Climate change impacts on hydrological processes in the Nordic region 2071-2100

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ABSTRACT
Climate change impact simulations for hydrological processes in the Nordic region for the period 2071-2100 have been estimated using results from 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. These climate scenarios were used for driving the HBV and WaSim-ETH hydrological models. Present conditions were determined from control runs using observed meteorological data and climate model results for 1961-1990. Maps presenting the spatial distribution of hydrological state variables and fluxes are presented. A moderate increase in annual runoff is expected in most parts of the Nordic region, with a decline in some parts for some scenarios. The changes depend on the spatial distribution of the atmospheric pressure fields as modelled by the two global climate models. Significant changes in the seasonal distribution of runoff are expected. Increase everywhere in the winter, increase in mountainous basins and inland basins in the spring and a decline in coastal and southern basins in the spring. Decrease will occur everywhere in the summer, while autumn runoff will increase everywhere except in southern parts. 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 rainfall intensities, number of rainfall events and total rainfall volume will most likely provide conditions that may be expected to yield larger rain floods.

KEYWORDS
Climate change, water resources, hydrological model

1. INTRODUCTION

Production of electricity in the Nordic countries 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 or statistics of hydrological state variables and fluxes for present and future climate conditions. Maps presenting spatial distributions of these statistics, e.g. annual or seasonal mean values and extremes are a useful way of communicating the results from modelling hydrological impacts of climate change. The results presented in this study have been produced by the Hydropower, Hydrological Models group of the Nordic research project Climate and Energy (CE). This project has the objective of a comprehensive assessment of the impacts of climate change on renewable energy sources in the Nordic countries, the Baltic States and Northwest Russia. The CE project is funded by the Nordic Energy Research, the Nordic energy sector and national institutions of the participating countries.

Within the CE project a set of maps of water resources under present and future conditions based on climate scenarios and hydrological modelling techniques have been produced. This may serve as a foundation for assessments of the future production potential of hydropower in the Nordic area. The maps are based on four regional climate scenarios, resulting from two general circulation models, each forced with two greenhouse gas emission scenarios. Climate change scenarios differ substantially due to uncertainties with regard to the climate forcing caused by greenhouse gas emissions, uncertainties caused by imperfect representation of processes in the atmospheric models, and uncertainties with regard to initial conditions. Hydrological climate change maps which are based on ensembles of climate change simulations from model runs using different approaches to predict the future represent one way of quantifying this uncertainty.

2. CLIMATE SCENARIOS

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. 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 (Nakicenovic *et al.*, 2000). The general circulation model simulations were used as boundary conditions for dynamical downscaling with two regional climate models. For Finland, Latvia, Norway and Sweden the Rossby Centre Regional Atmosphere-Ocean (RCAO) model (Doscher *et al.*, 2002) was run with boundary conditions supplied by the ECHAM4/OPYC3 and HadAM3H models for both A2 and B2 emission scenarios, resulting in four different hydrological climate change impact simulatios for each country. Regional climate model results for Iceland were supplied by the HIRHAM model (Bjørge *et al.*, 2000) with boundary conditions from the HadAM3H model. Mean values of HIRHAM results from the A2 and B2 scenarios were used as input to hydrological modelling in Iceland. HIRHAM results were provided by the Regional Climate Development Under Global Warming (RegClim) project (http://regclim.met.no).

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 models. Observed meteorological data were used as a control climate in all countries, with the exception of Iceland where observed data were replaced by results from the MM5 atmospheric model at spatial resolution 8 by 8 km^2 (Grell *et al.*, 1994). Changes in meteorological variables between the control and the scenario simulations from the regional climate models were transferred to a database of meteorological data. This can be referred to as the delta change approach, e.g. Hay *et al.* (2000) 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 daily meteorological data driving the hydrological models 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. Temperature changes were applied differently. Constant monthly temperature changes for all temperature intervals were applied for the impact simulations in Iceland, Latvia and Norway, while the Finnish and Swedish simulations used a temperature dependent function to take into account that temperature changes in the climate scenarios are most pronounced at low temperatures.

