ON INTERPRETING HYDROLOGICAL CHANGE FROM REGIONAL CLIMATE MODELS

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Abstract. Although representation of hydrology is included in all regional climate models (RCMs), the utility of hydrological results from RCMs varies considerably from model to model. Studies to evaluate and compare the hydrological components of a suite of RCMs and their use in assessing hydrological impacts from future climate change were carried out over Europe. This included using different methods to transfer RCM runoff directly to river discharge and coupling different RCMs to offline hydrological models using different methods to transfer the climate change signal between models. The work focused on drainage areas to the Baltic Basin, the Bothnian Bay Basin and the Rhine Basin. A total of 20 anthropogenic climate change scenario simulations from 11 different RCMs were used. One conclusion is that choice of GCM (global climate model) has a larger impact on projected hydrological change than either selection of emissions scenario or RCM used for downscaling.

revised version re-submitted to *Climatic Change*, June 2006

1. Introduction

This paper focuses on interpreting the hydrological response to projected changes in climate that for brevity we define as "hydrological change." Earlier work exists for a host of different drainage basins (Kaczmarek et al., 1996; Vehviläinen and Huttunen, 1997; Gellens and Roulin, 1998; Arnell, 1999; Hamlet and Lettenmaier, 1999; Middelkoop et al., 2001; Andréasson et al., 2004; Vanrheenen et al., 2004). The typical approach for such studies is to evaluate representative climate changes from the climate models and introduce these changes to a hydrological model. The majority of previous studies were based on climate change results from global general climate models (GCMs), while some included results from a regional climate model (RCM).

For this study, climate change inputs were derived from an ensemble of regional climate model (RCMs) simulations produced in the PRUDENCE Project (Christensen et al., 2006). RCMs provide a means to add regional detail to GCM simulations. Evaluating added benefits from RCMs and how additional uncertainty is introduced by using different models was a primary focus of PRUDENCE. More specific to hydrological applications is how well the hydrological cycle is represented. Although climate models include full representation of the hydrological cycle and usually resolve the overall water balance, they typically do not provide sufficient detail to satisfactorily address impacts on hydrology and water resources. Therefore, hydrological models are used.

This paper addresses how differences in the climate models affect estimates of projected hydrological change. Other changes due to direct human activity (e.g. modifications to floodplains or vegetation) are not considered here. For a suite of models applied over Europe, we evaluated the hydrological components from the RCMs by first comparing the partitioning of precipitation into evapotranspiration and runoff, and then using two different river routing schemes to compare to observed river discharge. The RCM simulations were further tested by inputting precipitation and temperature results directly into a hydrological model. Climate change impacts on river discharge were evaluated by using different methods to transfer the RCM simulation results to hydrological models (see also Graham et al., 2006). The drainage basins studied were the Bothnian Bay Basin and the entire Baltic Sea Basin in Northern Europe, and the Rhine River Basin in Central Europe (Figure 1).

1.1. THE BALTIC SEA BASIN

The Baltic Sea Basin covers some 1.6 million km^2 in 14 nations—Belarus, Czech Republic, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, Russia, Slovakia, Sweden and Ukraine. It is characterized by boreal forests in the north and agriculture in the south. The five largest rivers in descending order are Neva, Vistula, Daugava, Neman, and Oder. Several large lakes lie in the basin, including the two largest in Europe, Lake Ladoga and Lake Onega, both in Russia. There are mountains in the northwest (Scandinavian Mountains) and in the south (Carpathian Mountains). In total, 85 million people live in this region, with the highest concentrations in the south.

1.2. THE RHINE RIVER BASIN

The Rhine River Basin originates in the Alps of Central Europe and flows generally northwest to the North Sea. The total catchment contains 185,000 km^2 in 9 nations—Switzerland, Austria, Italy, Liechtenstein, Germany, France, Luxembourg, Belgium and The Netherlands. Some 50 million people live in this basin. It includes three major hydrological areas; these are Alpine, German Middle Mountain and Lowland.

1.3. REGIONAL CLIMATE MODELS USED

Due to the varying extent of RCM model domains and other limitations, all 11 PRUDENCE RCMs (Christensen and Christensen, 2006) were not used in all of the hydrological studies. Table I shows a summary of hydrological applications and the RCMs used. The majority of simulations were performed with a horizontal resolution around 50 km, using the global HadAM3H scenario A2 for boundary driving conditions. Two simulations were performed with 25 km resolution (henceforth referred to as RCAO25 and HIRHAM25). Four simulations used the global ECHAM4/OPYC3 for boundary conditions (henceforth designated with "E" after the name). For all cases, 30-year control climate simulations of present climate representing the period 1961-1990 were compared to future climate simulations representing the period 2071-2100. More detail on the RCMs and their results are found in Christensen and Christensen (2006), Déqué et al. (2006), and Jacob et al. (2006). The future climate scenarios are based on the IPCC (Intergovernmental Panel on Climate Change) A2 and B2 SRES anthropogenic emissions scenarios (Nakićenović et al., 2000).

2. Modelling and Analysis

2.1. RIVER ROUTING

Runoff generated from RCMs is the instantaneous excess water per grid square, without any translation or transformation for groundwater, lake and channel storage, or transport time. Two river routing schemes were used to convert RCM runoff to river discharge in offline applications. These are the HD Model, which was used for both the Baltic Basin and the Rhine Basin, and the RCroute scheme, which was used for the Baltic Basin. RCroute uses runoff directly from the RCMs whereas the HD Model performs its own re-partitioning of RCM precipitation into runoff and evapotranspiration. Both operate on a daily time step.

2.1.1. *HD Model*

The HD river discharge model (Hagemann and Dümenil Gates, 2001) simulates the lateral freshwater fluxes at the land surface. This has been applied and validated on the global scale, and is also part of the coupled atmosphere-ocean ECHAM5/MPI-OM GCM (Latif et al., 2003). Inputs required are daily time series of surface runoff and drainage from the soil. Applied on a standard 0.5 degree horizontal grid, these are converted into the three flow processes of overland flow, baseflow and river flow. The model parameters are functions of 1) topography gradient between gridboxes, 2) slope, 3) length, 4) lake area, and 5) wetland fraction for each gridbox.

Some modifications to the standard HD Model were needed. As only total runoff (surface runoff plus drainage) was available from the RCMs, it was necessary to partition this into representative components for fast and slow runoff responses. This was done with a simplified land surface scheme (SL), which uses daily fields of precipitation, 2 m temperature and evapotranspiration (Hagemann and Jacob, 2006).

2.1.2. *RCroute*

The RCroute scheme is the river routing module from the Rossby Centre Regional Atmosphere Ocean Model (RCAO; Döscher et al., 2002). Here, it is used in standalone mode, where input is total daily runoff generated from the PRUDENCE RCMs.

RCroute uses the same runoff response routine and subbasin delineation as HBV-Baltic (see below). It consists of a series of two linear reservoirs that represent fast and slow runoff responses. Flow recession parameters are associated with each linear reservoir for each subbasin modeled. Total runoff generation is the input to the routing routine and river discharge from the subbasins is the output. Where upstream subbasins connect to a downstream subbasin before reaching the sea, calibrated lag times were applied. The result is daily average river discharge in $m^3 s^{-1}$ to the Baltic Sea from each of the coastal subbasins.

2.2. HYDROLOGICAL MODELLING

Two hydrological models were used in this study; the conceptual rainfall-runoff HBV Model (Lindström et al., 1997) for the Baltic Basin and the physically-based distributed WASIM Model (Schulla, 1997) for the Rhine Basin. The two models were applied under substantially different considerations and scales. HBV could be used to generate many simulations of hydrological change whereas WASIM provides a more detailed distribution of hydrological results over a given basin.

2.2.1. *HBV-Baltic*

The Baltic Basin Water Balance Model—HBV-Baltic—was developed to perform large-scale hydrological modelling over the basin (Graham, 1999; Graham, 2004). It includes routines for snow accumulation and melt, soil moisture accounting, groundwater response and river routing. Although it uses large subbasins, detailed topography is included in the form of elevation zones. It operates on a daily basis using 2 m temperature and precipitation as inputs. A database of monthly runoff to the Baltic Sea (Bergström and Carlsson, 1994) was used for model calibration and verification. The simulated time period used as a baseline in this study was 1980-2003. Analysis here generally focuses on the five main Baltic Sea sub-regional drainage basins shown in Figure 1. Model performance is evaluated by the Nash and Sutcliffe (1970) efficiency criterion, R^2, which is a sum of squares function of the variance in observed river discharge to the variance in computed river discharge. The calibrated monthly efficiency criteria over the period 1980-1991 for the five sub-regional drainage basins are

0.95, 0.94, 0.81, 0.81 and 0.73, respectively, resulting in a value of 0.91 for the total Baltic Basin (a perfect fit would be 1.0; Graham, 1999).

2.2.2. *WASIM*

The Water Flow and Balance Simulation Model—WASIM—uses a horizontal grid size of 1 km for the Rhine Basin and operates on an hourly time step (Kleinn et al., 2005). It includes a soil-vegetation-atmosphere-transfer scheme (SVAT), a soil-water model, a groundwater model, and a runoff generation and routing scheme (Jasper and Kaufmann, 2003; Jasper et al., 2004). The WASIM simulations in this study cover 20 subcatchments of the Rhine River down to Cologne for a total area of 145,000 km^2. Results are summarized for river discharge stations along the Rhine at Diepoldsau, Rheinfelden, Kaub, and Cologne, as well as for Untersiggenthal on the Aare River and Cochem on the Mosel River.

2.3. TRANSFERRING CLIMATE CHANGE FROM RCMS TO HYDROLOGICAL MODELS

Transferring the signal of climate change from climate models to hydrological models is not a straightforward process as meteorological variables from climate models are often subject to systematic errors. For example, in the Alpine region, many RCMs exhibit a dry summertime precipitation bias on the order of 25% (Frei et al., 2003). Including such biases would affect hydrological simulations considerably.

