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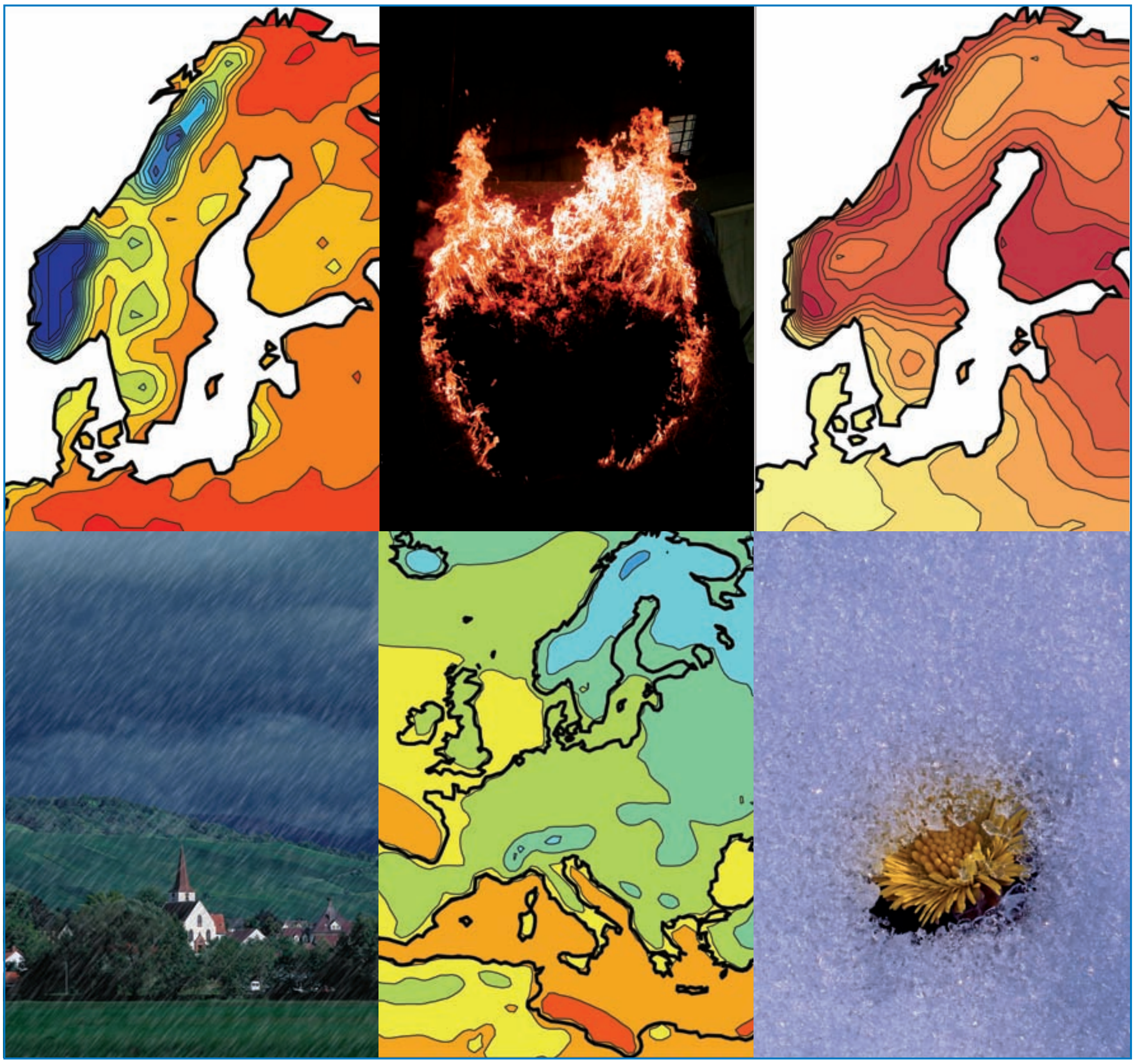

Climate indices for vulnerability assessments

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Abstract/Sammandrag

The demand is growing for practical information on climate projections and the impacts expected in different geographical regions and different sectors. It is a challenge to transform the vast amount of data produced in climate models into relevant information for climate change impact studies. Climate indices based on climate model data can be used as means to communicate climate change impact relations. In this report a vast amount of results is presented from a multitude of indices based on different regional climate scenarios.

