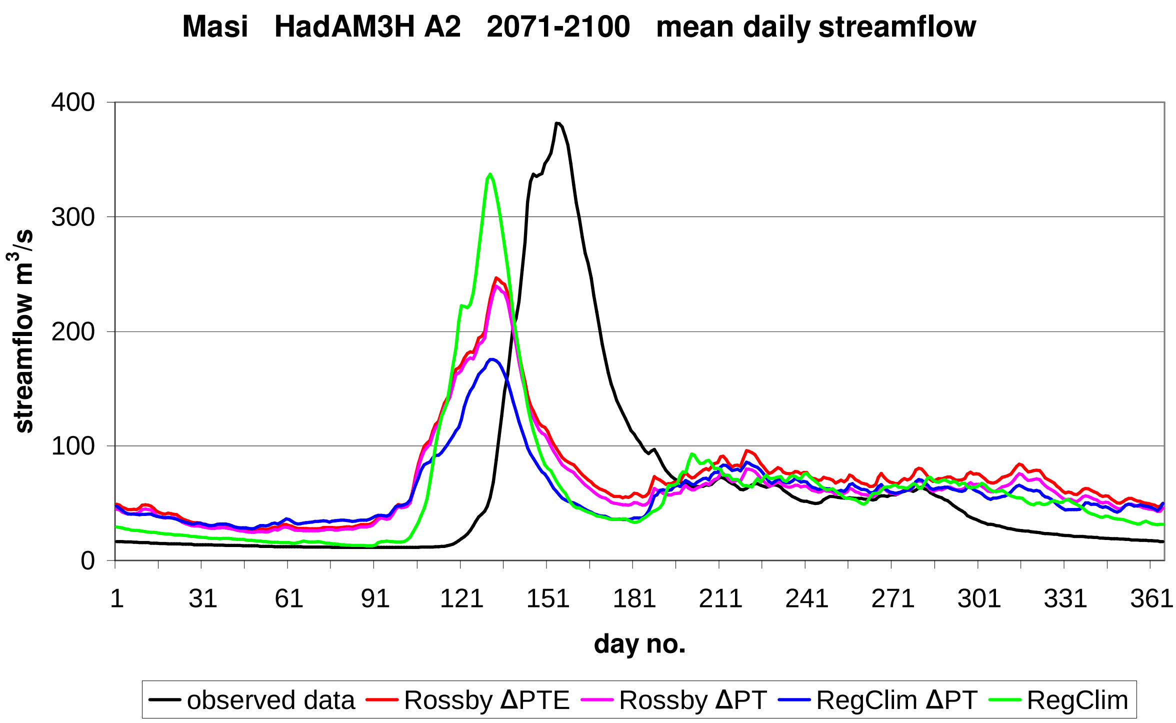
Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H B2 scenario 2071-2100 for Viksvatn basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 A2 scenario 2071-2100 for Viksvatn basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



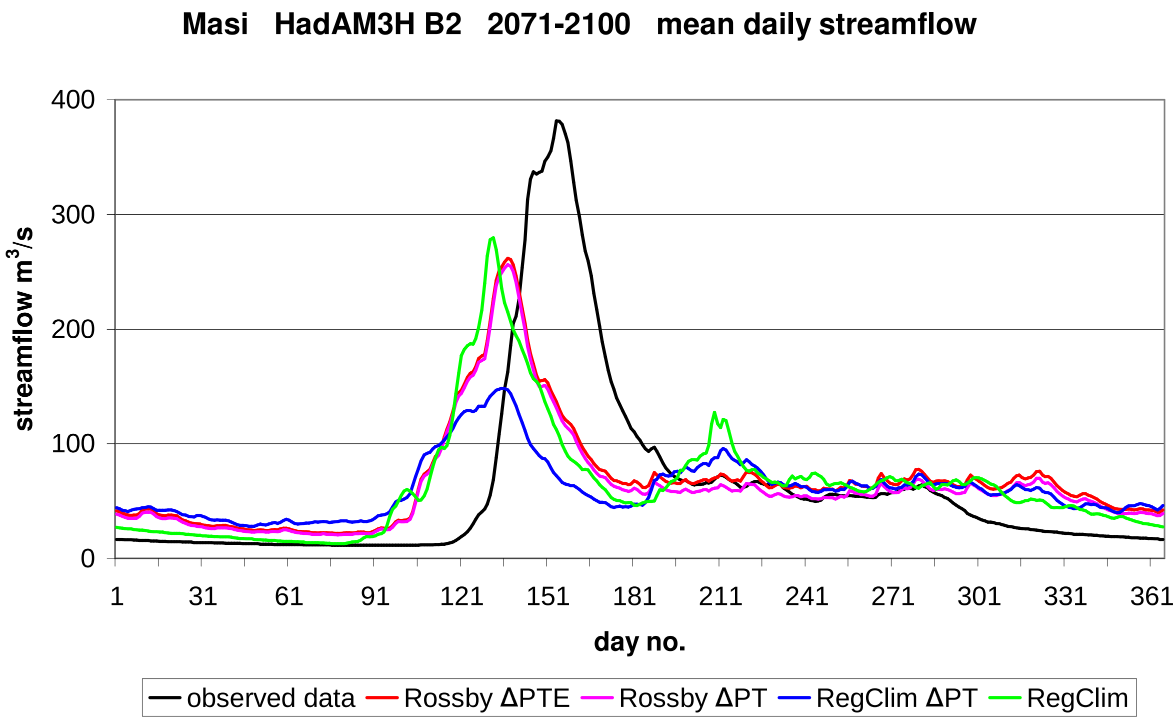


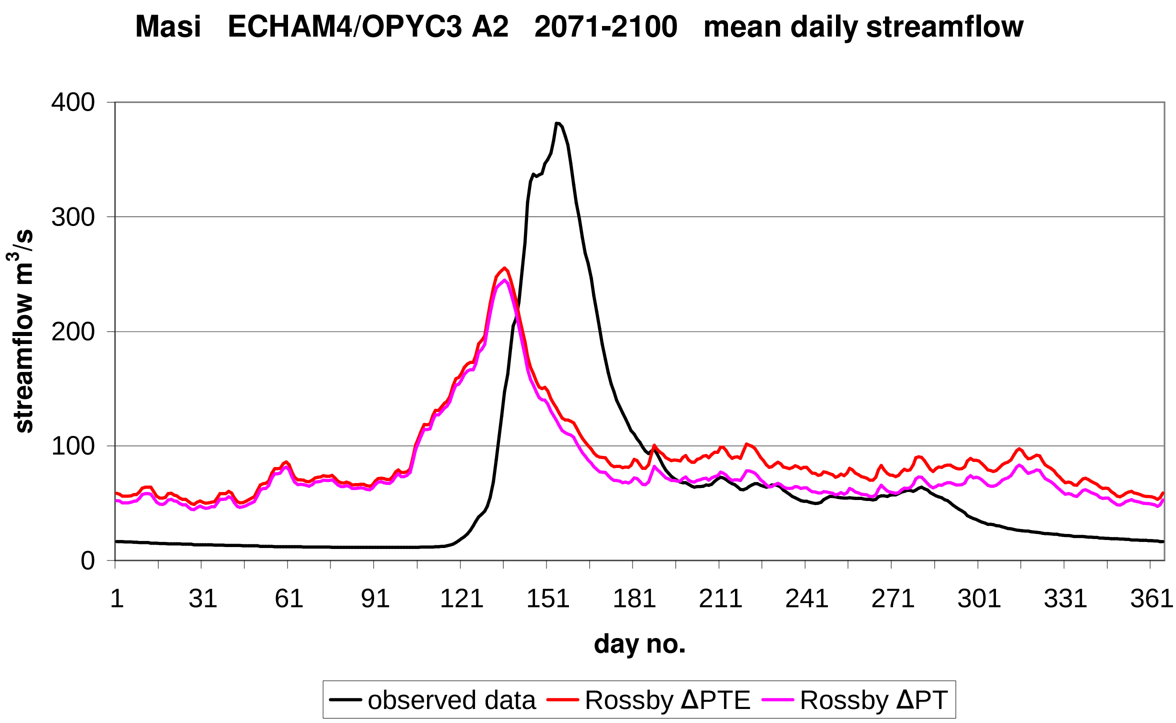
Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 B2 scenario 2071-2100 for Viksvatn basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H A2 scenario 2071-2100 for Masi basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).





Top: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for HadAM3H B2 scenario 2071-2100 for Masi basin.

Bottom: Mean daily observed streamflow 1961-1990 and projected mean daily streamflow for ECHAM4/OPYC3 A2 scenario 2071-2100 for Masi basin.

Rossby ΔPTE, Rossby ΔPT and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to meteorological station sites using the delta change approach.

RegClim scenario simulations transferred the HIRHAM climate change signal to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

Appendix B

This appendix presents hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Mean daily snow water equivalent for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and the scenario period 2071-2100 is presented.