Most studies of hydrological change to date have resorted to a *delta approach* (Hay et al., 2000), adding the change in climate to an observational database that is then used as input to hydrological models to represent the future climate. A major disadvantage of the delta approach is that representation of extremes from future climate scenarios effectively gets filtered out in the transfer process. The extremes resulting from this approach are simply the extremes from present climate observations that have either been enhanced or dampened according to the delta factors. More direct methods have recently been investigated. This requires modification to RCM outputs to correct for biases before transfer to hydrological models. Although such methods also have limitations, they are more consistent with the RCMs compared to the delta approach (Lenderink et al., 2006).

The studies performed here use both the delta approach, which is robust regardless of the quality of the RCMs, and more direct methods, which work best if seasonality is well-represented. The HBV Model was applied with both approaches. The WASIM Model used only a more direct, bias-correction approach.

2.3.1. *HBV Application*

The signal of climate change was transferred from the RCMs to HBV-Baltic via 2 m temperature, precipitation and evapotranspiration. As mentioned above, only *changes* between the future and the present climate simulations were used for the delta approach. Projected climate changes are most pronounced for colder temperatures (i.e. winter) in Northern Europe. Therefore, algorithms were derived from the climate simulation results to relate the magnitude of future change to present-day average daily temperatures. This provides a distribution of the change in temperature that represents the RCM simulated seasonal changes more accurately than simple monthly or seasonal means would. Trends in changes to precipitation were less systematic; these were input using monthly change factors applied to daily precipitation values.

Evapotranspiration is calculated by the hydrological model according to a temperature index method. Although this works well for present-day conditions where one can calibrate relevant parameters, there is no way to assure that this is valid for the future climate. Evapotranspiration was therefore modified in the future climate hydrological simulations so that the annual percent change matched the RCM simulations. More detail on delta procedures is found in Andréasson et al. (2004).

For the direct approach, 2 m temperature results from the RCMs was input directly per subbasin of HBV-Baltic. Biases in precipitation were adjusted with a simple precipitation scaling approach that corrected the mean annual RCM precipitation from control simulations to match the mean annual precipitation from observations used as a baseline condition. No attempt was made to perform seasonal precipitation bias corrections. A similar approach that includes seasonal corrections of both temperature and precipitation was tested for the Lule River Basin as reported by Graham et al. (2006). Evapotranspiration changes were restricted to match the respective RCM, as in the delta approach.

2.3.2. *WASIM Application*

WASIM simulations were only performed with the CHRM RCM (Vidale et al., 2003). RCM results for precipitation, 2 m temperature, net radiation, relative humidity, and wind speed were transferred from the CHRM grid (56 km) onto the WASIM grid (1 km) using parameter-specific interpolation schemes.

A simple bilinear interpolation was used for relative humidity and wind speed. For 2 m temperature, a lapse-rate approach was applied, where standardized temperatures are bilinearly interpolated to the WASIM grid and then lapsed to the elevation of the WASIM grid points. For precipitation high-resolution observational climatology was used (Schwarb et al., 2001) to introduce fine-scale precipitation patterns. This distributes precipitation within an RCM gridbox according to the climatological pattern, which is dominated by topographic features (Widmann and Bretherton, 2000).

Temperature and precipitation data from the RCM were corrected for systematic errors. The biases were determined from a simulation using the large-scale boundary conditions from the ECMWF 40-year reanalysis (ERA-40; Uppala et al., 2005) as a baseline period, compared to observed temperatures in the New et al. (2000) data set and observed precipitation in the Frei and Schär (1998) data set.

2.4. EMPIRICAL SNOW ANALYSIS

Mountain snowpack is a considerable control on surface runoff in the European Alps as it determines the timing of peak river discharge during melting in the spring and sustains discharge in numerous rivers during summer periods. Changes in temperature and precipitation will modify snow amounts and duration. However, orographic precipitation in general, and snowfall in particular, are among the most difficult variables to simulate, even at high spatial and temporal resolutions (Marinucci et al., 1995; Giorgi and Mearns, 1999).

As a complement to modelling approaches, observational studies of the behavior of the alpine snowpack were applied (Beniston et al., 2003a). This resulted in empirical relationships of how both the amount and duration of snow changes at various altitudes as a function of the type of winter (i.e., warm/moist, warm/dry, cold/moist, or cold/dry). The volume of snow in the Alps was determined under current climatic conditions (1961-1990) and departures of snow volume from average conditions during mild winters could be identified. Such information provides an analog to what could be expected in the future when similar mild winters are likely to occur with greater frequency.

3. Results for the Baltic Basin

Eight different RCMs were used for the Baltic Basin with the HD Model, RCroute and HBV-Baltic (Table I). A total of 18 scenario simulations were made with HBV-Baltic.

3.1. ANALYSIS OF THE RCMS – BALTIC

The mean annual cycle of precipitation, 2 m temperature and evapotranspiration from RCM control simulations is presented in Figure 2 for the Bothnian Bay and in Hagemann and Jacob (2006) for the total Baltic Basin. Comparison is made to GPCP (Global Precipitation Climatology Project; Huffman et al., 1997) and CMAP (CPC Merged Analysis of Precipitation; Xie and Arkin, 1997) databases. The GPCP data have been corrected for gauge losses, but this correction is reported to overestimate precipitation (Rudolf and Rubel, 2005). The CMAP data are uncorrected gauge data. One would thus expect "real" precipitation values to fall somewhere between GPCP and CMAP values. From this comparison, RCMs do a reasonable job of representing the seasonal distribution of precipitation in this region, but tend to overestimate its magnitude.

Regarding 2 m temperature, the RCM simulations are more evenly distributed around the observations. Annual biases for the total Baltic Basin range from -1.3ºC to +0.9ºC. Evapotranspiration varies considerably between the RCMs throughout the year. Results from ERA15 (ECMWF 15-year reanalysis) coincide fairly well with the multi-model ensemble mean during warm months, but are lower during cold months. This could indicate that cold season evapotranspiration is overestimated by many of the models, however there is considerable uncertainty associated with the ERA15 estimate (Hagemann et al., 2004).

An important factor in determining how well the hydrological cycle is represented by climate models is how they partition precipitation into evapotranspiration and runoff generation, as shown in Figure 3a for annual RCM values for the Baltic Basin. Results from HBV-Baltic using observations are also shown. As the latter were calibrated to observed river discharge, they should better represent the basinwide hydrological processes. Comparing these, many of the RCMs appear to overestimate evapotranspiration for the Baltic Basin, while runoff generation is underestimated.

Total river discharge from Bothnian Bay using the HD Model and RCroute for the RCM control simulations is shown in Figure 4. The two modelling approaches result in generally similar representations of the seasonal river flow. However, peak flows from the HD Model tend to occur almost one month later than those from RCroute. The magnitude of the peaks also varies between the models.

A further test of the hydrology in the RCMs used precipitation and temperature from control simulations directly in HBV-Baltic to produce estimates of river discharge, akin to Graham and Jacob (2000). Most models show overestimation of river discharge throughout the Baltic Basin, in some cases by as much as 70% more than observations (Table II). This reflects the overestimation of precipitation over this region by most of the models.

RCM generated changes in precipitation, 2 m temperature and evapotranspiration are shown in Figure 5 for the Bothnian Bay and in Hagemann and Jacob (2006) for the total Baltic Basin. Maximum changes in both precipitation and temperature occur during colder months. The model spread around the mean temperature signal is relatively small. Exceptions are HadRM3P, which deviates considerably from the other models in the summer, and CLM that shows large peaks in May. The largest increases in evapotranspiration are also shown for winter.

3.2. HYDROLOGICAL SIMULATIONS OF CLIMATE CHANGE – BALTIC

River discharge from hydrological simulations using HBV-Baltic together with RCM climate change simulations is shown in Figures 6 through 9, summarized as total inflows to the five main sub-regional Baltic Sea drainage basins and for the total Baltic Basin. The shaded area represents the present-day climate with results from HBV-Baltic using observations as model inputs for the baseline period of 1980-2003.

Figure 6 shows the A2 RCM simulations. Results between the different models for the HadAM3H simulations generally follow a similar pattern with the exception of more pronounced deviation by two models in late summer and early autumn. This is most clearly seen in the plot for the total Baltic, which is the accumulation of flow from all of the basins. The two simulations available using ECHAM4/OPYC3 show higher mean river discharge in all basins except for the Baltic Proper, compared to the HadAM3H simulations.

Figure 7a shows the B2 RCM simulations. Here again, the ECHAM4/OPYC3 simulations show higher future river discharge through most of the Baltic Basin as compared to HadAM3H. Figure 7b shows results according to variations in RCM resolution, including two RCMs at 50 km and 25 km resolution shown together with a hydrological simulation using HadAM3H (150 km). Little difference is apparent for the northernmost Bothnian Bay, but differences increase for basins further south and east. Although not shown here, larger differences are found for Bothnian Bay if one looks separately at the western part of the basin versus the eastern part.

Figure 8a shows results using direct input of precipitation and 2 m temperature from the control simulations after precipitation scaling to present-day observations. As only annual precipitation amounts were adjusted, the seasonal distribution of precipitation comes directly from the RCMs. Figure 8b shows results after applying the same precipitation scaling factors to the corresponding A2 scenarios of these RCMs. Although there are obvious differences between the three model simulations shown, they all differ considerably in character from the A2 delta approach simulations (Figure 6a). Both peak flows and low flows from the precipitation scaling approach are higher and lower, respectively, compared to the delta approach. The considerably lower river flow for the RACMO simulations for the eastern and southern basins (Gulf of Finland, Gulf of Riga, Baltic Proper) follows from lower precipitation in the RACMO-H/A2 simulation.

Figure 9 shows the period maximum and minimum values corresponding to the same 50 km scenario simulations using precipitation scaling (Figure 8). Also shown are values from the corresponding delta approach simulations. The simulations with the scaling approach show different patterns of extremes that more closely reflect the variability coming from the RCMs. The maximum and minimum curves from the delta approach follow each other quite closely, showing little difference between the two simulations.