The regional climate scenarios described in this report show many similarities with previous scenarios in terms of general evolution and amplitude of future European climate change. The broad features are manifested in increases in warm and decreases in cold indices. Likewise are presented increases in wet indices in the north and dry indices in the south.

Despite the extensive nature of the material presented, it does not cover the full range of possible climate change. We foresee a continued interactive process with stakeholders as well as continued efforts and updates of the results presented in the report.

Key words/sök-, nyckelord

Climate change, climate index, climate model, climate scenario, ERA40, RCA3, RCAO

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Sammanfattning

Behovet av information om klimatets förändring och dess effekter på olika regioner och sektorer ökar stadigt. För att belysa frågeställningar runt klimatets utveckling, dess påverkan och behov av anpassning behövs projektioner av framtidens klimat. Den generella kunskapen om klimat baseras oftast på erfarenhet av tidigare klimat, väderobservationer, prognoser och återanalyser av historiska data. För att hantera framtidens föränderliga klimat behöver vi utveckla metoder för att förfina användningen av information från klimatmodeller.

Klimatindex, formulerade med avnämarperspektiv i fokus och beräknade utifrån data från klimatmodeller, är ett sätt att kommunicera den komplexa frågan om effekter av klimatets framtida utveckling. Klimatindex kan vara välkänd information som summerad nederbörd eller medeltemperaturer men kan också beskriva mer komplexa relationer och då innefatta till exempel tröskelvärden eller exponeringstid för olika förhållanden.

I denna rapport beskrivs ett omfattande material av klimatindex baserade på beräkningar med två regionala klimatmodeller utifrån olika utsläppsscenarier och globala klimatmodeller. Materialet har legat till grund för arbetet inom den svenska Klimat- och sårbarhetsutredningen (M2005:03), men har även framtagits i samarbete med andra avnämargrupper. De flesta klimatmodeller och klimatscenarier som ligger till grund för indexberäkningarna har tidigare dokumenterats i andra rapporter men ges här en övergripande beskrivning. Till rapporten bifogas en DVD med det omfattande kartmaterial som illustrerar indexberäkningarna och tillhörande information. Materialet finns även tillgängligt på www.smhi.se.

I linje med tidigare scenarier visar de regionala klimatscenarierna på ett gradvis allt varmare klimat i takt med att den mänskliga klimatpåverkan blir större framöver. Uppvärmningen är särskilt markerad under vinterhalvåret i norra och östra Europa. Det mildare vinterklimatet gör att snötäckets utbredning minskar vilket i sin tur förstärker uppvärmningen som blir allra tydligast för de allra kallaste episoderna. I centrala och södra Europa är uppvärmningen som störst under sommarhalvåret och då med kraftigast ökning av de extremt höga temperaturerna. I övrigt visar scenarierna på mer nederbörd längst i norr under sommaren och i hela Europa utom Medelhavsområdet under vintern. När det gäller vindklimatet finns ingen entydig förändring. Olika scenarier med olika globala klimatmodeller ger väsentliga skillnader i hur vindklimatet förändras, några visar på kraftigt ökande vindar under vinterhalvåret medan andra bara visar på små skillnader gentemot dagens klimat.

Arbetet med att ta fram och analysera klimatscenarier och att utveckla klimatindex fortsätter. Vi ser också fram emot en fortsatt dialog med avnämarna.