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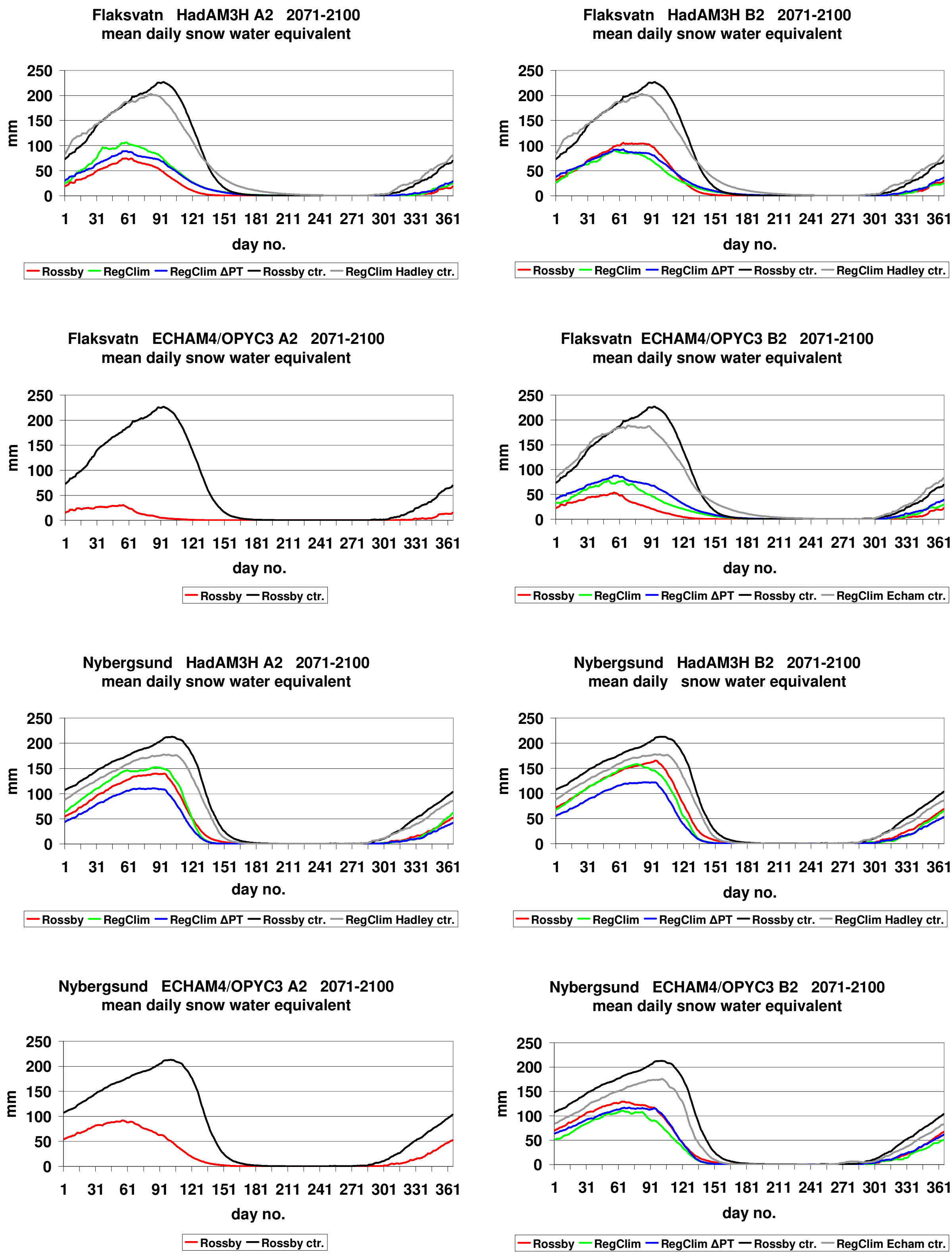
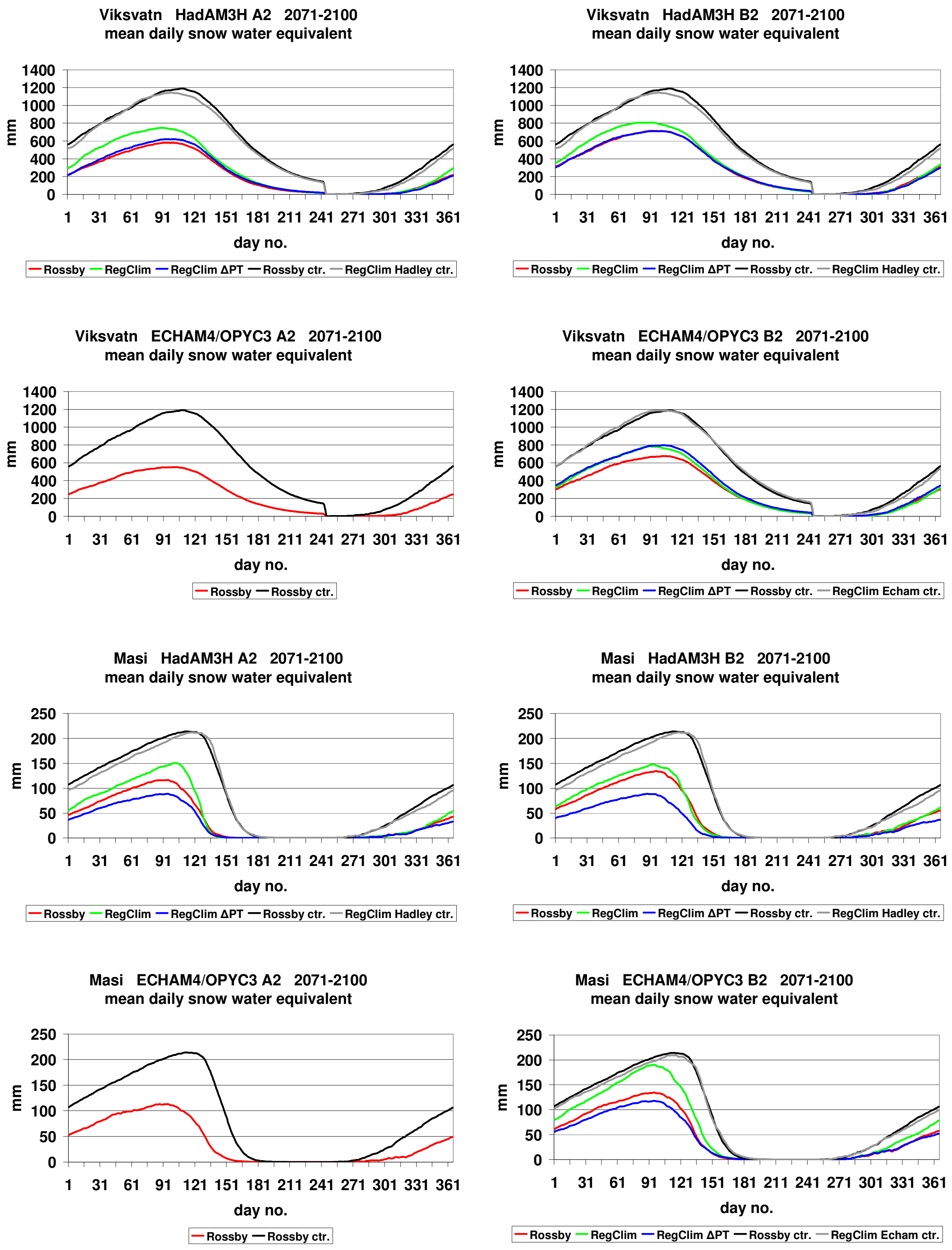


Mean daily simulated snow water equivalent for 1961-1990 and projected mean daily snow water equivalent for 2071-2100 for Flaksvatn and Nybergsund basins.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to the hydrological model using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



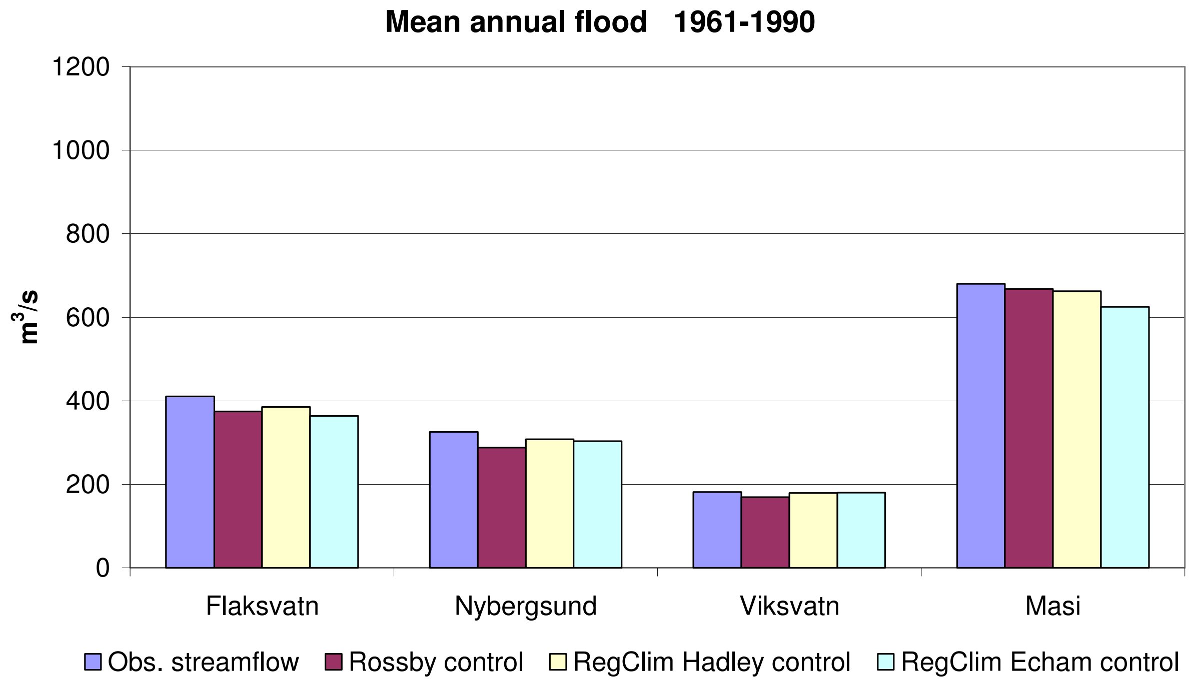
Mean daily simulated snow water equivalent for 1961-1990 and projected mean daily snow water equivalent for 2071-2100 for Viksvatn and Masi basins.

