Nordic Hydrology, 34 (5), 2003, 399-412

Regional Climate Scenarios for use in Nordic Water Resources Studies

Paper presented at the Nordic Hydrological Conference
(Røros, Norway 4-7 August 2002)

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According to global climate projections, a substantial global climate change will occur during the next decades, under the assumption of continuous anthropogenic climate forcing. Global models, although fundamental in simulating the response of the climate system to anthropogenic forcing are typically geographically too coarse to well represent many regional or local features. In the Nordic region, climate studies are conducted in each of the Nordic countries to prepare regional climate projections with more detail than in global ones. Results so far indicate larger temperature changes in the Nordic region than in the global mean, regional increases and decreases in net precipitation, longer growing season, shorter snow season etc. These in turn affect runoff, snowpack, groundwater, soil frost and moisture, and thus hydropower production potential, flooding risks etc. Regional climate models do not yet fully incorporate hydrology. Water resources studies are carried out off-line using hydrological models. This requires archived meteorological output from climate models. This paper discusses Nordic regional climate scenarios for use in regional water resources studies. Potential end-users of water resources scenarios are the hydropower industry, dam safety instances and planners of other lasting infrastructure exposed to precipitation, river flows and flooding.

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Introduction

The anticipated global climate change, driven by anthropogenic emission of greenhouse gases, implies regional climate change that will vary between regions. Global-scale projections are relatively stable across a suite of different climate models (viz. the sensitivity of the climate system). The expected warming increases with the accumulated emissions (IPCC 2001). Studies over a wide range of emission scenarios and based on a number of global models project a global mean temperature increase of 1.4-5.8°C from the year 1990 to the year 2100. On regional scales, such as for the Nordic region, the simulated climate changes vary more between different global models, even when the same emission scenario is used (*e.g.* Räisänen 2001). Nevertheless, it is likely that climatic conditions in the Nordic region will significantly change during the next decades. Common across the available projections are milder and wetter winters and warmer summers with regionally varying net precipitation changes. Under such changes, practical consequences can be expected for human and natural systems alike. Future regional water resources (*e.g.* Bergström *et al.* 2001; Graham *et al.* 2001; Sælthun *et al.* 1998) is one of the central issues. It has links to the energy sector, physical planning, human safety, forestry and agriculture, as well as the future of various ecosystems in the region, including those of the Baltic Sea.

Earlier impact assessment of climate change on the regional water resources has been done by Sælthun *et al.* (1998). Since then, new types of Nordic regional climate projections have become available, ideas have evolved on hydrological impact modeling and users have become more aware of the issues. A new Nordic assessment is now underway, called Climate, Water and Energy (CWE). It readdresses the topic of climate change and Nordic water resources. One of the goals is to develop a common regional climate projection for the region. This paper introduces the CWE Nordic climate scenario (CWE-NCS) and discusses some aspects of its application to water resources studies.

Nordic Climate Scenarios

During the past few years, regional climate projections have been prepared in Sweden, Norway and Denmark, using regional climate models that allow for a more detailed description of the regional climate system than global climate models. These different regional simulations apply for different time horizons and different scenarios of future anthropogenic forcing. They are not totally independent, however. For example, three of the four simulations used in CWE-NCS build on boundary conditions from different simulations made with the same global model, the ECHAM4/OPYC3.

It is still not possible to attach probabilities to individual climate projections, i.e. there is no objective measure for the realism of a single projection. However, a combination of several results, such as a set of projections, should add value to the description (*cf.* Krishnamurti *et al.* 1999). This is the principle motivating the CWE-NCS.

Before different projections can be combined, they need to be harmonized with respect to time horizon and/or emission scenario. A first attempt in the context of Nordic projections was by Christensen *et al.* (2001). They considered the same set of four Nordic regional climate simulations that are used in CWE-NCS. These experiments are the two Swedish RCA runs (the RCA-H with boundary conditions from the HadCM2 global model and the RCA-E with boundary conditions from the ECHAM4/OPYC3 global model), the Danish HIRHAM run with boundary conditions from the ECHAM4/OPYC3 global model and the Norwegian HIRHAM run with boundary conditions from the same global model, but a different emission scenario. Christensen *et al.* harmonized only with respect to the time horizon, but not for the emission scenario. The analysis was focused on regionally averaged monthly mean temperature and precipitation, including a measure of heavy precipitation. When catering for water resources applications as attempted by CWE-NCS, more geographical detail is needed of the projection(s), as well as results for additional meteorological parameters, such as snow and evapotranspiration.