3. HYDROLOGICAL SIMULATIONS

Hydrological simulations were performed on a daily time step with the conceptual HBV model (c.f. Lindstrom *et al.*, 1997) for all countries except for Iceland, where the WaSiM-ETH model (Schulla and Jasper, 2001) was used. The HBV model is a conceptual, semi-distributed precipitation-runoff model originally developed for operational streamflow forecasting. The model includes routines for snow accumulation and melt, soil moisture accounting, groundwater response and river routing. It exists in different versions in each of the Nordic countries. Due to the geological conditions prevailing in Iceland the hydrological model structure must be able to describe groundwater flow in aquifers with large vertical extent. WaSiM-ETH was chosen because it allows the user to choose modules with different levels of complexity for simulation of subsurface processes. The hydrological models were calibrated to catchments representing different runoff regimes and land surface characteristics in each country. Landscape elements which could be expected to have similar hydrological behaviour were parameterised in the same way, and calibrated parameter sets were transferred to ungauged catchments based on a classification of land surface properties. Temperature and precipitation data from the meteorological stations of the different countries were interpolated to the computational elements of the hydrological models.

The hydrological simulations for Finland were done with a spatially distributed HBV model comprising of several small lumped models (Vehviläinen and Huttunen, 2002). The model consist of a rainfall-runoff model and river and lake models. The watersheds in the model have been divided into sub-catchments of approximately 100 km^2. Each of the sub-catchments has its own set of parameters and simulated storages and is divided into 1 km^2 grid cells.

Present conditions in Iceland were evaluated from a control run using the grid based hydrological model WaSiM-ETH (Schulla and Jasper, 2001). The hydrological model was calibrated against runoff data from 70 watersheds covering 1/3 of the country. Then, model parameters were evaluated for ungauged watersheds by comparing model parameters from nearby watersheds with similar characteristics based on a recent classification of watersheds. The hydrological model was applied at a 1 by 1 km^2 grid.

The HBV-96 model (Lindstrom *et al.*, 1997) was used for climate change impacts simulations for three basins representative for different hydrological regimes in Latvia: Irbe basin (1920 km^2) is located in western part of Latvia and discharges to the Baltic sea; Gauja basin (8510 km^2) covers north-eastern part of Latvia and discharges to the Gulf of Riga; Aiviekste basin (8660 km^2) covers eastern part of Latvia and discharges to the Daugava river.

A spatially distributed version of the HBV model (Beldring *et al.*, 2003) was used for hydrological climate change impact simulations in Norway. The model performs water balance calculations for 1 by 1 km^2 square grid cell landscape elements characterized by their elevation and land use. A regionally applicable set of model parameters 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.

The HBV-96 model (Lindstrom *et al.*, 1997) was used for interpretation of the impacts of climate change on water resources in Sweden. The model, referred to as HBV-Sweden, was originally set up to calculate runoff and associated transport of nitrogen to the sea (Brandt and Ejhed, 2002). The model simulates hydrological processes in Sweden with more than 1000 sub-basins, which gives an average spatial resolution of approximately 450 km^2.

4. RESULTS AND DISCUSSION

The hydrological simulations have generated a large amount of time series on hydrological variables and fluxes for the land surface computational elements used by the hydrological models. Annual and seasonal mean values and annual extremes of several characteristics are presented in Figures 1, 2, 3 and 4. Evaporation was determined as the sum of all latent heat fluxes from the land surface to the atmosphere; evaporation of intercepted water, transpiration, soil evaporation and open water evaporation. Mean annual maximum snow water equivalent and mean annual minimum soil moisture are the mean values of annual maxima or minima for all years in the control or scenario periods. The entire set of results were presented by Beldring *et al.* (2006).

Maps of projected runoff changes presented in Figures 1 and 2 show that annual runoff will generally increase for the Nordic region, except for southern parts of Sweden. Latvia and some regions in southern Norway will also experience reduced annual runoff for some scenarios. Seasonal runoff change results for the HadAM3H/B2 scenario are presented in Figure 3. There will be an increase in runoff everywhere in the winter, increase in mountainous basins and inland basins in the spring, and a decline in coastal and southern basins in the spring. Decrease will occur almost everywhere in the summer with the possibility for more severe droughts. The exceptions are parts of Finland and some coastal regions in Norway. Autumn runoff will generally increase in northern and high elevation parts of the Nordic region, while a decrease is expected in southern parts. Although there are differences between the climate scenarios used in this study, the projected climate change impacts on runoff conditions in the Nordic region are relatively consistent.