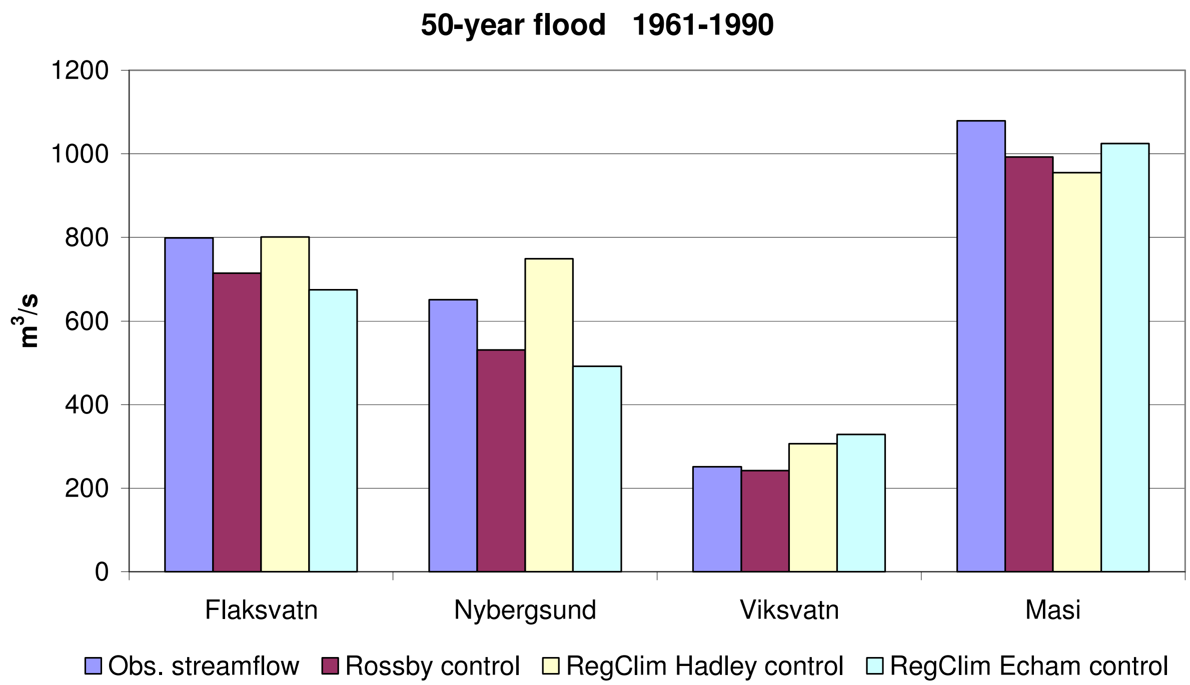
Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby and RegClim ΔPT simulations for the scenario period transferred the RCAO or HIRHAM climate change signal to the hydrological model using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

Appendix C

This appendix presents flood statistics estimated from hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Estimated mean annual and 50-year floods for yearly maxima of daily streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990 and changes in the flood magnitudes from the control period 1961-1990 to the scenario period 2071-2100 are presented. Flood quantiles were based on the General Extreme Value distribution and parameter estimation by the Probability Weighted Moments method (Hosking and Wallis, 1997).



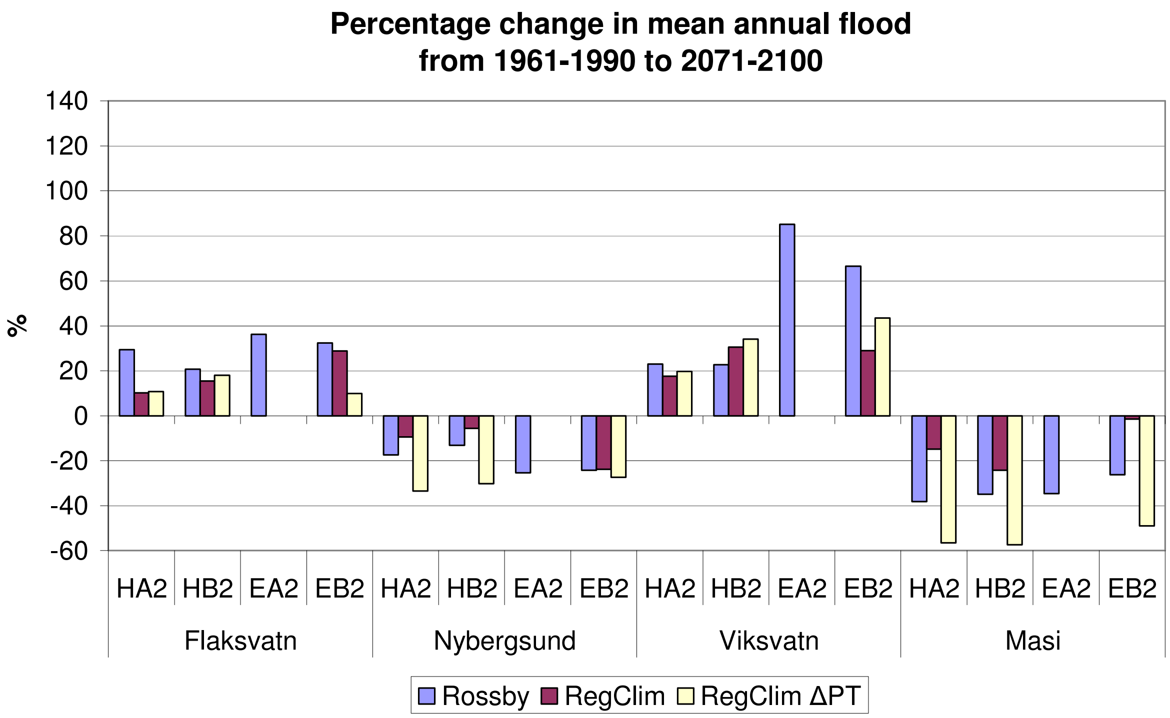


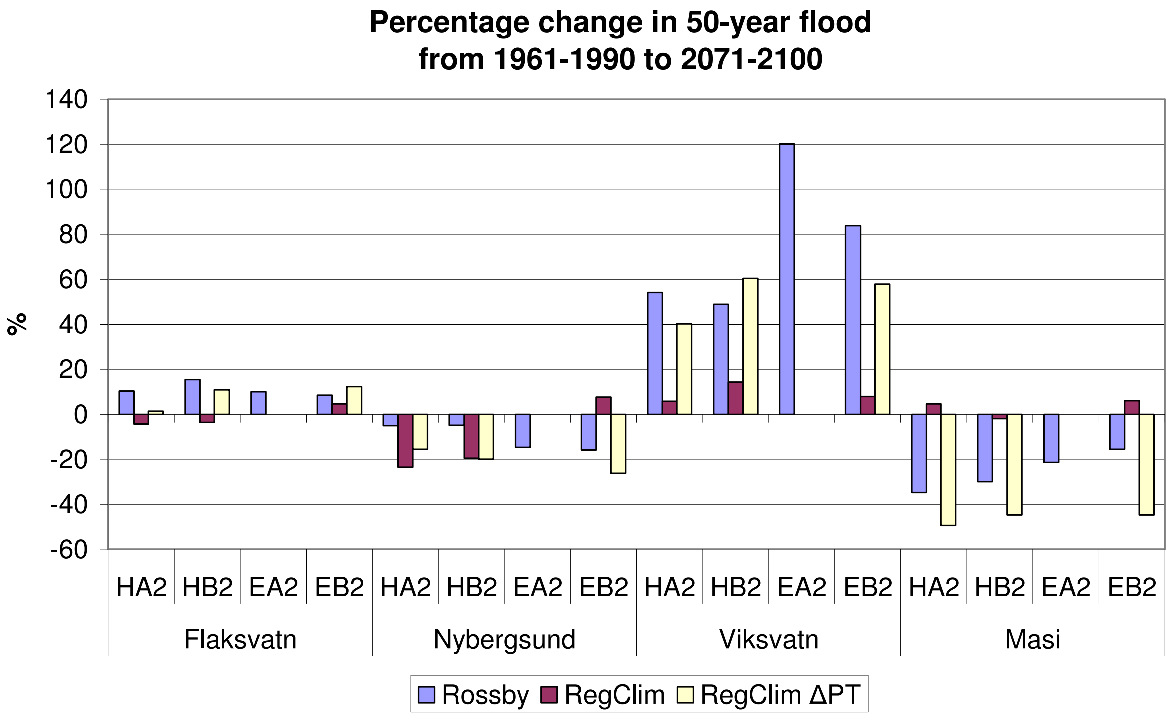
Estimated mean annual (top) and 50-year floods (bottom) for yearly maxima of mean streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi for the control period 1961-1990.