So far, when input to impact analyses is obtained from climate projections, it is used as derived (climate) changes. These are then projected on a set of observed meteorological time series to obtain the forcing data for impact models. This is called the "delta-change" method. The CWE-NCS is designed to be used as delta-changes. The advantage of this method is that it contributes to canceling out possible biases in climate models as well as to compensate for possible under representation of extremes and fine-scale detail. The disadvantage is that a historical time series might not in a meaningful manner describe future variability and occurrence of extremes. The choice of the base time series locks the analyses to a certain course of natural variability and very possibly misrepresents extreme events in one way or another. A further problem arises from the need of an interface between climate model results and impact models. It is not a simple matter how such an interface is constructed. The changes to be added to the base data are needed not only for mean quantities, but also for variability, extremes and possible non-linear features. In the specific case of water resources studies, such features include the intensity distribution of precipitation and the sequences of dry spells and wet spells.

Pattern-Scaling of Regional Scenarios

The harmonization of Nordic regional climate scenarios by Christensen *et al.* (2001) follows Mitchell *et al.* (1999). They suggest that geographical patterns produced in a transient climate simulation could be scaled in time, using the evolution of the global mean temperature as a salient measure. This is called pattern-scaling. It gives a means to derive regional climate projections even for other periods than those explicitly studied by regional simulations. Regional climate simulations are mainly run in a time-slice fashion. First a 10-30 year control or present-day climate run is done. It is followed by an another run for a future period. The further in the future the second time slice is and the stronger the climate forcing, the easier it is to distinguish the forced climate change (estimated from the difference of the two simulations) from natural variability. Natural variability is larger in the Nordic region than in the global mean sense. This means that regionally a larger signal of a forced climate change is needed than globally for it to emerge from natural variability. When projections from different models are compared, the same is true. The challenge of regional projections is therefore different from global projections. In the latter, the forced climate change emerges much earlier from natural variability. Indeed, global projections can provide a rather tight set of projections on time scales shorter than 50 years, but diverge more beyond that (*e.g.* Zwiers 2002; Stott and Kettleborough 2002; Knutti *et al.* 2002). In any case, many end-users desire also regional projections and impact analyses for periods as close to the present-day as possible.

Pattern-scaling is of course an approximation. Scaling back in time, from some more distant future time period, is felt to be acceptable, whereas scaling forward in time is not advised, in fear of non-linear changes that develop with increasing time horizon and climate forcing. How such scaling harmonizes between the four Nordic regional climate projections is illustrated in Fig. 1 where scaling is done with respect to both time (1990-2050) and global emissions (IPCC SRES B2). The scaling follows Christensen *et al.* (2001), replacing the scenario minus control climate changes, for any variable of interest, (ΔX) by

$$\Delta X_{\mathrm{scaled}} \equiv \Delta X \frac{\Delta T_{\mathrm{glob}(B2,1990-2050)}}{\Delta T_{\mathrm{glob}}} \qquad (1)$$

where ΔT_{Glob} is the global mean warming in the driving global model between the actual control and scenario periods and $\Delta T_{\mathrm{Glob(B2,\ 1990\text{-}2050)}}$ the corresponding global mean warming from 1990 to 2050, according to the global model under the SRES B2 –emissions. The same scaling is applied to measures of both the time mean climate and to those of variability. For example, the scaled change in standard deviation is obtained by multiplying the difference in standard deviation between the original scenario and the control periods by the scaling factor given by Eq.(1). In principle, more sophisticated scaling techniques could be constructed. However, we feel that there are not sufficient grounds to go beyond a linear approach.