In addition to the runoff maps, there are maps presenting present and future conditions and changes from the present to the future for annual maximum snow water equivalent, number of days per year with snow covered ground, and annual minimum soil moisture. Finally, maps showing evaporation changes from the present to the future have been produced. The changes in these variables for the HadAm3H/B2 scenario are presented in Figure 4.

Runoff changes in the Nordic countries are strongly linked to changes in snow regime. Snow cover will be more unstable and all scenarios indicate increase in winter and autumn runoff in areas where the snow cover has a major impact on runoff in the control climate. 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.

The projected changes in runoff differ between the two general circulation models HadAM3H and ECHAM4/OPYC3 due to different modes of natural climate variability represented by the two models. These two general circulation models result in different dominating atmospheric circulation patterns, with increasing dominance from the west in ECHAM4/OPYC3 scenarios and a more easterly pattern in the HadAM3H scenarios. This results in different distributions of precipitation, runoff and other hydrological variables (Tveito and Roald, 2005).

Furthermore, the two IPCC SRES scenarios A2 and B2 result in different projections of future radiative forcing and temperature changes, with A2 yielding the largest increase in greenhouse gas concentrations and temperature. These differences influence the hydrological cycle, leading to different changes in hydrological state variables and fluxes.

The model simulations have not considered land use changes caused by climate change or human transformation of the land surface, However, this should be taken into account, as it is likely that changes in land-cover may interact with climate, leading to different projections of future hydrological conditions. Neither were water balance simulations for future climate conditions in glacier covered areas entirely realistic since the areal extent of glaciers were assumed to be constant. There was one exception, however, a dynamical glacier model was used for modelling changes in the extent of Icelandic glaciers before the hydrological model simulations were performed (Johannesson *et al.,* 2006).