Flood quantiles were estimated from observed streamflow data and from hydrological model results.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred RCAO regional climate model results to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).





Projected percentage change in mean annual (top) and 50-year floods (bottom) for yearly maxima of daily streamflow for basins Flaksvatn, Nybergsund, Viksvatn and Masi from the control period 1961-1990 to the scenario period 2071-2100.

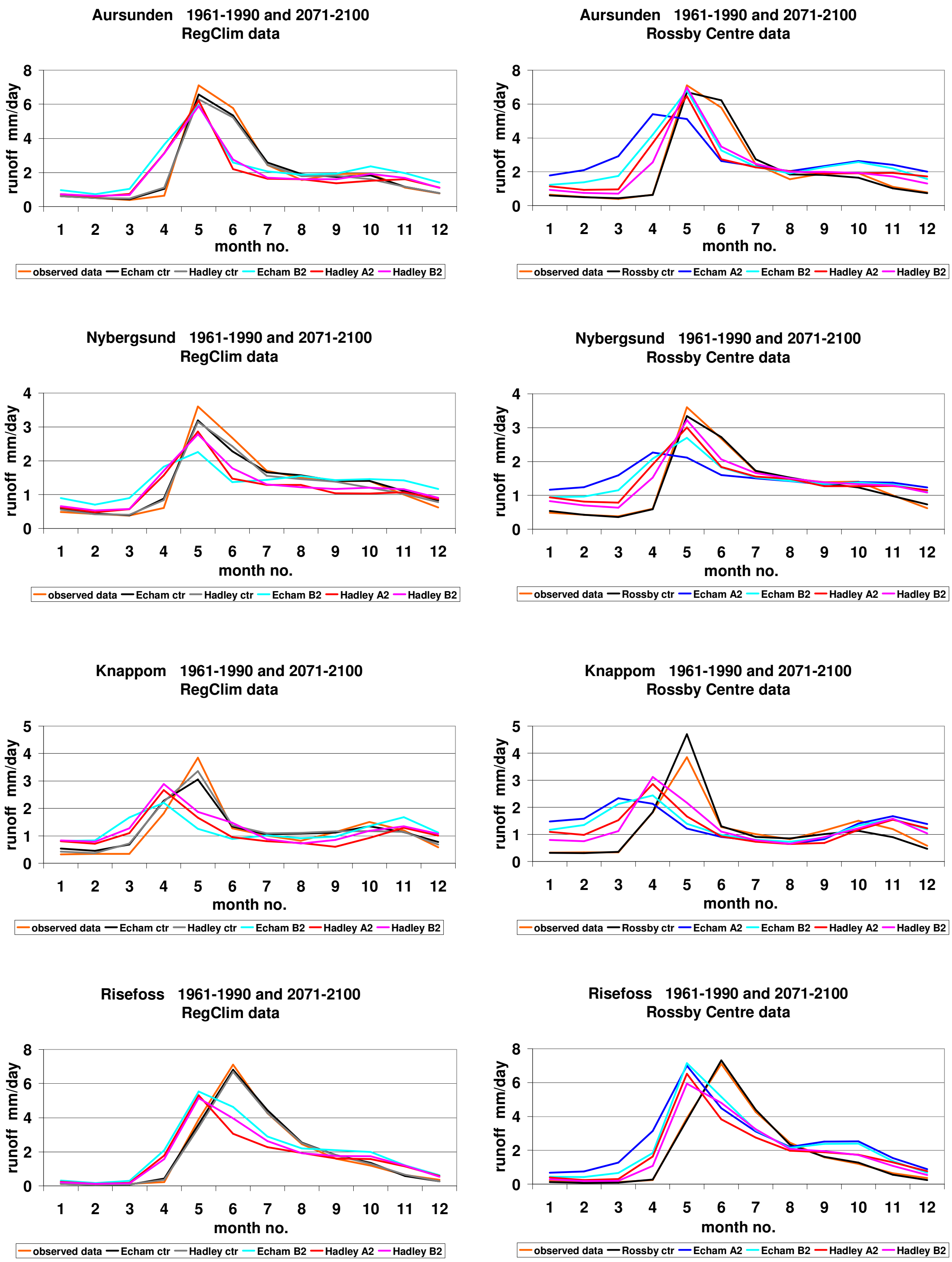
Flood quantiles were estimated from observed streamflow data and from hydrological model results.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred RCAO regional climate model results to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

Appendix D

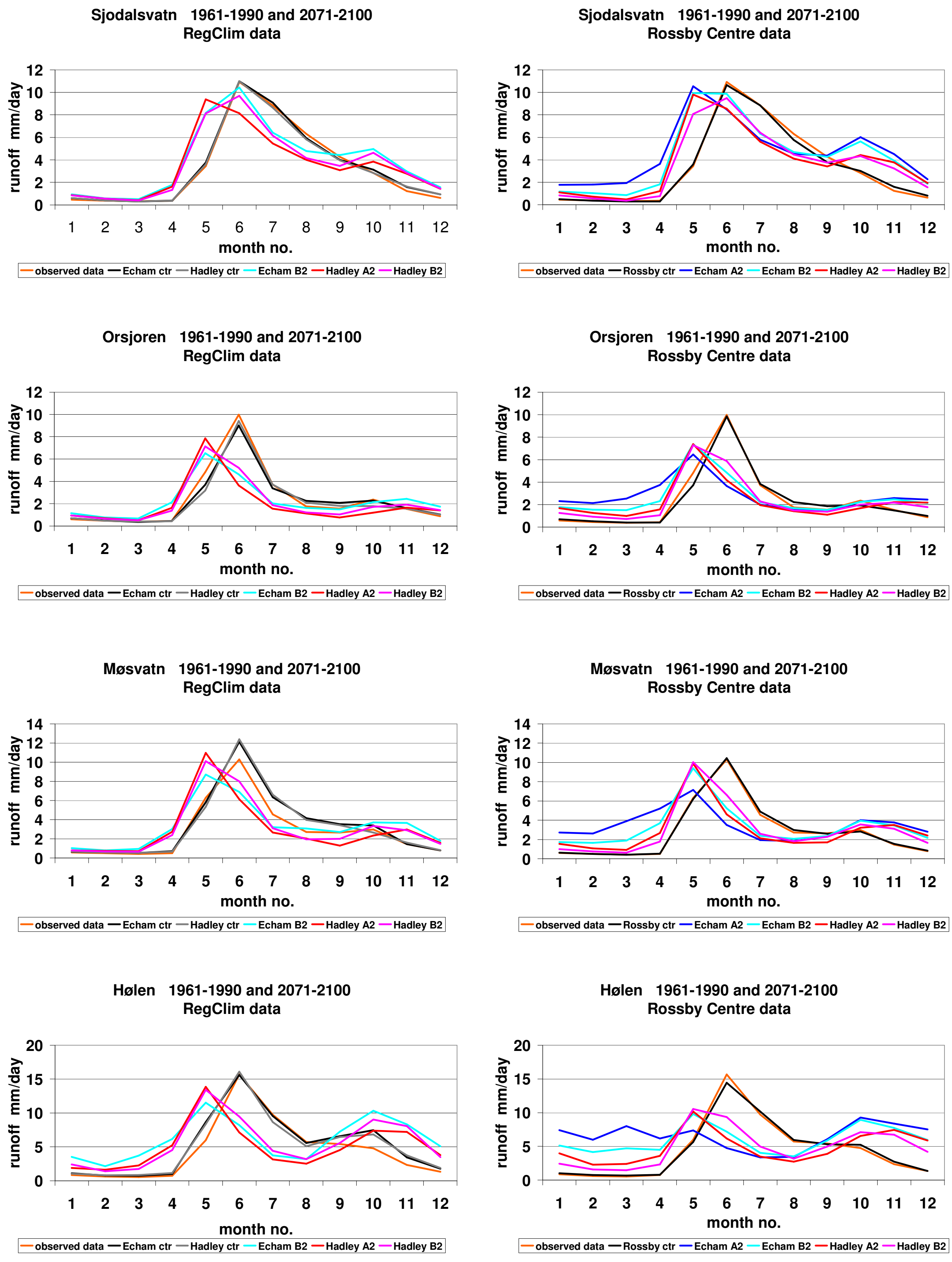
This appendix presents hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100 are presented.



Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred the RCAO climate change signal to the hydrological model using the delta change approach.

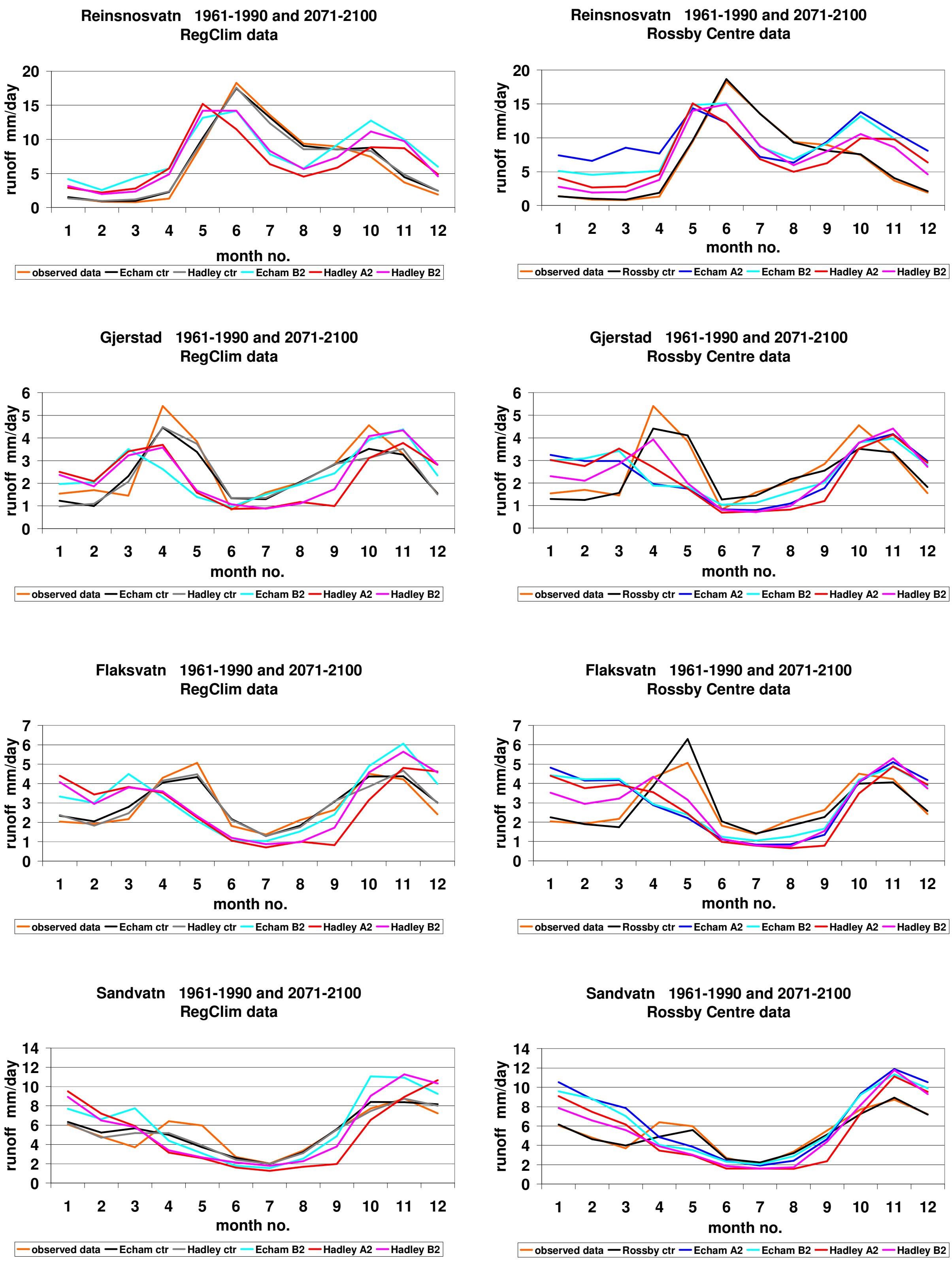
RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred the RCAO climate change signal to the hydrological model using the delta change approach.

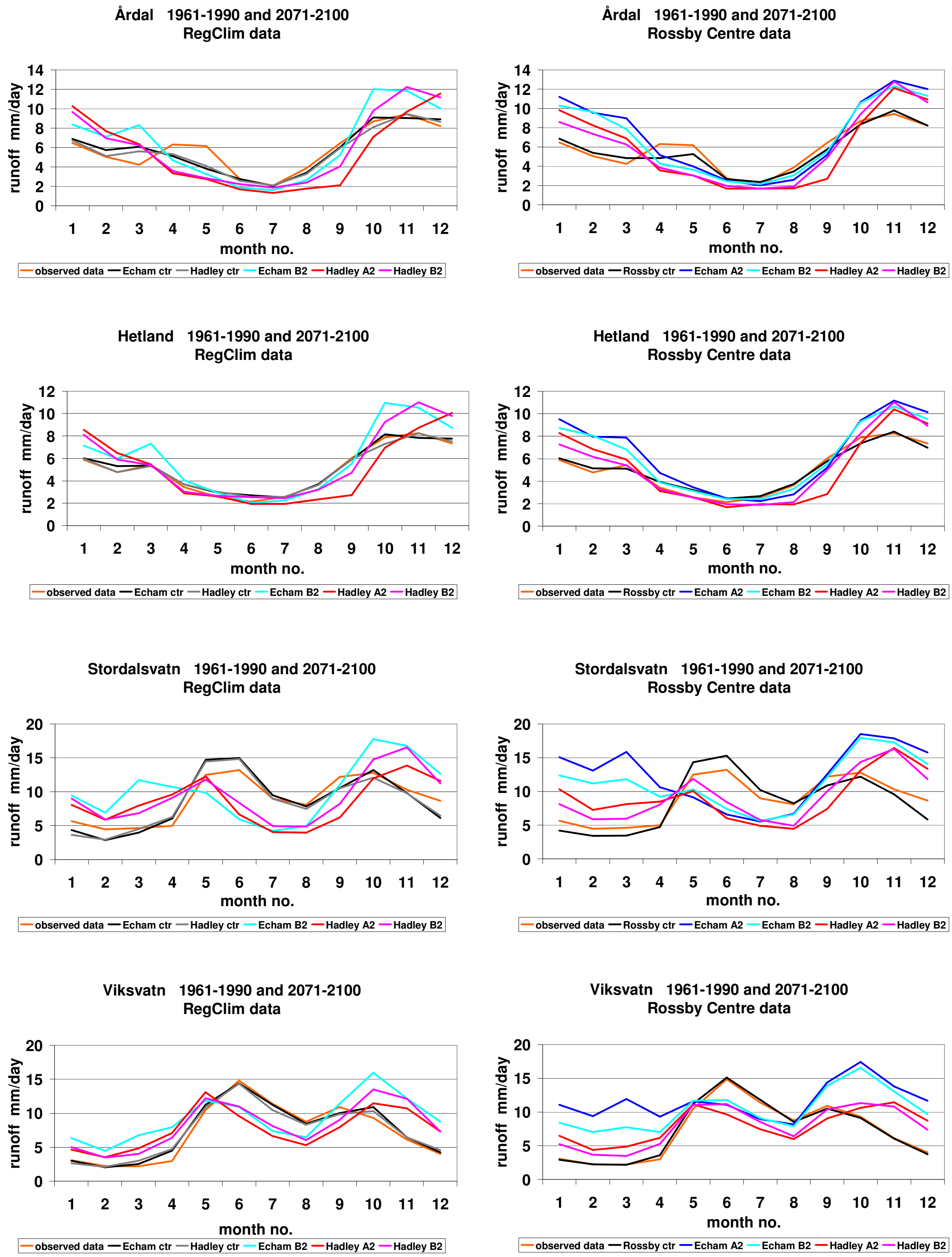
RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred the RCAO climate change signal to the hydrological model using the delta change approach.