The illustrated climate measure in Fig. 1 is the Nordic land area mean temperature change vs. the global mean temperature change. In the mean sense, the scenarios cluster close together after the scaling to the common time horizon and emission scenario. One of the regional projections, the met.no one, is actually scaled forward in time, as the original simulation was based on a much shorter time horizon and

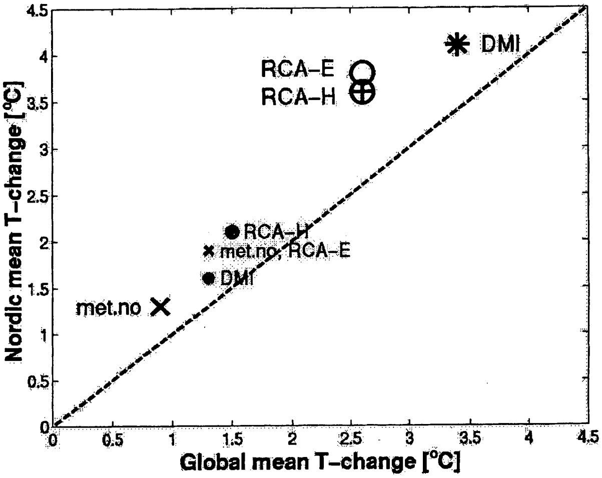

Fig. 1. The large symbols show Nordic and global mean temperature changes in four Nordic regional climate projections. The small symbols show the projections after the normalization to a common time horizon 1990-2050 and a common emission scenario (IPCC SRES B2).

smaller net climate forcing compared with the other ones. Even after the scaling procedure, one of the regional projections, the RCA-H, is slightly different from the rest in terms of global mean temperature increase. This is due to the fact that the RCA-H is based on a different global model and thus another estimate of the global climate sensitivity to a given forcing than the other regional simulations.

Some climate variables should perhaps be treated with a more sophisticated procedure than pattern-scaling based on global mean temperature. However, we feel that more complicated approaches would at this point rather add to the uncertainty than diminish it.

Temporal Smoothing

Climate models also simulate natural variability, which complicates the interpretation of climate projections. The differences between a future climate run and a control run include, in addition to the forced climate change, a contribution from differences due to simulated natural variability in the respective runs. As the contribution of the latter tends to increase in magnitude with a decreasing sample size, the problem is larger for the seasonal details than for the annual means. This is illustrated for the simulated changes in monthly mean temperature and precipitation in Fig. 2(a-b). Unrealistic-looking jumps appear in the simulated temperature change and more frequently in the simulated precipitation change. These do not indicate

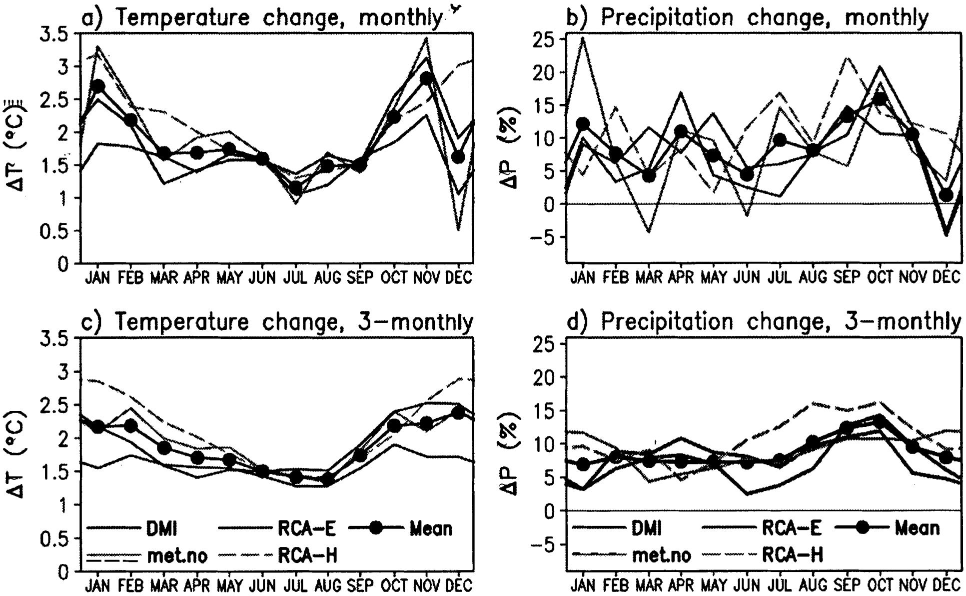

Fig. 2. The pattern-scaled four Nordic regional climate projections for monthly mean temperature and precipitation change for the Nordic land region. The mean of the four projections is also showed in each case. (a) pattern-scaled monthly mean temperature changes. (b) as (a), but with a 3-month running average filter. (c) pattern-scaled monthly mean precipitation changes. (d) as (c), but with a 3-month running average filter.