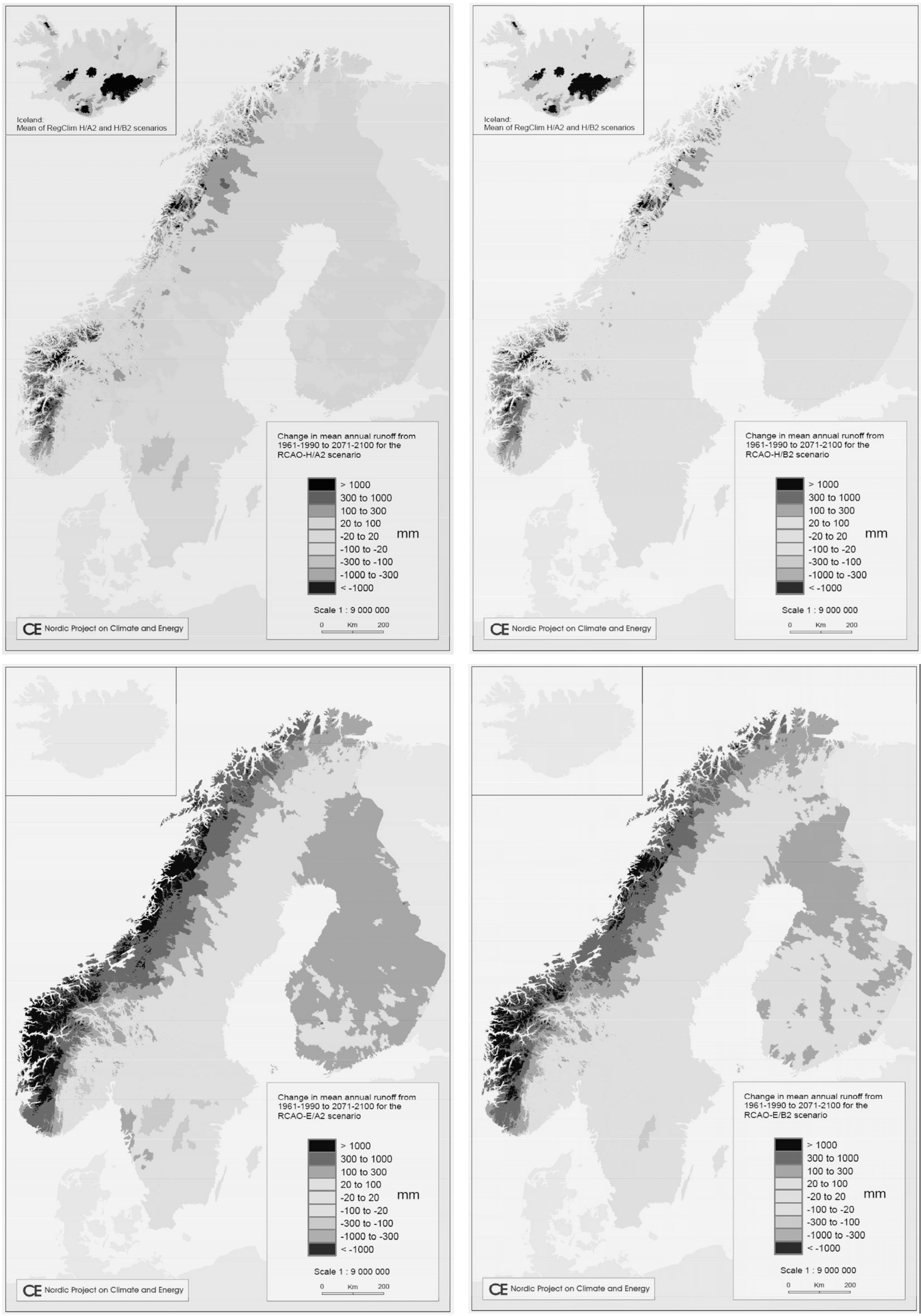

Figure 1. Change in mean annual runoff (mm) for Finland, Iceland, Norway and Sweden from 1961-1990 to 2071-2100. Top left: HadAM3H/A2 scenario. Top right: HadAM3H/B2 scenario. Bottom left: ECHAM4/OPYC3/A2 scenario. Bottom right: ECHAM4/OPYC3/B2 scenario.