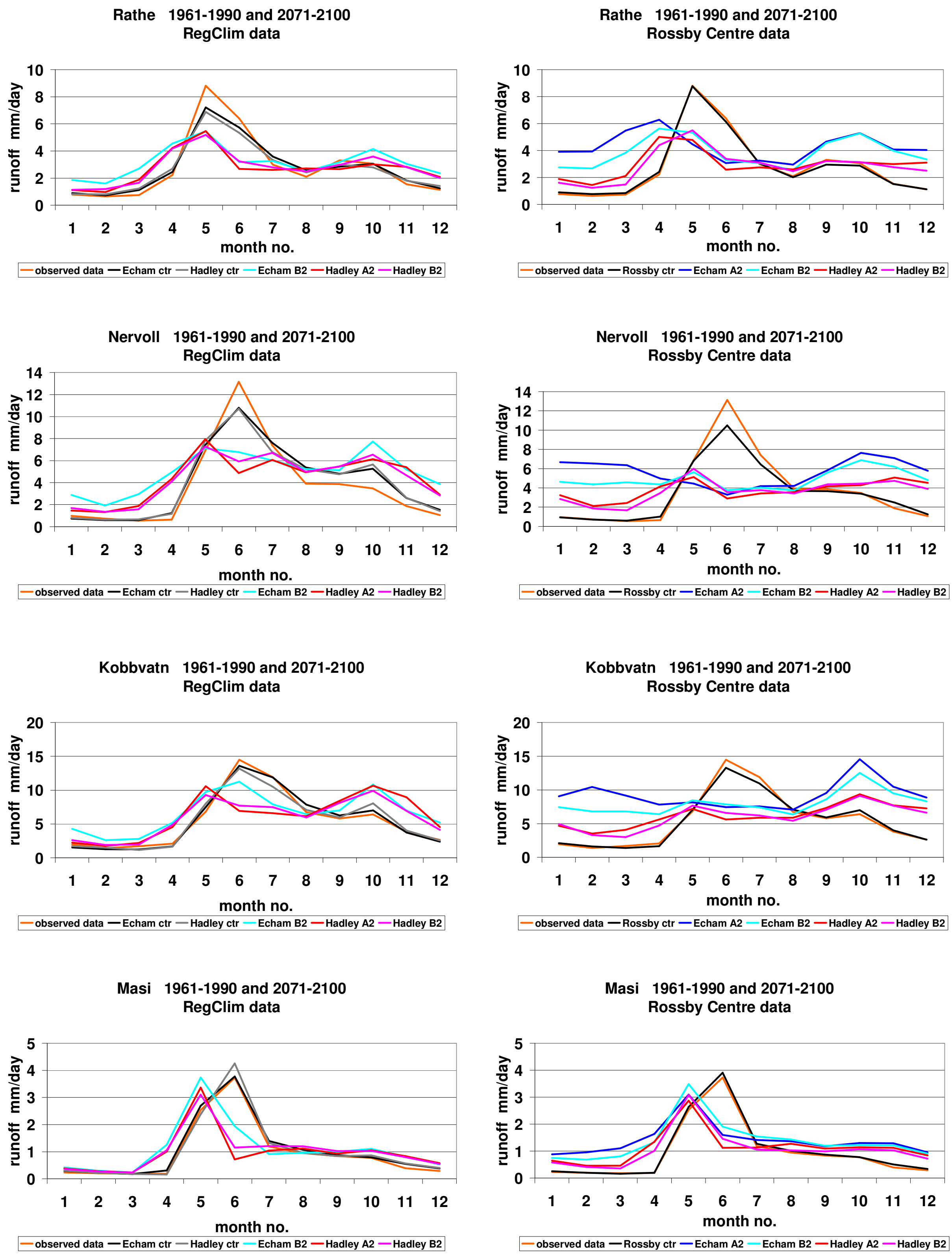
RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred the RCAO climate change signal to the hydrological model using the delta change approach.

RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).



Observed and model simulated mean monthly runoff for the control period 1961-1990 and projected mean monthly runoff for the scenario period 2071-2100.

Rossby control simulations used observed meteorological data for driving the hydrological model, while Rossby simulations for the scenario period transferred the RCAO climate change signal to the hydrological model using the delta change approach.

RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

Appendix E

This appendix presents box-and-whisker plots summarising changes in runoff from the control period 1961-1990 to the scenario period 2071-2100 based on different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites.

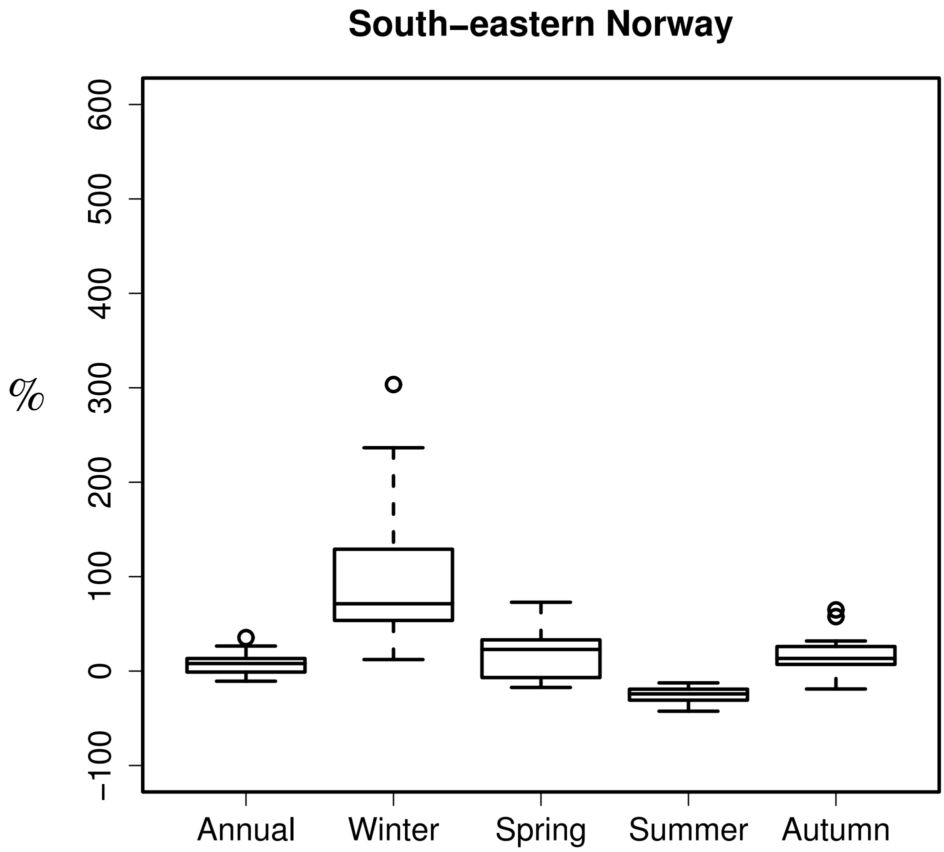
Hydrological model results for the control period were based on observed meteorological data for Rossby Centre RCAO control simulations, while Rossby simulations for the scenario period transferred RCAO regional climate model results to meteorological station sites using the delta change approach.

RegClim Hadley control, RegClim Echam control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

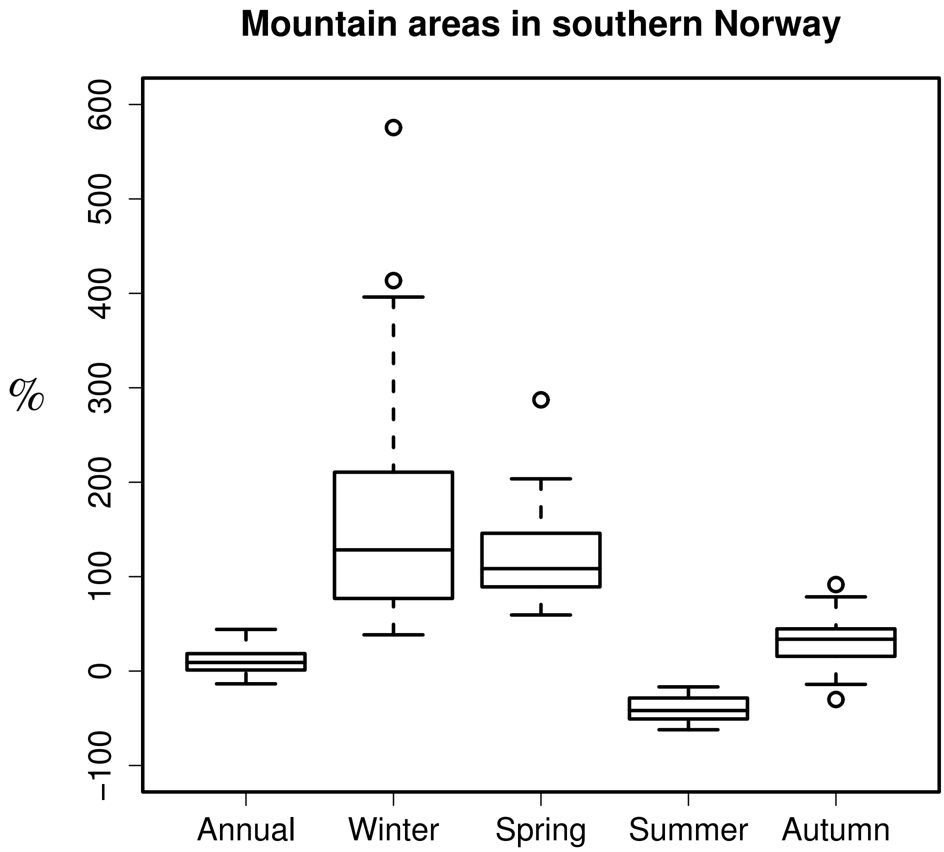
The box-and-whisker plots are based on all model results from catchments within a region. Changes in annual and seasonal runoff for seven climate change scenarios have been considered:

1. Rossby control to Rossby HadAm3H A2 scenario
2. Rossby control to Rossby HadAm3H B2 scenario
3. Rossby control to Rossby ECHAM4/OPYC3 A2 scenario
4. Rossby control to Rossby ECHAM4/OPYC3 B2 scenario
5. RegClim Hadley control to RegClim HadAm3H A2 scenario
6. RegClim Echam control to RegClim HadAm3H B2 scenario
7. RegClim Echam control to RegClim ECHAM4/OPYC3 B2 scenario