problems in the models. Rather, they illustrate the large natural variability in the Nordic climate. Temporal smoothing such as taking the running mean of three consecutive months (Fig. 2c-d) is felt to better bring forth the forced climate change signal. We recommend using running 3-month means, but also suggest that in impact analyses, the impact of the choice for temporal smoothing is investigated by varying the filter. Observe that the combination of different projections into one common projection also provides for some smoothing.

Spatial Smoothing

The simulated changes vary geographically across the Nordic region. As illustrated in Figs. 3-4, this variation is stronger and typically of smaller scale for precipitation compared with temperature. It is also evident that the variation in space is somewhat reduced in the mean of the four regional projections (Fig. 3e and Fig. 4e) than in each of the projections *per se*. The small-scale details of change are less robust across the projections than the large-scale features. Consequently, the small-scale

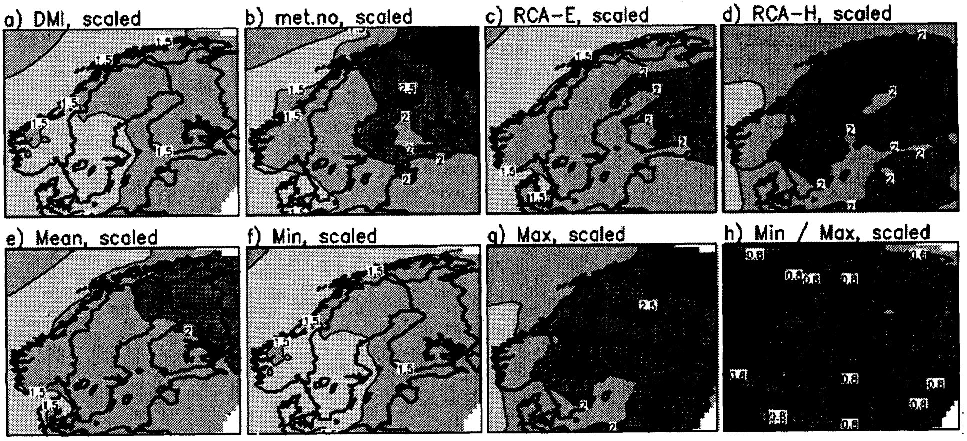

Fig. 3. Scaled annual mean temperature changes. In the Nordic region, the change ranges from 1.5 to 2.5°C, when harmonized to the time period of 1990-2050. Extending the time period to 2100 would likely double the changes.

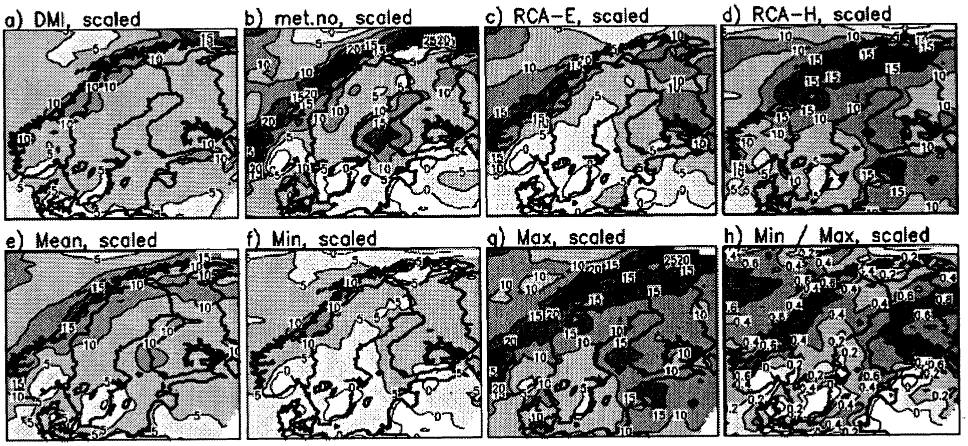

Fig. 4. Scaled annual mean precipitation changes. For the period of 1990-2050, changes up to 15% are seen in some areas, especially in the west, north and east. In southern Scandinavia, no increase is evident. The local water resources would, however, decrease in southern Scandinavia, as temperature increase affects evaporation.