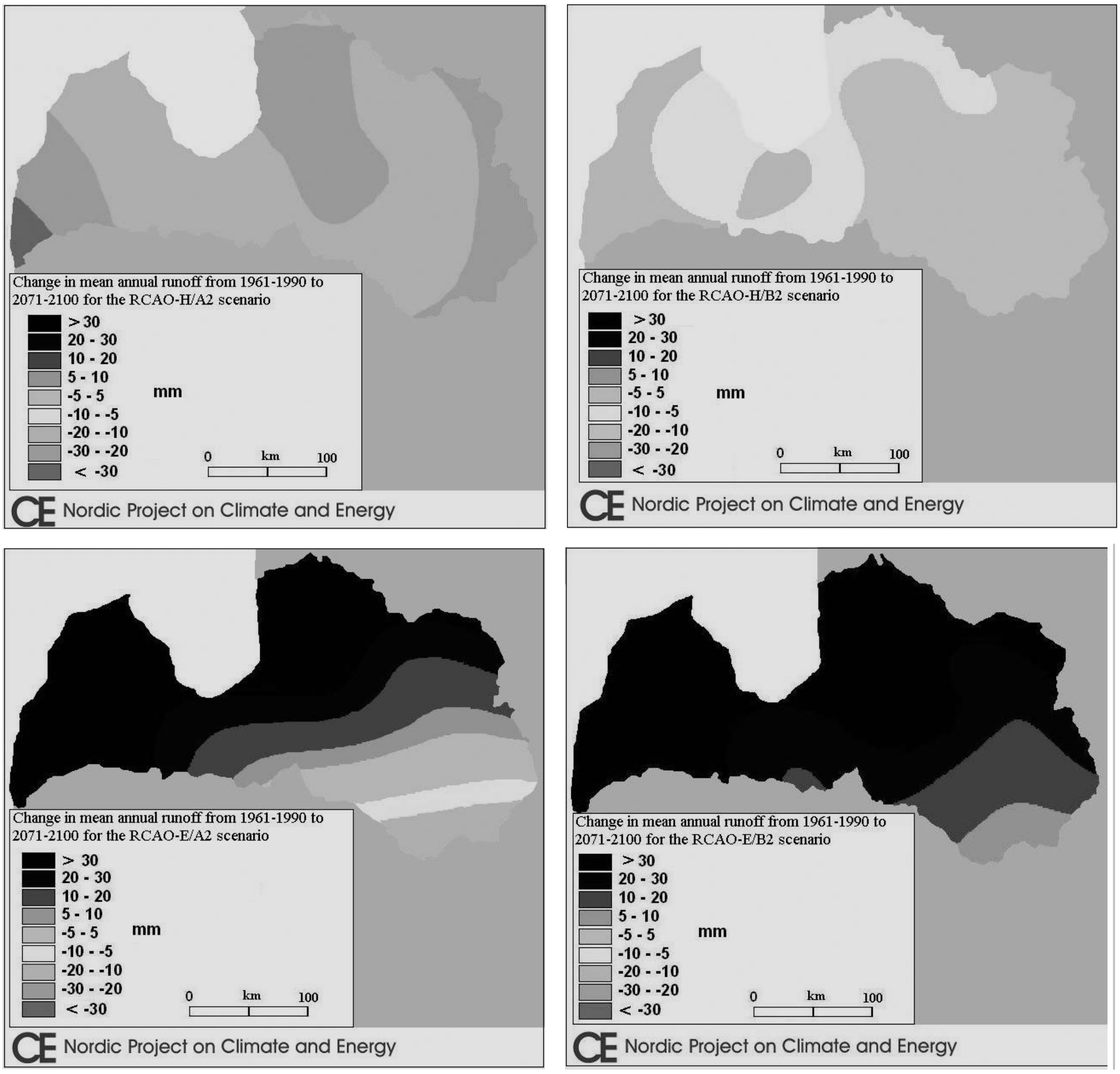

Figure 2. Change in mean annual runoff (mm) for Latvia from 1961-1990 to 2071-2100. Top left: HadAM3H/A2 scenario. Top right: HadAM3H/B2 scenario. Bottom left: ECHAM4/OPYC3/A2 scenario. Bottom right: ECHAM4/OPYC3/B2 scenario.