Figure 10 shows routed river discharge from RCM-A2 scenario simulations for the Bothnian Bay Basin from the HD Model and RCroute. Both applications show similar trends of increased river flow for winter/spring months and decreases during summer, which are in agreement with the offline HBV-Baltic results above. However, the range of differences between RCM simulations is much greater for RCroute than for HD, particularly during cold season months.

4. Results for the Rhine Basin

Ten different RCMs were used by the HD Model for the Rhine Basin (Table I). The WASIM Model used only the CHRM RCM simulations; these are referred to as WASIM-CTRL, WASIM-A2 and WASIM-ERA40 (see section 2.3.2) in the remainder of the paper.

4.1. ANALYSIS OF THE RCMS – RHINE

The mean annual cycle for precipitation and evapotranspiration from ten RCM control simulations over the Rhine Basin is presented in Hagemann and Jacob (2006), and compared with observations from the GPCP and CMAP. The models all show a similar seasonal distribution for precipitation, with a common drying problem apparent in September. Many of the models also tend to overestimate precipitation in the spring. For evapotranspiration, the range between the models is quite large and particularly pronounced during the warm summer months, although the multi-model ensemble mean tends to agree well with ERA15. Partitioning of annual RCM precipitation into evapotranspiration and runoff generation is shown in Figure 3b. Almost all of the RCMs show a higher percentage of runoff for the Rhine Basin than for the Baltic Basin. River discharge simulated directly from the RCM control simulations with the HD Model is shown in Figure 11. For all of the models, peak discharge is out of phase with observations. This delayed peak is partly caused by insufficient representation of the complex snow processes in the Alpine part of the Rhine Basin in the SL scheme (Hagemann and Jacob, 2006).

RCM generated changes in precipitation, 2 m temperature and evapotranspiration are shown in Figure 12 for the Rhine Basin. Although the RCMs follow similar trends throughout the year, large differences are apparent, particularly in summer and autumn. Maximum temperature change is shown for the summer months, with a peak in August for most RCMs. HadRM3P deviates considerably from the other models and RCAO shows a large deviation in August. Regarding precipitation, an increase is shown for mid to late winter, a considerable decrease is shown for summer, and autumn months oscillate between increases and decreases.

Evapotranspiration for summer months remains almost unchanged for most models, likely as a result of low soil moisture values due to the warmer, dryer future climate. Exceptions are HadRM3P and PROMES, which show considerable decreasing and increasing values, respectively. During wetter winter months, warming enhances evapotranspiration.

4.2. HYDROLOGICAL SIMULATION OF CLIMATE CHANGE – RHINE

Looking first at the performance for the present climate, Figure 13a compares Rhine river discharge from the bias-corrected WASIM-CTRL and WASIM-ERA40 simulations to observations. The simulations reproduce the predominant pattern of the mean seasonal river discharge cycle at Cologne. Also the characteristic regime change along the river course

(Disse and Engel, 2001) is captured, from predominantly snowmelt dominated with peak discharge in early summer (e.g. Diepoldsau) to rainfall dominated with peak discharge in winter (e.g. Cologne). However, for the upper reaches of the basin at Diepoldsau and Rheinfelden, the spring snowmelt peak is underestimated and occurs approximately one month too late. Mean river discharge at downstream Kaub and Cologne is overestimated, particularly for late summer and autumn.

Figure 13b shows Rhine river discharge from WASIM-A2 compared to WASIM-CTRL. An overall decrease in runoff for summer and autumn is apparent, reaching up to 40%. This primarily reflects the substantial decrease in mean summer precipitation. In late winter and early spring, runoff increases at downstream Kaub and Cologne, reflecting a change in regime for the larger lower elevation subbasins. These changes result from decreased winter snow storage combined with increased precipitation and a shift in the winter maximum precipitation to later months. For Alpine catchments at Diepoldsau and Rheinfelden, the spring snowmelt peak occurs about one month earlier with a reduced magnitude of some 20% from the control simulation.

Figure 12d shows change in Rhine river discharge simulated by the HD Model directly from the RCM-A2 scenario simulations. As with the WASIM-A2 simulation, the largest changes occur as decreases from summer to early winter. River discharge increases for late winter and spring. Figure 14 compares change in river discharge using the CHRM RCM in both the HD Model and WASIM. The two approaches agree for the overall trend of change.

4.3. CONSIDERATION OF SNOW IN THE ALPS

Large Alpine areas in the Rhine Basin exceed elevations of 1000 m.a.s.l. and have seasonal snow cover with a duration of some 70 days or more per year for the present climate, on average (Schär et al., 1998). Using results from WASIM, snow cover duration can be shown in relation to elevation. Figure 15 shows vertical snow profiles for the control and A2 scenario simulations from a combined Alpine area with elevations predominantly exceeding 1000 m.a.s.l. The reduction in the annual number of snow cover days in the scenario is 75-100 days at 1500 to 3000 m.a.s.l. At 1000 m.a.s.l., duration goes from about 50 days at present to about 7 days for the future. These changes correspond to a vertical shift of snow conditions by approximately 500 m.

The empirical snow analysis examined average observed snow volume in the Alps as a function of elevation for the present long-term mean and for winters where the average temperature was 4°C warmer than the long-term mean. The maximum snow volume is observed at an altitude of about 2000 m.a.s.l. and tails off both above and below this level. Reduction in snow volume during the warm winters is close to 95% at the 1000 m level, some 40% at 2000 m, and only about 10% at elevations above 3500 m. This suggests that warm conditions at low elevations would lead to little or no snow, while changes at very high elevations would be minor. The 4°C temperature criterion corresponds to scenario changes from many of the PRUDENCE RCMs for the Alps.

Empirical methods combined with climatological data (Beniston et al., 2003a) were also used to estimate the duration of snow cover as a function of mean winter temperature and precipitation, as shown in Figure 16. Superimposing projected future climate change onto the chart shows that an increase in mean winter minimum temperature of 4°C would reduce the length of the snow season by more than 100 days at sites such as Säntis (eastern Switzerland) and Arosa (south-eastern Switzerland). Such estimates can be viable as the simulated increase in winter precipitation for the climate scenarios only slightly offsets the influence of warming and temperature is the dominant control on snow duration and seasonal snow accumulation (Beniston et al., 2003b). The empirical result using CHRM-A2 scenario changes leads to similar conclusions about snow cover duration to those from the WASIM Model.

5. Discussion

The primary goal of hydrological change studies (as defined here) is to obtain a plausible estimate of projected future climate impacts on hydrology and water resources. None of the methods investigated here are completely satisfactory in their approach. However, taken as a whole this work provides new insights.

All of the steps used in downscaling from the global climate to local hydrological regimes add some transformation of climate information. Using multiple RCMs helps identify how much the hydrological change signal can vary due to using different dynamical models to go from global to regional scale. Using different hydrological approaches helps identify how much the signal can vary due to hydrological modelling.

Analysis of outputs from the RCMs themselves indicates that most of the RCMs do not provide a reasonable apportioning of the hydrological cycle for the Baltic Basin. A much larger portion of precipitation goes to evapotranspiration than to runoff generation, in excess of what is expected for this northern climate. The case of RCAO-E is an exception and shows slightly more runoff than evapotranspiration. HIRHAM-E shows more evapotranspiration than the HIRHAM simulation. If these two cases are representative, it appears that apportionment of the hydrological cycle in the models is also sensitive to the driving GCMs. For the Rhine, there is generally more variation between models, however most show a smaller percentage of precipitation going to evapotranspiration than for the Baltic. Thus, the RCMs show a gradient with higher apportionment of precipitation going to evapotranspiration in Northern Europe than in Central Europe.

Runoff generation from the RCM simulations was also investigated with two river routing models. This resulted in a wide range of results, both in timing and magnitude, reflecting both model biases in precipitation and how the respective models partition precipitation into runoff. For some models river discharge shows considerable deviation from observations even though precipitation may be reasonably represented. For others, overestimation of evapotranspiration helps to dampen biases of overestimated precipitation. Comparing routing methods, the HD Model performs its own precipitation partitioning and enhances the RCM results. This qualitatively improves the seasonal distribution of river discharge, although annual peak flows lag after observed peaks. RCroute uses a simpler approach, which gives a more stringent comparison of RCM runoff outputs.

The RCM simulations were also tested by inputting precipitation and temperature results directly into a hydrological model. Results from this rather tough test are a further indication of the overestimation of precipitation from all models. This shows by example why hydrological change studies require an interface between climate models and hydrological models. As seen in this ensemble of simulations, annual river discharge from a continental scale basin can deviate from observations by +6% to +72% for the same representative period (1961-1990) if no scaling of present RCM inputs is performed.

For the Baltic Basin, a number of hydrological change simulations were carried out using the delta approach to transfer the climate change signal from RCMs to a hydrological model. The range of outcomes from an ensemble of RCMs driven by the same GCM with the same emissions scenario represents the uncertainty due to using different RCMs. For RCMs driven by HadAM3H, this range is fairly narrow. The largest deviation occurs in late summer and autumn months for the Gulf of Finland and other eastern drainage basins. According to Kjellström and Ruosteenoja (2006), the climate change signal for precipitation in this area is affected by different approaches in the RCMs to represent feedback from the Baltic Sea itself, in particular anomalously high sea surface temperatures (SSTs).

Further applications of the delta approach included looking at varying effects from using a different GCM, different emissions scenarios and different RCM resolutions. Use of

ECHAM4/OPYC3-A2 produced considerably different river discharge response than simulations using HadAM3H-A2. This difference is also clearly seen in simulations from the B2 scenarios. These differences generally exceed the differences between RCM simulations driven by the same GCM.

Results using different RCM resolutions with the delta approach are less conclusive. There is little difference in hydrological change simulations for the Bothnian Bay Basin, regardless of whether one uses RCMs with 25 or 50 km, or HadAM3H at 150 km resolution. The Bothnian Bay may be less sensitive in this application due to a combination of coarse resolution in HBV-Baltic, and a hydrological regime dominated by energy-limited snow hydrology (Bowling et al., 2003). Differences are more apparent in other drainage basins, where using HadAM3H deviates considerably from all of the RCM simulations. However, the finer resolution RCM simulations resulted in only slightly higher river flow than simulations using the same model at coarser resolution. A possible explanation for this is that the delta approach does not fully take advantage of differences that result in RCMs due to increasing resolution.