details are smoothed out more than the large-scale variations when the mean is taken. This reflects also the characteristic feature that the forced climate change signal is least discernible from natural variability on the smallest scales. As further illustrated in the last three panels of Fig. 4, there are areas where the projections of annual precipitation change differ in sign between the four simulations.

In applying climate model results for climate scenario construction, it is advisable to smooth the simulated fields of change by taking a mean over a number of adjoining grid cells, rather than to use the results for individual cells that can be seriously affected by natural variability. Numerical uncertainties also have to be taken into account and the so-called representative scale in climate models is of the order of a few grid points, instead the formal grid size. It is, however, difficult to give any general recommendation of a suitable degree of spatial smoothing. This likely depends, for example, on the type of impact model that is used.

A Common Scenario for Water Resources Applications

The CWE-NCS is a multi-member regional climate projection created for the Nordic region. Each of the four projections contributes to the projection over the land area of Norway, Sweden, Finland and Denmark. This is called the "Nordic mainland" in the discussion below. The CWE-NCS over Greenland and Iceland is based on only one of the parent projections, the one from met.no. The CWE-NCS is scaled to the IPCC SRES B2 emission scenario and the time period of 1990-2050. The variables included are the mean screen temperature, its daily maximum and minimum and the screen dew point temperature, total precipitation, evapotranspiration, local runoff generation and the snow water equivalent. The common projection is made available as delta-changes with monthly time resolution and a 0.5° spacing in latitude and in longitude. We recommend that the users apply temporal and spatial smoothing to these data as discussed in the previous sections.

Table 1 – The CWE-NCS projection changes as averaged over Nordic mainland. (Greenland and Iceland are not included.) T2 = screen (2-meter) temperature; T2max = maximum screen temperature; T2min = minimum screen temperature; T2dew = screen dew point temperature; P = precipitation; E = evapo(transpi)ration; R = local runoff generation; SWE = snow water equivalent.

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)	Annual
T2 (°C)	2.2	1.7	1.4	2.2	1.9
T2max (°C)	1.9	1.7	1.3	2.0	1.7
T2min (°C)	2.5	1.8	1.5	2.4	2.0
T2max-min (°C)	–0.5	–0.2	–0.2	–0.3	–0.3
T2dew (°C)	2.1	1.6	1.5	2.2	1.8
T2 – T2dew (°C)	0.1	0.2	–0.1	0.0	0.1
P (%)	7	7	8	13	9
E (%)	–1	3	3	8	4
R (%)	39	–3	2	31	13
SWE (%)	–30	–38	–64	–44	–35

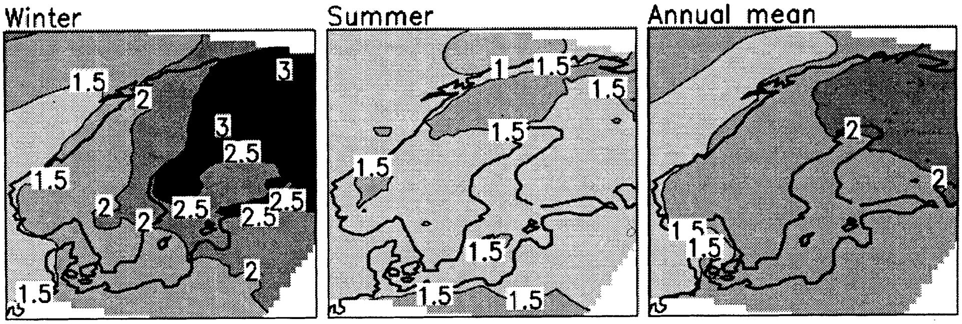

Fig. 5. The CWE-NCS projected changes in winter, summer and annual mean screen temperature (°C).