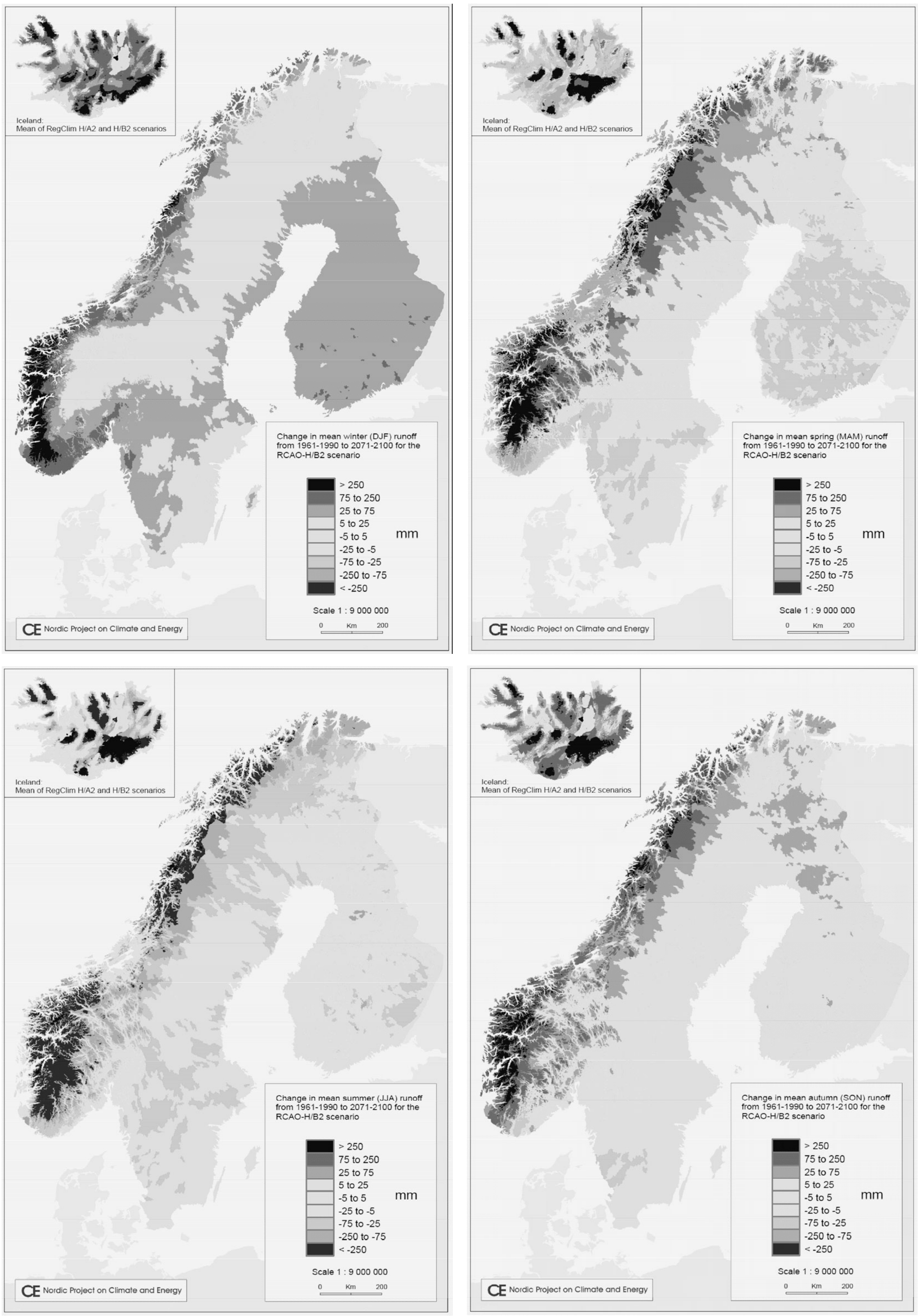

Figure 3. Change in seasonal runoff (mm) for Finland, Iceland, Norway and Sweden from 1961-1990 to 2071-2100 for HadAM3H/B2 scenario. Top left: Winter (Dec., Jan., Feb.). Top right: Spring (Mar., Apr., May). Bottom left: Summer (Jun., Jul., Aug.). Bottom right: Autumn (Sep., Oct., Nov.).