Use of precipitation scaling as a transfer method to hydrological models provides results that are more consistent with the RCMs. Although past studies have calculated changes to such variables as the 100-year flow (e.g. Bergström et al., 2001), such results are of limited use when based upon the delta approach. In comparison, hydrological simulations with precipitation scaling provide representation of changes in variability. However, RCM simulations with large biases in the seasonal cycle do not respond well to simple precipitation scaling. This leads to additional scaling to get good representation of hydrological regimes in the present climate (Graham et al., 2006). This methodology shows promise, but one must keep in mind the alterations that are made to the RCM results, and the important assumption that RCM model biases in the future climate are systematically the same as in the control climate. The more scaling applied, the further away one gets from "direct" use of the RCM.

Regarding hydrological change from river routing techniques, the magnitude of these results are highly influenced by RCM biases. They are best used when expressed as percent change in river discharge. Despite large differences in individual RCM simulations, the overall signal of the response is in agreement between the HD Model and RCroute. These are also qualitatively in agreement with the results using HBV-Baltic. However, choosing a single RCM as a basis for further impact study, e.g. socio-economic response, would result in quite different answers depending on the model used. Results from the HD Model show a narrower range of uncertainty around the mean than those from RCroute. This is likely due to more consistency in partitioning precipitation to runoff with the SL scheme (Hagemann and Jacob, 2006).

High resolution hydrological change simulations using the WASIM model for the Rhine Basin provide detailed modelling of hydrological regimes at a horizontal resolution of 1 km and a timestep of 1 hour. Although results are promising, one should question their applicability at the finest scales of the model. It is also evident that WASIM is less skillful in Alpine catchments compared to flatland catchments. As precipitation scaling was used, one explanation is inadequate precipitation distribution over the Alps in the CHRM simulation (Kleinn et al., 2005). Additional factors include the lack of a glacier model, and lack of lake retention and regulation in WASIM, all of which become more important the finer the resolution of the model.

The percent change in river discharge from the HD Model over the Rhine Basin is in basic agreement with WASIM at Cologne. Change in river discharge from the other nine RCMs provides some estimate of the general uncertainty in hydrological change from these models over the Rhine Basin. This range is considerably narrower than shown for the Bothnian Bay.

This implies that the RCMs react with a more unanimous signal of hydrological change for the Rhine than for Bothnian Bay farther north.

Recognizing the complexity of representing the Alps with numerical models, an alternative approach is the use of empirical methods to estimate changes in the snowpack. The methods presented here complement modelling techniques by providing an independent check on model results. An application would be to use these relationships as a type of updating approach within the models themselves, although this warrants further investigation.

6. Conclusions

6.1. MODEL OUTCOMES

Using different RCMs with the same GCM forcing and emissions scenario results in similar hydrological trends. Using different GCMs for forcing the RCMs has more effect on hydrological impacts than using different RCMs with the same GCM forcing. Partitioning of precipitation into evapotranspiration and runoff varies widely between RCMs and many tend to overestimate evapotranspiration in the Baltic Basin. Use of the delta approach to transfer climate change to hydrological models offers a robust method to compare average outcome from different climate models, but not hydrological extremes. Using a scaling approach better preserves changes in variability from the RCMs, however successful use of precipitation scaling varies between RCMs. River flow routing of RCM runoff can be used to analyse both model performance and scenario trends, but regard must be given to the precipitation biases that most RCMs show.

6.2. PROJECTED BALTIC BASIN HYDROLOGICAL IMPACTS FROM FUTURE SCENARIO SIMULATIONS

Summer river flows show a decrease of as much as -16% , while winter flows show an increase of up to 54%, on average for the total Baltic Basin. Annual river flows show an increase in the northernmost catchments, while the southernmost catchments show a decrease. The occurrence of medium to high river flow events shows a higher frequency. High flow events show no pronounced increase in magnitude on the large scale. The greatest range of variation in flow due to different RCMs occurs during summer and autumn.

6.3. PROJECTED RHINE BASIN HYDROLOGICAL IMPACTS FROM FUTURE SCENARIO SIMULATIONS

Summer and autumn river flows show a decrease of as much as -42% , while winter flows show an increase of up to 14%, on average for the Rhine Basin. Most of the winter river flow increase comes from lowland catchments. Winter river flow increase for lowland catchments is cancelled out by a decrease in alpine catchments in some years. Snowpack volume in Alpine catchments could be reduced by up to 60% and snowmelt peak flows shift to occur earlier in the season. Snowpack duration in Alpine catchments shows a reduction of about 3 weeks for each degree (ºC) of warming.

6.4. SOCIO-ECONOMIC RELEVANCE

The water sector must oversee the management of both excess and scarcity of water in society. Specific applications of relevance include, among others, municipal and industrial water supply, hydropower, flood prevention, drought management, irrigation management, dam safety, storm sewer design and maintenance, and nutrient transport analysis. Identification of potential trends for change thus has both strategic and policy implications.

Conclusions about model outcomes provide an indication of how large the range of uncertainties is according to different model combinations and configurations. This provides insight into the error sources of impacts assessments. It also highlights how impact assessment results can vary with different hydrological methods.

Conclusions about the specific river basin impacts provide initial insight to decisionmakers on how hydrological regimes in these areas will respond to projected climate change. For some sectors this overview may be enough to initiate preliminary action; for others this may identify where further or more detailed studies are needed.

Acknowledgements

This work was carried out within the PRUDENCE Project with funds from the European Commission's Programme Environment and Climate (Contract No. EVK2-CT-2001-00132). It was also supported in part by the Swiss Ministry for Education and the Swiss National Science Foundation (NCCR). The HadAM3H data were provided by the Hadley Centre of the United Kingdom Meteorological Office. The ECHAM4/OPYC3 data were provided by the Max Planck Institute for Meteorology in Germany and the Danish Meteorological Institute (DMI). CRU data were supplied by the Climate Impacts LINK Project (UK Department of the Environment Contract EPG 1/1/16) on behalf of the Climatic Research Unit, University of East Anglia. PRUDENCE RCM results were provided by the participating regional modelling centers in the project. Special recognition is given to Ole Bøssing Christensen (DMI) for design, maintenance and support of the PRUDENCE data center, and to Anders Ullerstig (SMHI) for processing RCM results for use in the hydrological modelling. The authors also wish to acknowledge Christoph Frei (ETH), Jan Kleinn (ETH) and Daniela Jacob (MPI), researchers who provided both hands-on contributions and scientific guidance in this work.

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Table I Summary of RCM simulations used in this study. Each “x” indicates a projected hydrological change simulation. The table headings specify boundary GCM, hydrological basin, hydrological application, SRES emissions scenario and approximate RCM resolution.

Table II Mean annual river discharge from HBV-Baltic using direct input of precipitation and 2 m temperature from RCM control simulations. Most of the RCM simulations used boundary conditions from HadAM3H. Two RCMs used boundary conditions from ECHAM4/OPYC3 and are specified with “-E” in the model name. Observations shown in the top row are from 1961-1990. The separate column to the right shows the percent difference between each control simulation and observations for the total Baltic Basin.

Figure 1. Location map of basin study areas.

Figure 2. a) Precipitation, b) 2 m temperature and c) evapotranspiration from RCM control simulations for the Bothnian Bay Basin.

Figure 3. RCM partitioning of precipitation into evapotranspiration and runoff generation over a) the total Baltic Basin and b) the Rhine Basin. All used HadAM3H boundary conditions with the exception of two that used ECHAM4/OPYC3 (marked with “E”). HBV-Baltic results using observations are also shown in a) (HBV-base).

Figure 4. Routed river discharge from RCM control simulations for the Bothnian Bay Basin from a) HD Model and b) RCroute.

Figure 5. Change in a) precipitation, b) 2 m temperature and c) evapotranspiration from RCM-H/A2 scenario simulations for the Bothnian Bay Basin. The pronounced percent increases in c) for some models reflects the relatively small evapotranspiration values generated for the control climate.

Figure 6. Mean daily river discharge from HBV-Baltic using the delta approach for RCM-A2 scenarios at ~50 km resolution, driven by a) HadAM3H and b) ECHAM4/OPYC3. Shown in gray shading is the present climate.

Figure 7. Mean daily river discharge from HBV-Baltic using the delta approach for a) RCM-B2 scenarios at ~50 km resolution driven by HadAM3H and ECHAM4/OPYC3, and b) RCM-A2 scenarios driven by HadAM3H at resolutions of ~25 km and ~50 km, and HadAM3H at ~150 km. Shown in gray shading is the present climate.

Figure 8. Mean daily river discharge from HBV-Baltic using the precipitation scaling approach for three RCMs driven by HadAM3H-A2 for a) control simulation, and b) scenario simulation. Shown in gray shading is the present climate.

Figure 9. Model period maximum and minimum daily river discharge from HBV-Baltic using both the precipitation scaling approach and the delta approach for two RCMs (RACMO and RCAO) driven by the HadAM3H-A2 scenario. Shown in

gray shading are corresponding maximum and minimum values for the present climate.

Figure 10. Percent change in routed river discharge from RCM-A2 scenario simulations for the Bothnian Bay Basin from a) HD Model and b) RCroute.

Figure 11. HD Model routed river discharge from RCM control simulations for the Rhine Basin.

Figure 12. Change in a) precipitation, b) 2 m temperature, c) evapotranspiration and d) HD Model routed river discharge from RCM-H/A2 scenario simulations for the Rhine Basin.

Figure 13. Mean monthly river discharge at four locations along the Rhine River for a) the WASIM-CTRL and WASIM-ERA40 simulations, and b) the WASIM-H/A2 simulation. Cologne is shown with bolder lines to emphasize that it is the most downstream location.

Figure 14. Comparison of WASIM and HD Model generated Rhine river discharge changes at Cologne using the CHRM-H/A2 scenario.