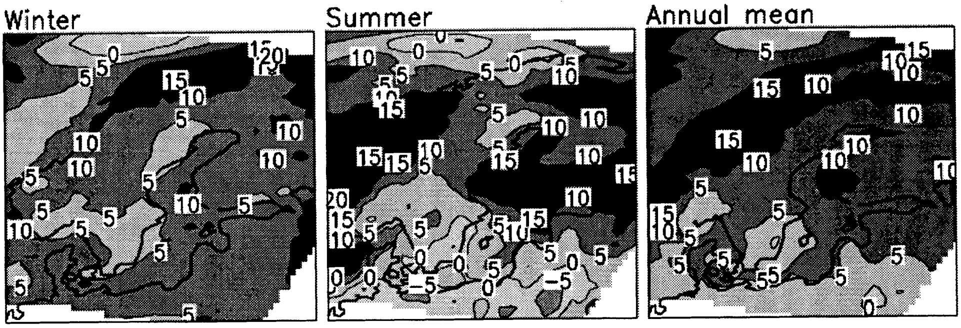

Fig. 6. The CWE-NCS projected changes in winter, summer and annual precipitation (%).

The CWE-NCS is available from the project website (http://www.os.is/cwe/), or by contacting the authors. Table 1 lists the annual and seasonal changes averaged over the Nordic mainland. The winter, summer and annual mean changes in temperature and precipitation are shown in Figs. 5 and 6.

Changes in precipitation intensities are also investigated, as well as how temperature change varies within seasons. These are important details in water resources studies.

There is no systematic difference between the changes in maximum and average summer temperature. A larger change in the winter minimum than in the winter mean is evident in CWE-NCS. An intensification of precipitation in excess of the change projected for the mean precipitation is evident in many climate projections. In CWE-NCS, the average maximum precipitation increases slightly more than the annual mean precipitation in all the experiments, but the difference is small.

The data allow for additional investigations. For example they suggest that

- Snow season becoms shorter, typically by about 30 days. The snow mass also decreases. This is the case even in northern Scandinavia, where the increase in precipitation could be speculated to lead to an increase in the seasonal snow pack. Apparently, increases in precipitation are more than compensated by the higher temperature that delays the beginning of the snow season in the fall and leads to more melting even in winter.
- The diurnal temperature range (average difference of daily maximum and minimum temperature) decreases slightly. The change is largest in the fall and winter, when regular night-day temperature variability is small but reduced snow and ice damps the irregular variation associated with synoptic-scale low pressure and high pressure systems.
- The difference between the screen temperature and the screen dew point temperature changes little. This indicates little change in relative humidity, but an increase in absolute humidity.
- Evaporation is projected to increase in the annual mean, but in relative terms less than the precipitation. The annual mean runoff generation increases in relative terms more than the precipitation. The spring peak in runoff is reduced, however, due to reduced snow mass.

The changes in mean climate are accompanied by changes in variability and extremes. On the grid box scale, these are even more heavily contaminated by the noise associated with natural variability than the changes in mean climate. The projected area mean changes for the Nordic mainland (Table 2) allow for some general conclusions. We hope that these prove helpful to the construction of an interface between the CWE-NCS and impact models.

The standard deviation of daily mean temperature, calculated after removing the

Table 2 – CWE-NCS projections for changes in climate variability and extremes, as averaged over Nordic mainland. (Greenland and Iceland are not included.) SD of T = standard deviation of daily mean temperature; T2max, max = average seasonal or annual maximum maximum temperature; T2min, min = average seasonal or annual minimum minimum temperature; SD of P24 = standard deviation of daily precipitation; CV of P24 = coefficient of variation of daily precipitation; P24, max = average seasonal or annual maximum one-day precipitation.