Contents

1. Introduction

The issue of climate change raises a wide range of burning questions related to the impacts of climate change and adaptation needs. The demand is rapidly growing for practical information on climate projections and the impacts that can be expected in light of them, in different geographical regions and on different sectors. Until now, most of the general knowledge on climate and weather impacts is based on the experience of earlier experienced events, weather observations, forecasts and reanalyses of historical data. The use of climate model results is much less common. The latter are, however, the principle means of gaining insights on climate change that lies ahead of us. As the concerns on climate change impacts keep on increasing, the use of climate change projections is becoming increasingly essential on all sectors that deal with weather, water and climate.

It is a challenge to transform the vast amount of data produced in climate models into information that is suitable and relevant for climate change impact studies. While annual, seasonal and monthly mean values of temperature, precipitation and other common variables provide essential and indispensable information regarding the climate and how it may change, they are typically not directly linked to climate impacts. During the last few years the need for information more directly linked to impacts has resulted in a wide range of climate indices.

Climate indices are developed to in a simplified way communicate more complex climate change impact relations. Mean temperature and precipitation sums can be seen as (simple) climate indices, and the same applies for various measures of climate extremes. The power of the climate index concept, however, is strikingly illustrated with the more complex climate indices that incorporate information on the sensitivity of a specific system, such as exposure time, threshold levels of event intensity etc.

The work on climate indices that are the subject of this report, has in general been motivated by overall research and development of climate scenario analysis for decision-support, and in particular, by the Commission on Climate and Vulnerability[1] in Sweden. It was appointed by the Swedish Government in June 2005, to assess the vulnerability of the Swedish society to climate change, by means of mapping regional and local consequences of climate change, related costs and damages. In addition, the Commission was to suggest measures to reduce the vulnerability and consider some other aspects on taking action. The Commission of Climate and Vulnerability was to carry out the first wide-ranging assessment across the Swedish society within a limited time-frame. A common framework of consistent and plausible scenarios for the future was to be used throughout the work. The Commission was to co-operate with a wide range of authorities, regional governments and communities as well as with representatives from trade and industry, scientific institutions and organisations across the Swedish society.

[1] Official reference number M2005:03

The work by the Commission was conducted in four groups composed of representatives from different sectors: agriculture, forestry and natural environment; health, water resources and water quality; technical infrastructure and physical planning (subdivided into energy and electronic communications, transportation, and physical planning and the built environment); flooding and issues related to the large lakes. In addition, separate task force groups focussed on fisheries and the marine environment, tourism and mountain region issues including reindeer herding. At an early stage the Commission initiated a dialogue with the SMHI Rossby Centre regarding provision of climate scenarios. The result was that the regional climate change scenarios from the Rossby Centre at SMHI were adopted as the common climate scenario basis for Commission efforts.

Several meetings were held with the different sectorial working groups, in which, the scientific climate change basis was presented as well as the available climate scenarios. Discussions were carried out on what information was needed by the groups and how this could be provided. The basic approach was that the working groups suggested what indices they required and, as far as possible these indices where then processed for the selected set of Rossby Centre regional climate model scenarios. This led to the calculation of a wide range of climate indices starting in the spring of 2006.

The combination of a multitude of indices, several global and regional models and emissions scenarios, four time periods, and variety of monthly, seasonal and annual selections led to a vast amount of results. These were presented especially as climate index maps. In addition to the material on climate change scenarios, extensive provision of near-past climate information was also made, building on the recent ECMWF global reanalysis known as ERA40. On-line electronic access was made possible for the users, through a website. The information was also updated as needed, and metadata on the results successively added.

Parallel to these efforts for the Commission, targeted scenario analyses building on the same methods and material were produced within two projects commissioned by Elforsk AB and the Geological Survey of Sweden (SGU). Also these results were added to the site serving the Commission.

A final version of the site mentioned above is made available via the SMHI external website. The contents are, at the time of publishing this report, the same as on the DVD attached.