Figure 15. Snow duration versus elevation from WASIM-CTRL and WASIM-H/A2 simulations for the combined Alpine area of Aare, Limmat, Reuss and Rhine subbasins.

Figure 16. 2-D contour surfaces of snow cover duration as a function of winter (DJF) minimum temperature and precipitation, based on climatological data from 20 sites in Switzerland. The numbered isolines refer to the length of the snow season in days. Superimposed on the contour surface is temperature/precipitation/snow-duration data for Arosa (1865 m.a.s.l.) and Säntis (2500 m.a.s.l.) for both current climate conditions and projections of the last three decades of the 21st century. Arrows indicate change from current to future climate conditions.

Table I

Summary of RCM simulations used in this study. Each “x” indicates a projected hydrological change simulation. The table headings specify boundary GCM, hydrological basin, hydrological application, SRES emissions scenario and approximate RCM resolution.

	HadAM3H (150 km)							**ECHAM4/ OPYC3 (250 km)**	
	Baltic Basin					**Rhine Basin**		**Baltic Basin**	
	HBV-Baltic			Rcroute	**HD Model**	**HD Model**	**WaSIM**	**HBV-Baltic**	
RCM	**A2 50 km**	**B2 50 km**	**A2 25 km**	**A2 50 km**	**A2 50 km**	**A2 50 km**	**A2 50 km**	**A2 50 km**	**B2 50 km**
REMO	x			x	x	x			
HIRHAM (HIRHAM25)	x		x	x	x	x		x	x
CLM	x			x	x	x			
RACMO	x			x	x	x			
ARPEGE*	x	x			x	x			
CHRM	x			x	x	x	x		
HadRM3H	x								
HadRM3P	x	x		x	x	x			
RCAO (RCAO25)	x	x	x	x	x	x		x	x
PROMES						x			
RegCM						x			

(*ARPEGE is technically a GCM, but it uses a variable resolution grid that corresponds to RCM resolution over Europe, see Déqué et al., 2006.)

Table II

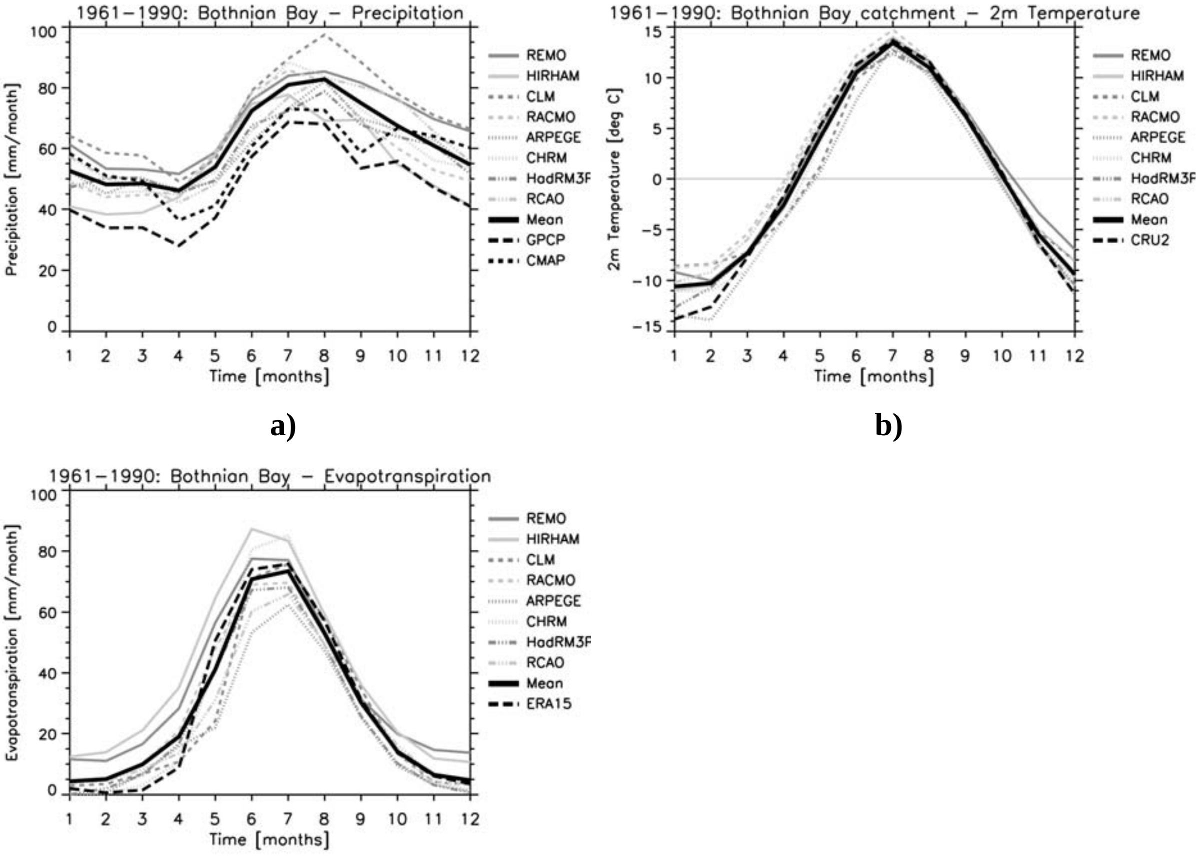
Mean annual river discharge from HBV-Baltic using direct input of precipitation and 2 m temperature from RCM control simulations. Most of the RCM simulations used boundary conditions from HadAM3H. Two RCMs used boundary conditions from ECHAM4/OPYC3 and are specified with "-E" in the model name. Observations shown in the top row are from 1961-1990. The separate column to the right shows the percent difference between each control simulation and observations for the total Baltic Basin.

	River Discharge (m^3/s) from the main Baltic Sea sub-regional drainage basins and the total basin						
	BB	**BS**	**GOF**	**GOR**	**BP**	**BT**	**BT**
Observations	3108	2893	3540	994	3675	14210	**% difference**
REMO	4923	4296	5924	1295	5481	21918	+54%
HIRHAM	3667	3184	3703	767	3690	15011	+6%
HIRHAM-E	4411	4212	6010	1423	6648	22705	+60%
HIRHAM25	3814	3279	4157	870	4202	16322	+15%
CLM	3814	3311	4375	944	4288	16733	+18%
RACMO	3941	3684	4828	1162	4874	18489	+30%
ARPEGE	4545	4607	6577	1540	7210	24479	+72%
CHRM	4509	3889	5401	1280	4685	19763	+39%
HadRM3H	4124	3960	5160	1106	5021	19371	+36%
HadRM3P	3912	3470	4001	815	4005	16204	+14%
RCAO	4239	4033	4695	1173	4966	19106	+34%
RCAO-E	4375	4714	6181	1658	7271	24199	+70%
RCAO25	4778	4299	5110	1156	5374	20717	+46%

(*BB* – Bothnian Bay, *BS* – Bothnian Sea, *GOF* – Gulf of Finland, *GOR* – Gulf of Riga, *BP* – Baltic Proper, *BT* – total Baltic Basin)


Bothnian Bay
Bothnian Sea
Gulf of Finland
Baltic Sea
Gulf of Riga
Baltic Proper
Rhine

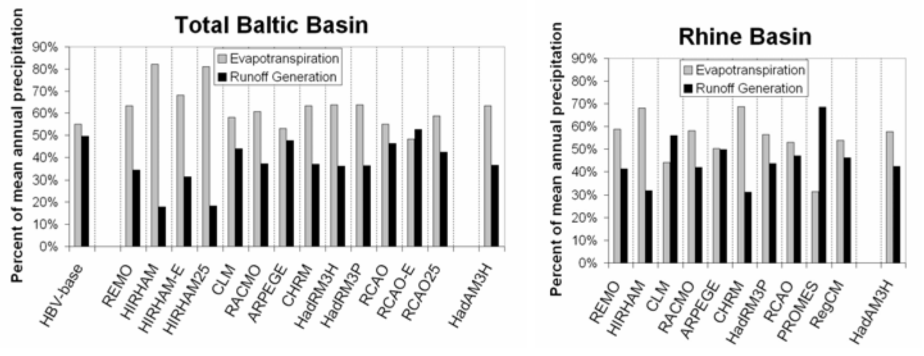
Figure 1.



a) b)

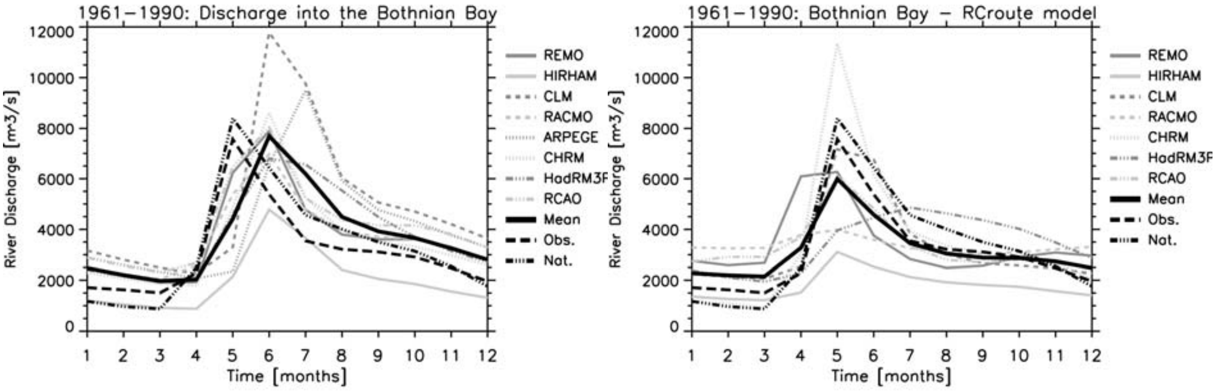
c)

Figure 2.