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Fall (SON)	Annual
SD of T2 (%)	–10	–5	3	–12	–7
T2max, max (°C)	1.4	1.6	1.3	1.4	1.3
T2min, min (°C)	3.8	2.7	1.9	5.0	3.8
SD of P24 (%)	10	11	9	11	10
CV of P24 (%)	4	3	2	–1	2
P24, max (%)	12	12	10	10	10

mean annual cycle, is projected to decrease, especially in winter and fall, and to a lesser extent in spring. This decrease in variability likely relates, at least in part, to reduced snow and ice. The impact on temperature extremes is substantial. The lowest winter minimum temperature in an average year is projected to increase by almost 4°C, well in excess of the mean winter warming, whereas the increase in the highest winter temperatures is relatively modest. Similar conclusions apply to the fall, with, in particular a large increase in the lowest temperatures of the season that tend to occur in November. By contrast, the projected increase in the highest summer maximum temperatures is similar to the mean summer warming. The standard deviation of the daily precipitation generally increases, but the relative change is not very different from the change in the mean precipitation. Thus, the coefficient of variation of precipitation (the standard deviation divided by the mean precipitation) changes little, although there is a slight tendency to increase in most seasons. The relative change in extreme daily precipitation is diagnosed here for the average seasonal or yearly one-day maxima. Changes in these are quite similar to the increase in mean precipitation. This similarity is unlikely to be valid for all geographical areas of the world. For example, in analyzing the two RCA experiments, Räisänen and Joelsson (2001) found extreme daily precipitation to increase in almost the whole of Europe. The mean precipitation increased in northern Europe but it decreased further south, where the general increase in precipitation intensity was compensated by a decrease in the number of precipitation days.

Discussion

The CWE regional climate scenario will allow for constructing new regional water resources scenarios. Driving data are generated for other applications as well. The different Nordic regional scenarios need to be harmonized to a common time horizon, and smoothed temporally and in space so that the forced changes can be better separated from unforced natural variability. Incorporating results from as many climate simulations as possible is expected to improve the climate scenario description by reducing random errors and thus also impact analyses.

A single climate projection that builds on a single emission scenario does not account for the uncertainty that is inherent in projections of the future. As stated in IPCC (2001) there are no grounds to assume that one SRES-scenario is more likely than another, so the B2 should probably be considered to be "as likely" as any other. In terms of climate projections, the uncertainties are composed of different factors: the unknown future emissions, the uncertain sensitivity of the global climate system to emissions, the uncertain sensitivity of the regional climate system to global climate change, and how natural climate forcing factors and natural variability of the climate operate during some future period. On top of this, there will also be a development in the society and the management and demand of *e.g.* water resources. The

CWE regional climate projection is made to conform to one time horizon and one emission scenario. It does build on two estimates of the global climate system sensitivity (viz. global models) to emissions, and three estimates of the regional climate system sensitivity (viz. regional models) to global climate change. Being a combined projection, the CWE-NCS averages out some of the uncertainties in the individual scenarios, in favor of the more robust features shared across the individual projections.

Using only one projection has its practical advantages. First, even though it in principle is advisable to perform impact analysis based on multiple climate projections, there is a practical limit to how many analyses can be made. It is also difficult to state how many analyses would compose a "sufficient" set for end-users. Second, the availability of one common Nordic climate projection offers a new avenue to study another aspect of the uncertainty. Different Nordic impact research groups, having different models, will be able to run their models with the same input, and obtain a measure of how much the choice of *e.g.* the hydrological model affects the analysis. Preferably the impact models should be run for the same geographical domain, or at least a common catchment, for this aspect to be explored.

In the long term, there is a need to integrate climate models with impact models as much as possible. This implies a more complete description of the climate system and in principle incorporates a larger set of feedback mechanisms in the projections. It also provides impact analysis directly from the climate simulations. Last, but not least, it shortens the chain of model/analysis tools now starting from emission scenarios and global models, proceeding through regional models and ending at regional impact models. The removal of the interface between regional climate and impact models should lead to a less complicated analysis of the uncertainty in assessing the practical consequences of global change to water resources in the Nordic region.

Acknowledgements

The CWE-project is supported by the Nordic Council of Ministers. The work at DMI has been supported by EU-projects EV5V-CT92-0216 and EV5V-CT94-0505 and by ELSAM. The DNMI (met.no) simulations belong to the RegClim program, supported by the Norwegian Research Council. The SMHI simulations are a part of the SWECLIM program, supported mainly by the Foundation for Strategic Environmental Research (MISTRA) and SMHI.

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Received: 10 October, 2002
Revised: 25 June, 2003
Accepted: 15 July, 2003

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