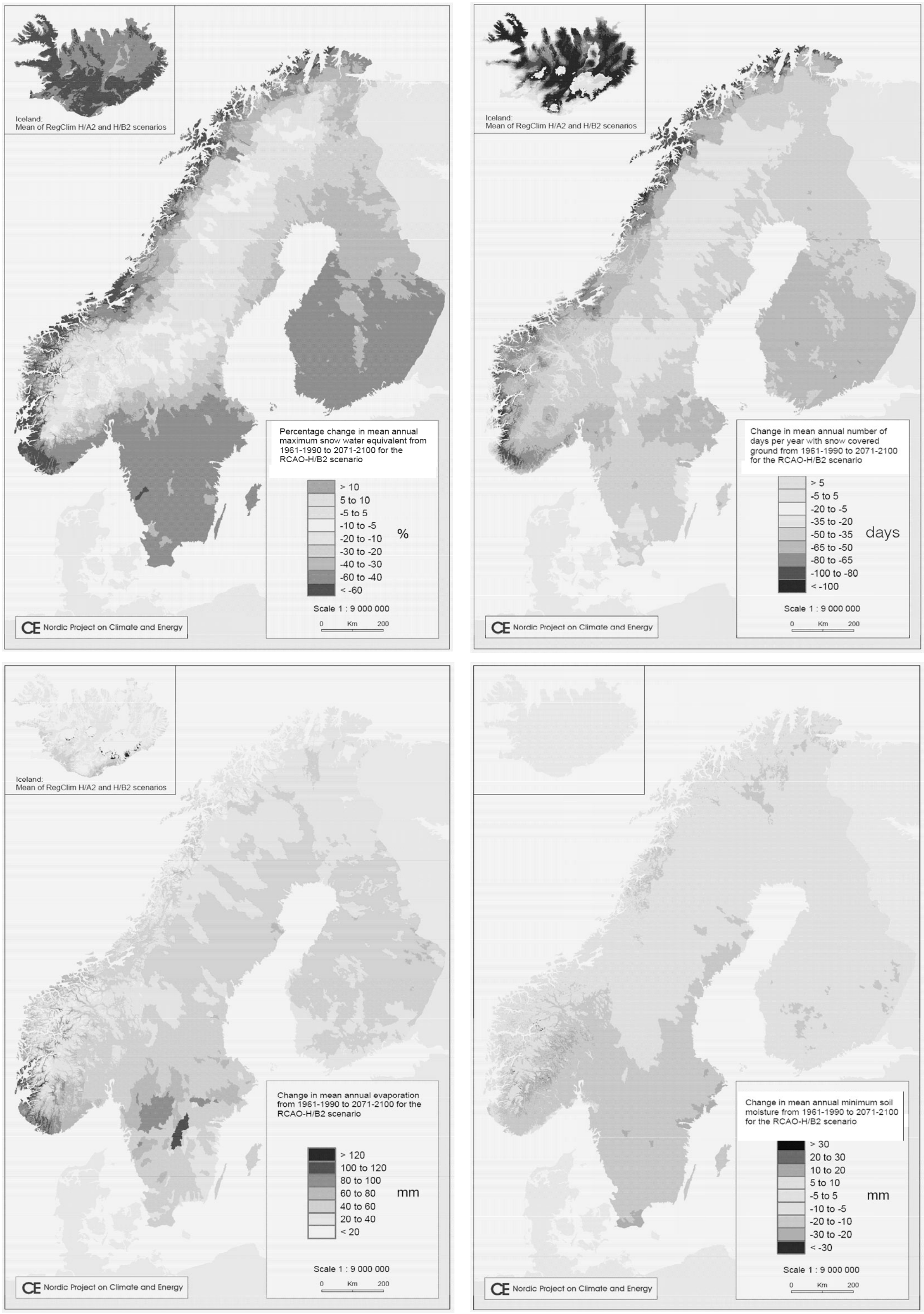

Figure 4. Changes in hydrological characteristics for Finland, Iceland, Norway and Sweden from 1961-1990 to 2071-2100 for HadAM3H/B2 scenario. Top left: Percentage change in mean annual maximum snow water equivalent. Top right: Change in mean annual no. of days per year with snow covered ground. Bottom left: Change in mean annual evaporation (mm). Bottom right: Change in mean annual minimum soil moisture (mm).

Although model structure, process parameterisation, input data and spatial resolution vary between the hydrological models applied in the different countries, the maps present a relatively consistent view of hydrological conditions in the Nordic region. Nevertheless, there are gradients in the values presented by the maps across the borders between Finland, Norway and Sweden. These gradients are too a large extent caused by differences in model structure, model calibration, spatial discretisation and interpolation of precipitation and temperature data to the computational elements of the hydrological models.

5. CONCLUSIONS

Projections of climate change impacts on water resources in the Nordic countries have been quantified using combinations of two greenhouse gas emission scenarios, two general circulation model, two regional climate models and two hydrological models. Overall the maps show an increase in the available water resources, but in some areas dryer conditions are indicated. The latter may be due to decreased precipitation or an increase in evaporation that overrides the increase in precipitation. A closer look at the seasonal maps shows that water shortage may become a problem in some locations for the summer season. The use of several global climate scenarios gives an indication of the involved uncertainties. The hydrological climate change scenarios vary due to different dominance of atmospheric circulation patterns in the general circulation models and different external forcing caused by greenhouse gas emissions.

The results from the CE project show that the impacts of global warming on the hydropower sector can be quite strong. It will shorten the Nordic winter and make it less stable. This leads to more river flow the year around, a profitable situation for the industry. There is also potential for increased production as the highest modelled increase in river flow is simulated in areas with extensive development of hydropower, i.e. the Scandinavian mountains.

Hydrological processes influence the natural environment at a range of spatial and temporal scales through their impacts on biological activity and water chemistry. Furthermore, water is 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 circulations. The water resources maps presented in this study are therefore useful for climate change impact studies in natural and social sciences where land surface hydrological conditions exert a major control on the phenomena under consideration.

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