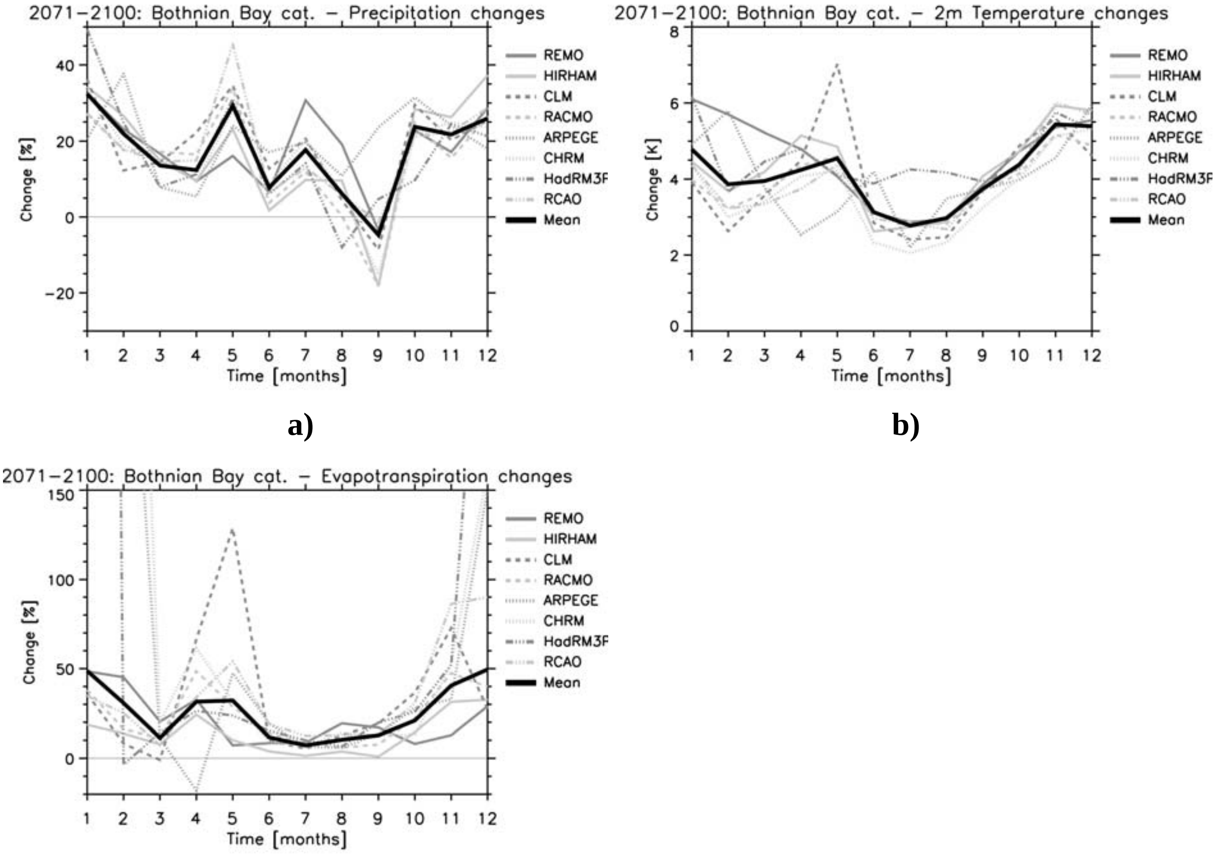
a) b)

Figure 3.



a) **b)**

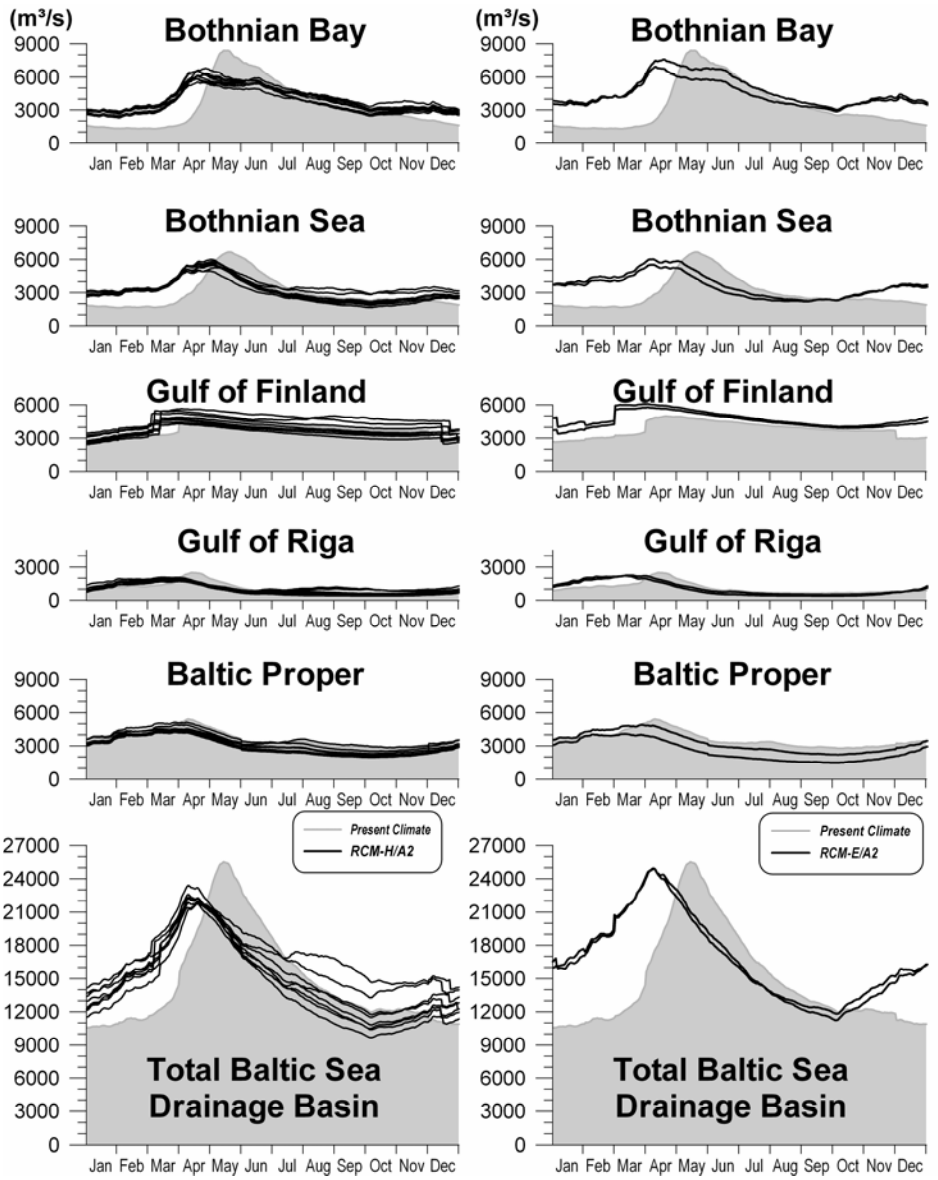
Figure 4.



a) **b)**

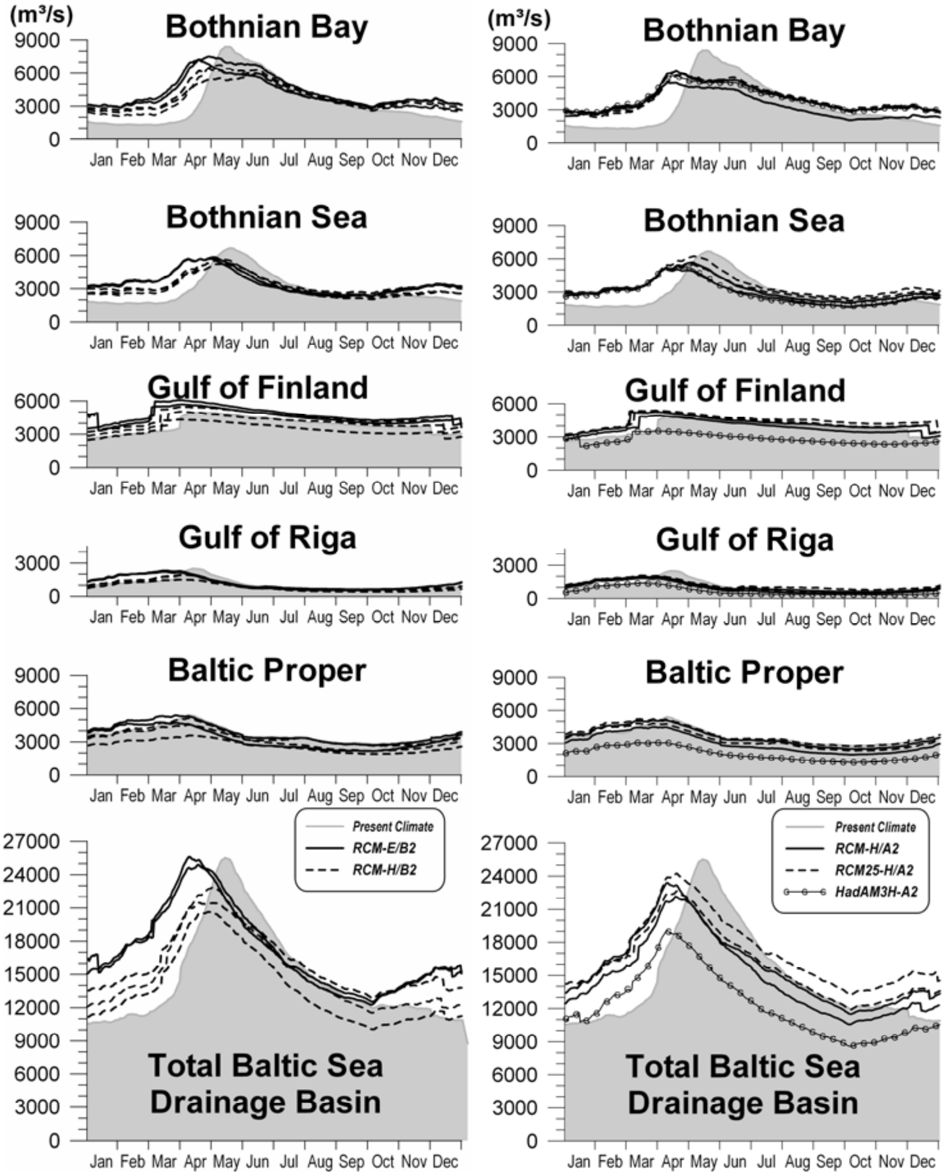
c)

Figure 5.