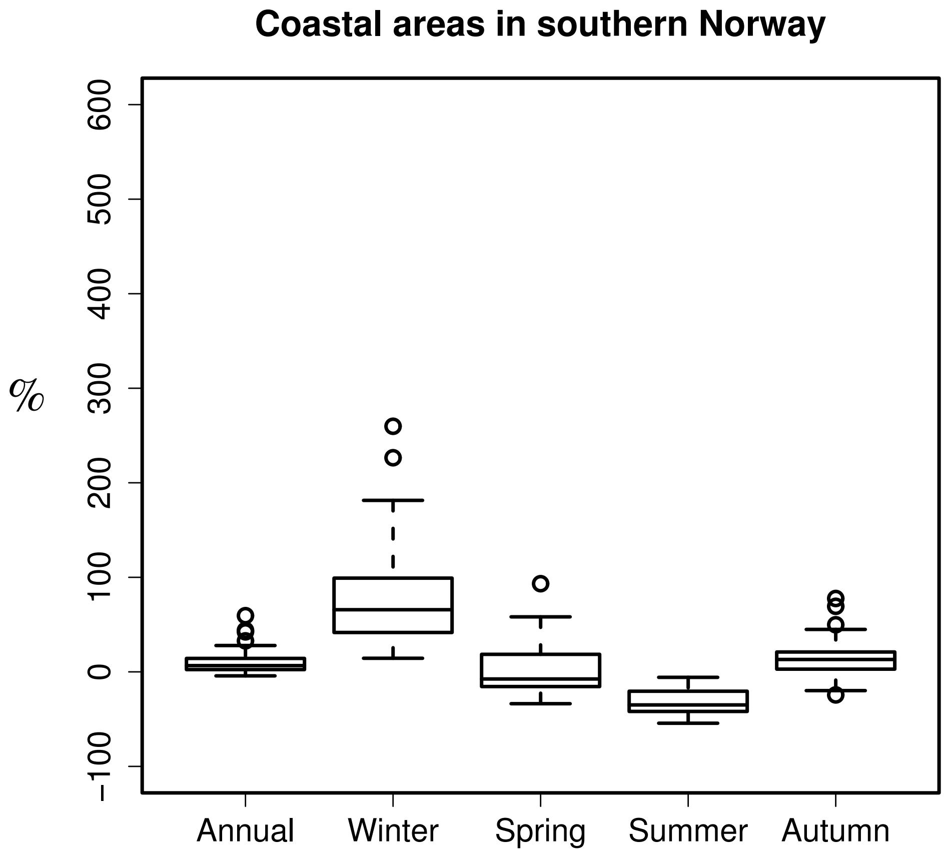
The box shows the interquartile range (IQR:25-75 percentiles), the horizontal line gives the median value and the whiskers extend to the most extreme data-points which are not more than |1.5| times the interquartile range from the box.



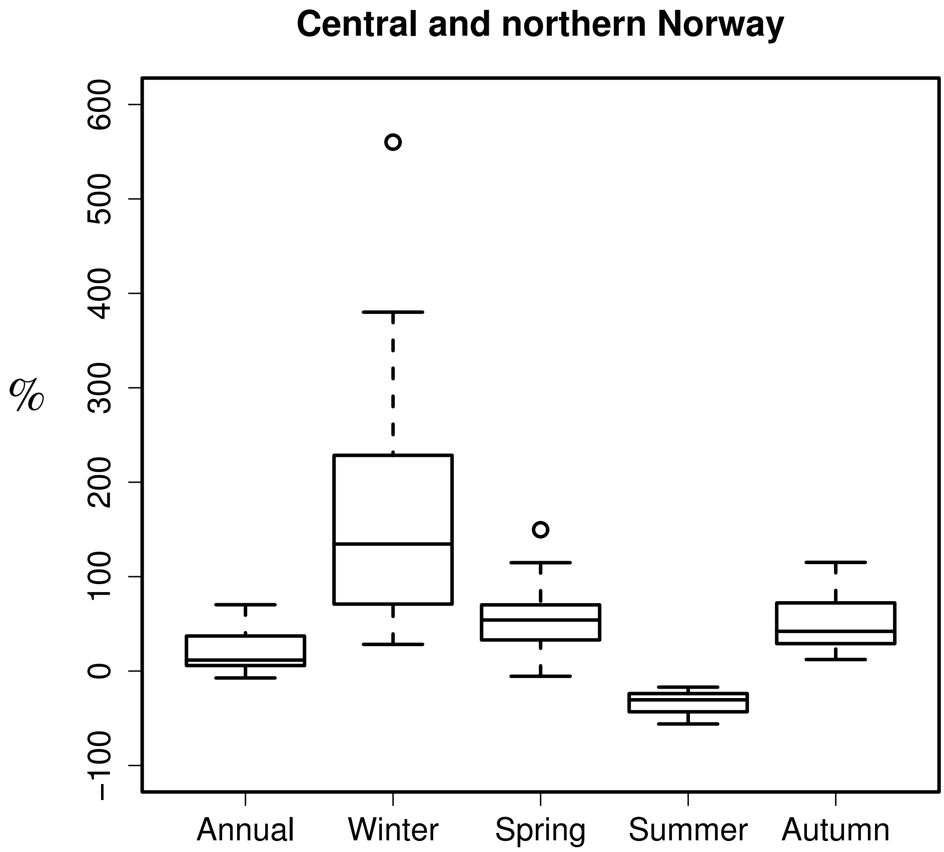
Percentage change in annual and seasonal runoff for basin Aursunden, Nybergsund and Knappom in south-eastern Norway.



Percentage change in annual and seasonal runoff for basin Risefoss, Sjodalsvatn, Orsjoren, Møsvatn, Hølen and Reinsnosvatn in mountain areas in southern Norway.



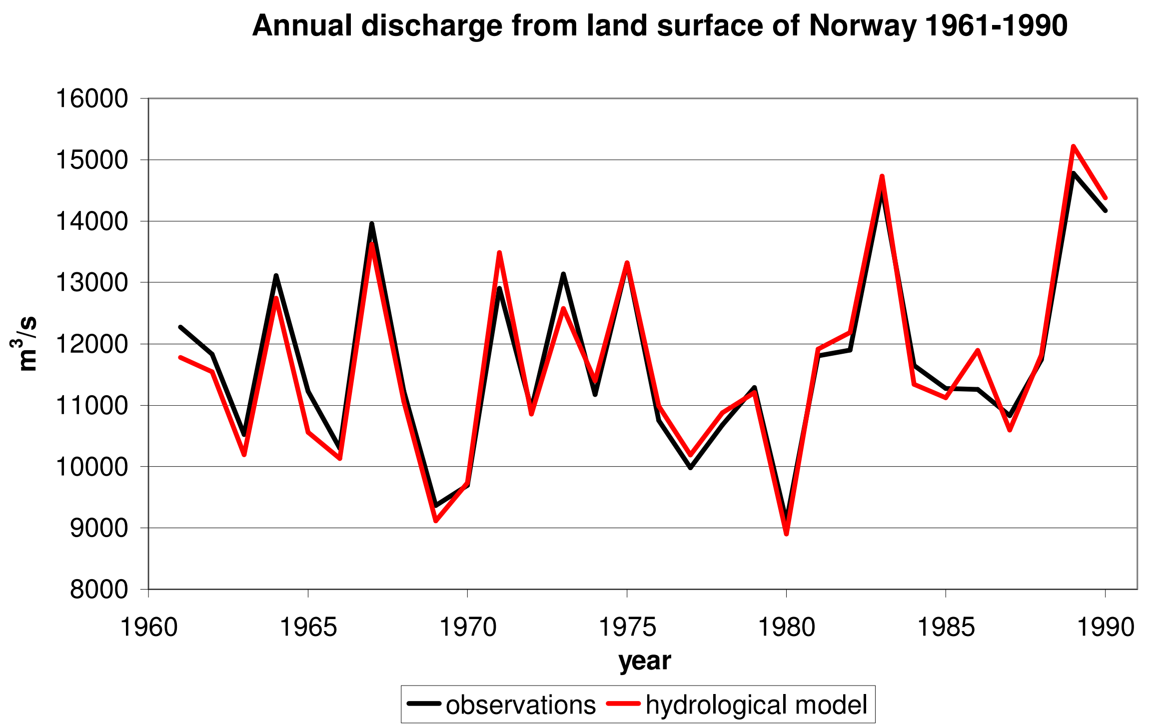
Percentage change in annual and seasonal runoff for basin Gjerstad, Flaksvatn, Sandvatn, Årdal, Hetland, Stordalsvatn and Viksvatn in coastal areas in southern Norway.