(m³/s)
Bothnian Bay
9000
6000
3000
0
Bothnian Sea
Gulf of Finland
Gulf of Riga
Baltic Proper
27000
24000
21000
18000
15000
12000
Total Baltic Sea Drainage Basin
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Present Climate
RCM-H/A2
RCM-E/A2

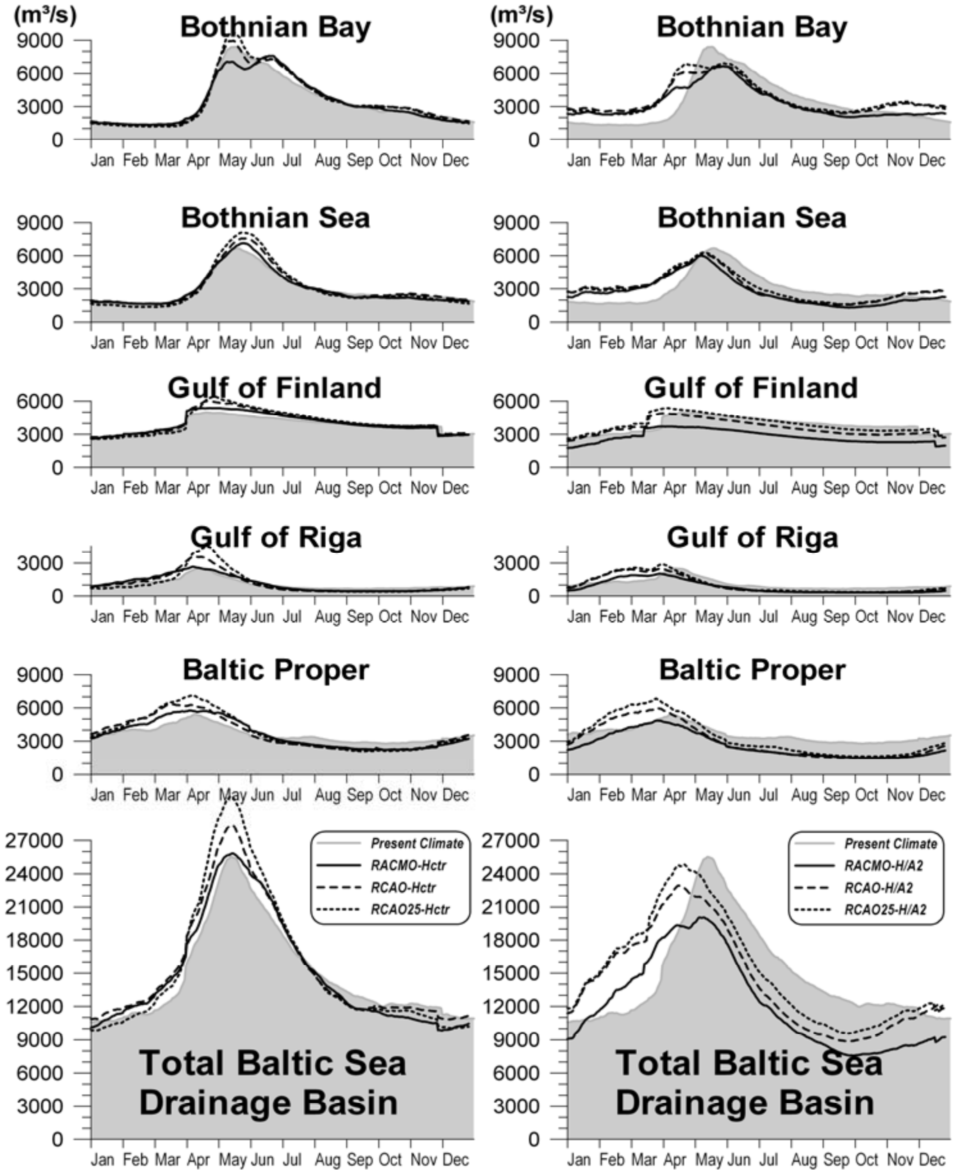
a) **b)**

Figure 6.


(m³/s)
Bothnian Bay
Bothnian Sea
Gulf of Finland
Gulf of Riga
Baltic Proper
Total Baltic Sea Drainage Basin
9000
6000
3000
0
27000
24000
21000
18000
15000
12000
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Present Climate
RCM-E/B2
RCM-H/B2
RCM-H/A2
RCM25-H/A2
HadAM3H-A2

a) b)

Figure 7.


(m³/s)
Bothnian Bay
9000
6000
3000
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Bothnian Sea
Gulf of Finland
Gulf of Riga
Baltic Proper
27000
24000
21000
18000
15000
12000
Total Baltic Sea Drainage Basin
Present Climate
RACMO-Hctr
RCAO-Hctr
RCAO25-Hctr
RACMO-H/A2
RCAO-H/A2
RCAO25-H/A2

a) **b)**

Figure 8.

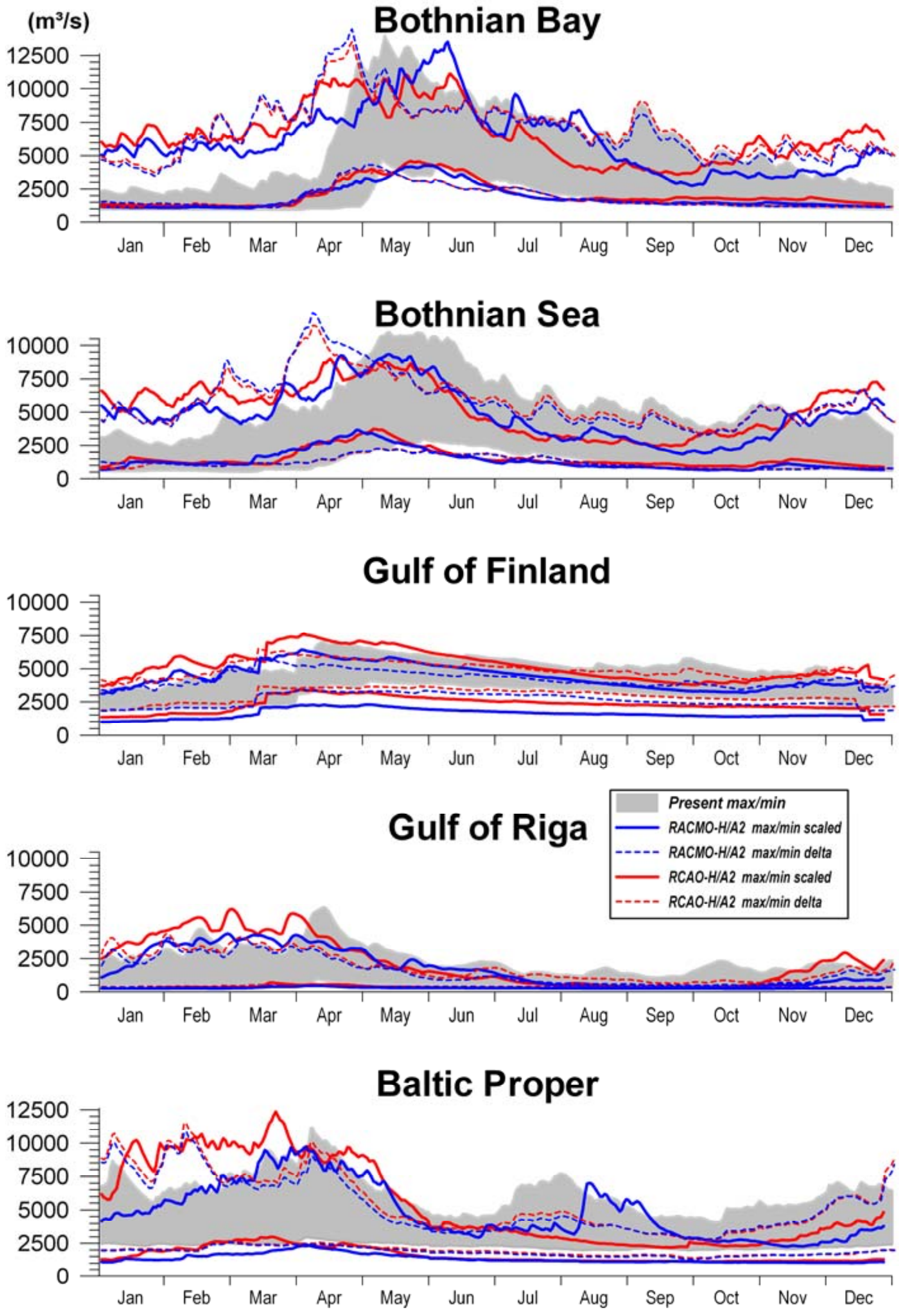
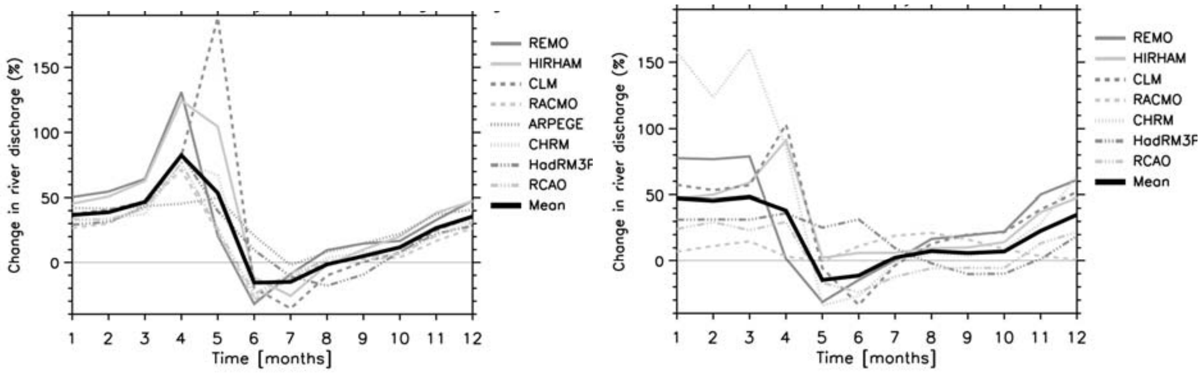


Figure 9.



a) **b)**

Figure 10.