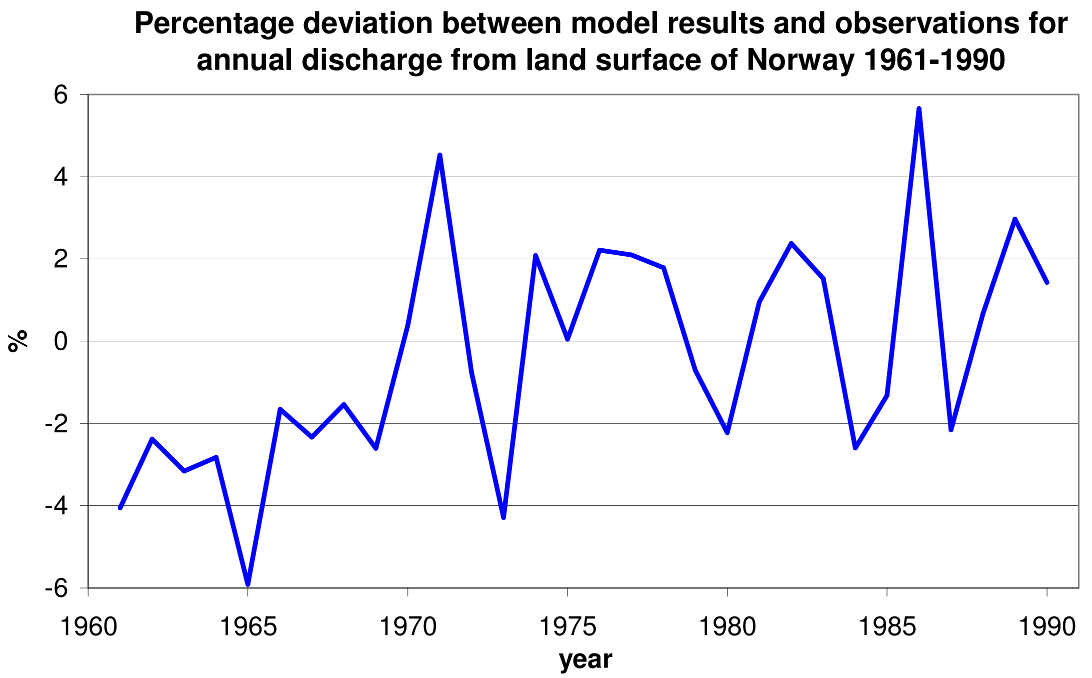


Percentage change in annual and seasonal runoff for basins Rathe, Nervoll, Kobbvatn and Masi in central and northern Norway .

Appendix F

This appendix presents hydrological model results based on observed meteorological data and different approaches for transferring the climate change signal from Rossby Centre RCAO and RegClim HIRHAM regional climate models to meteorological station sites. Model simulated mean weekly total discharge from the land surface of Norway for the control period 1961-1990 and projected mean weekly total discharge from the land surface of Norway for the scenario period 2071-2100 are presented.

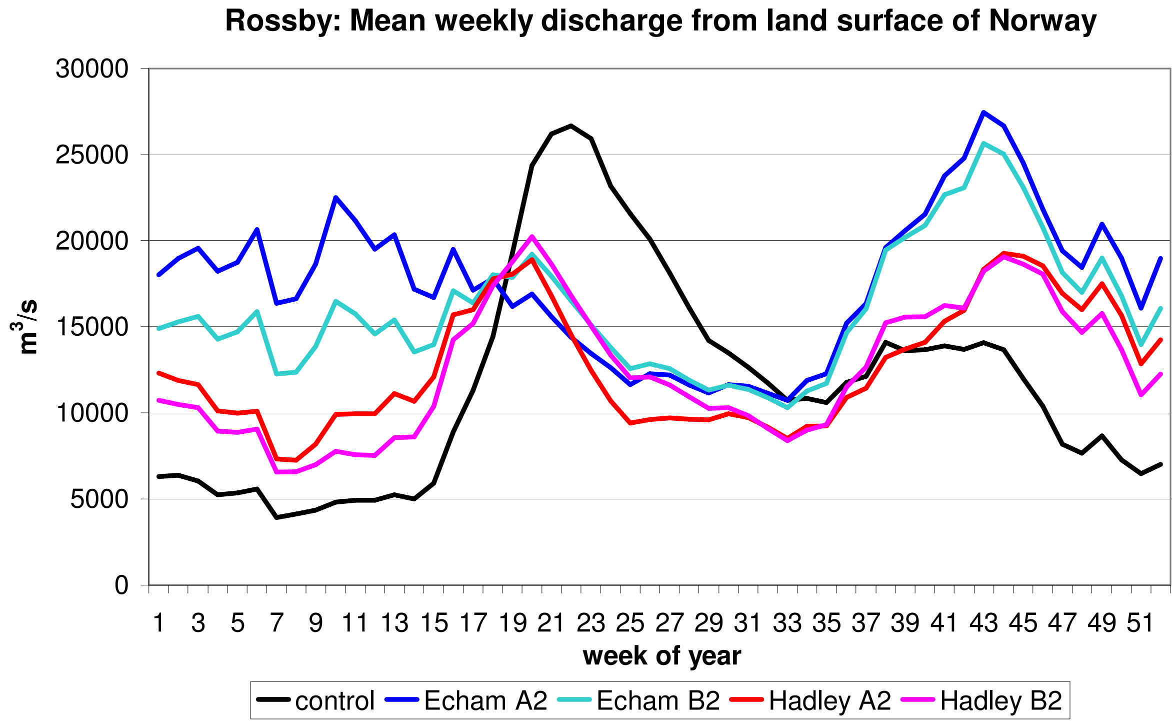


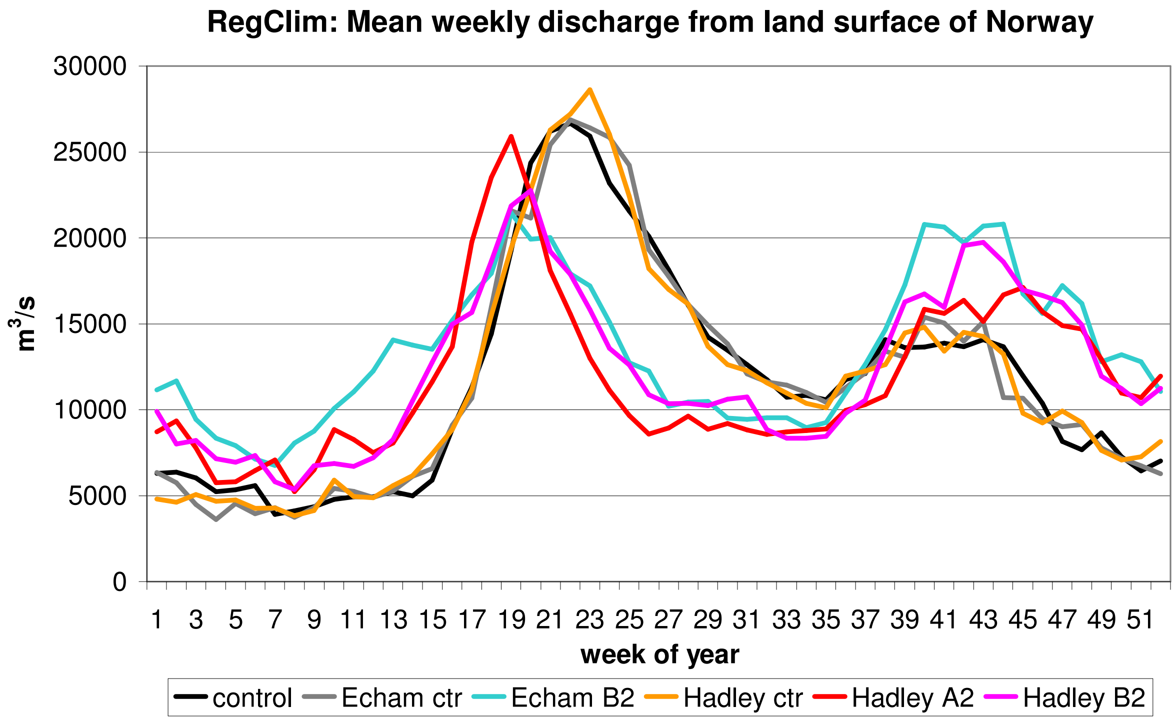


Top: Observed and model simulated annual total discharge from the land surface of Norway for 1961-1990. Observed meteorological data were used for driving the hydrological model.

Bottom: Percentage deviation between model results and observations for annual total discharge from the land surface of Norway for 1961-1990.

Observed discharge data from the station network of Norwegian Water Resources and Energy Directorate were used for evaluation of model results (Pettersson, 2004).





Mean weekly simulated total discharge from the land surface of Norway for 1961-1990 and projected mean weekly total discharge from the land surface of Norway for 2071-2100 based on Rossby Centre RCAO (top) and RegClim HIRHAM (bottom) regional climate model results.

Control simulations used observed meteorological data for driving the hydrological model.

Rossby scenario simulations transferred the RCAO climate change signal to meteorological station sites using the delta change approach.

RegClim Echam control, RegClim Hadley control and RegClim scenario simulations transferred HIRHAM regional climate model results to meteorological station sites with the empirical adjustment procedure developed by Engen-Skaugen (2004).

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