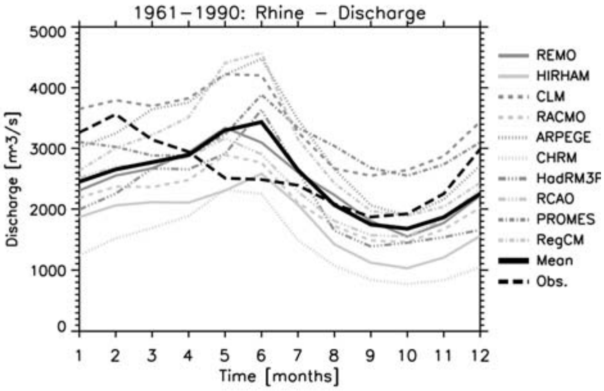
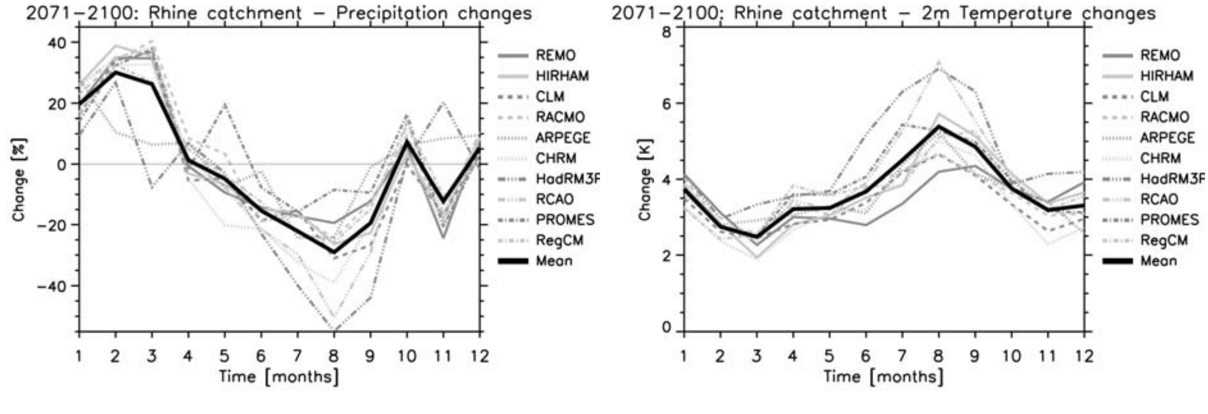
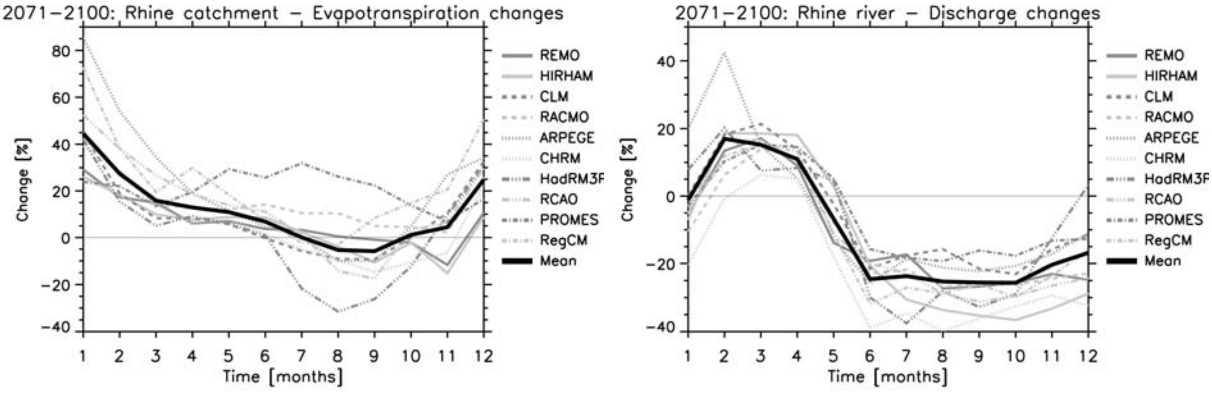


Figure 11.

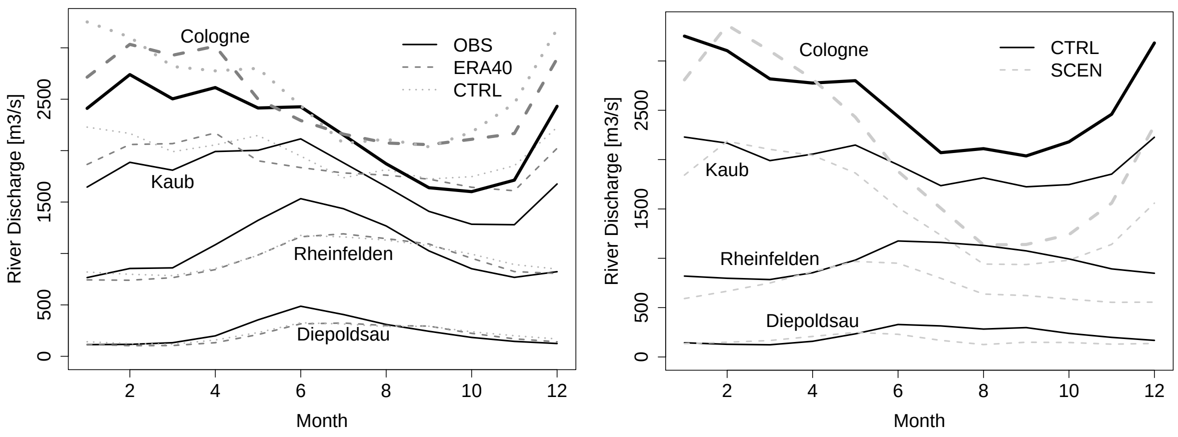


a) **b)**



c) **d)**

Figure 12.



a) **b)**

Figure 13.

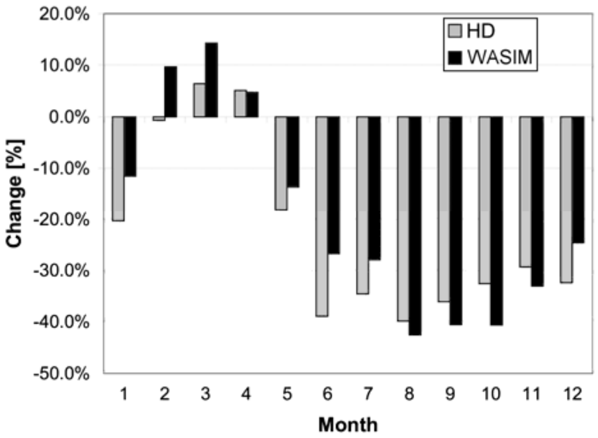


Figure 14.

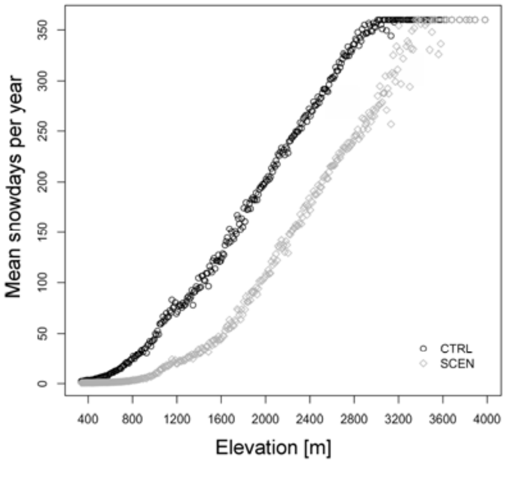


Figure 15.

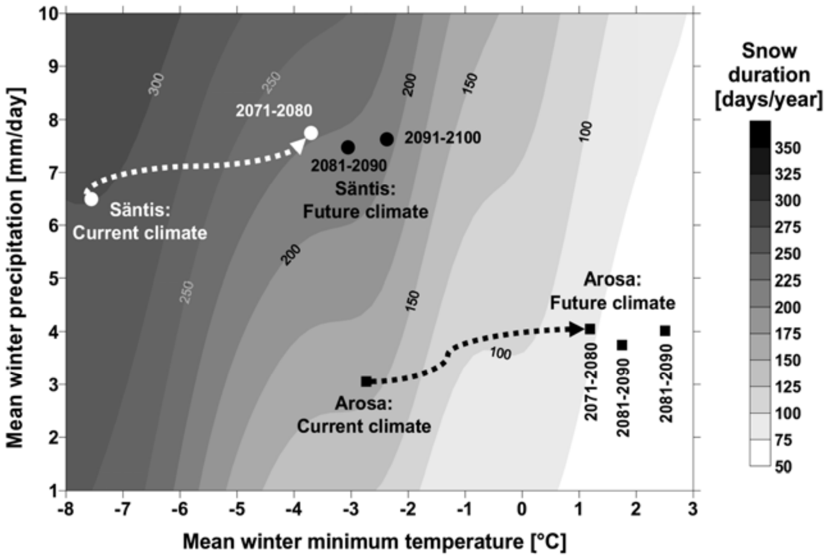

Mean winter precipitation [mm/day]
Mean winter minimum temperature [°C]
Snow duration [days/year]
350
325
300
275
250
225
200
175
150
125
100
75
50
300
250
200
150
100
2071-2080
2081-2090
2091-2100
Säntis: Current climate
Säntis: Future climate
Arosa: Future climate
Arosa: Current climate
2071-2080
2081-2090
2081-2090
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
1
2
3
4
5
6
7
8
9
10

Figure 16.