2. Climate modelling and experimental setup

Climate modelling is pursued by means of models of varying complexity ranging from simple energy-balance models to complex three-dimensional coupled global models. On a global scale GCMs (general circulation models, a.k.a. global climate models) are used. These consist of individual model components describing the atmosphere and the ocean. They also describe the atmosphere-ocean interactions as well as with the land surface, snow and sea ice and some aspects of the biosphere. Regional climate models (RCMs) are a means to downscale results from the GCMs, so as to achieve a higher spatial resolution over a specific region. The main advantage of the finer resolution that is feasible in RCMs, is a better description of local topography, land-sea distribution, vegetation and other land surface properties. These have an influence on surface and near-surface climate conditions. Also, the finer resolution allows for a better simulation of such regional-scale features in the atmosphere as frontal and meso-scale convective systems, compared to coarser-scale models. The recent IPCC assessment report on climate change presents an overview of improvements in GCMs and RCMs over the past years, their ability of simulating present-day climate and use in providing climate projections (Randall et al., 2007; Christensen et al., 2007a).

The uncertainties of projected regional climate change arise from a number of factors (Christensen et al., 2007a). One is, of course, the external forcing scenarios (in this case the changes in greenhouse gas and aerosol concentrations). Another factor concerns the changes in the large-scale circulation determined by the GCM. This, in turn, depends both on model formulation and internal variability. Different RCMs can respond differently to the forcing conditions and the course of unforced internal variability in specific model simulations differs. A handle on these uncertainties can be gained when several models, forcing scenarios and simulations are considered. However, whenever the results do not vary overly much across models and scenarios, it can be taken as an indication of robustness and perhaps of a useful degree of certainty.

Future climate change depends on changes in the external forcing of the climate system and, depending on which time-scale considered, to some degree on unforced internal variability in the climate system, as already alluded to above. Future changes in the atmospheric content of greenhouse gases and aerosols are not known, but the changes are assumed to be within the range of a set of scenarios developed for the IPCC (Nakićenović et al., 2000). These scenarios build on consistent assumptions of the underlying socio-economic driving forces of emissions, such as future population growth, economic and technical development. The global mean net warming response is rather uniform across these emissions scenarios during the next few decades but diverges more and more after that. Even in a shorter term, there are some notable differences in some of the elements in these emissions scenarios that might be significant in regional climate change (such as emission of sulphur) or in dealing with climate impacts (adaptive capacity). The three emissions scenarios we have used sample quite a lot of the spread of the scenarios developed for the IPCC, as well as the ensuing global mean warming.

The regional climate change signal is to a large extent determined by the large-scale climate response to emissions that is solved with a GCM. This enters in regional climate modelling as boundary conditions. Changes in seasonal mean temperature and precipitation over Europe are examples of variables for which there is uncertainty associated with the boundary conditions (e.g. Déqué et al., 2007). Since the projected changes in the large-scale circulation in various regions can vary across different GCMs, the projected regional changes will be sensitive to the choice of the GCM providing the boundary data. This implies that using boundary conditions from multiple GCMs is preferable to just using one. In the present work boundary data from three different GCMs is used to force the RCM.

One way to approach the model (RCM) uncertainty is to use a multitude of different RCMs. The sampling uncertainty can be addressed by repeating simulations, always with the same combination of emissions scenario, GCM and RCM, but different initial conditions. These methods have been tested in the European PRUDENCE project (Christensen et al., 2007b). The results show that the uncertainties due to boundary conditions and radiative forcing dominates for changes in seasonal mean conditions (Déqué et al., 2007) but that the RCM uncertainty can also be large, especially for extreme conditions (Kjellström et al., 2007). The sampling uncertainty is generally less significant for larger projected changes than smaller ones.

2.1 Regional climate models

The regional climate model system developed at the Rossby Centre is used for all downscaling simulations in this report. Two versions of its atmosphere component, the RCA, are relevant here; RCA2 (Jones, 2001; Jones et al., 2004), and RCA3 (Kjellström et al., 2005). RCA includes a description of the atmosphere, a land surface model and a lake model, PROBE (Ljungemyr et al., 1996). RCA3 has a completely new land surface scheme (Samuelsson et al., 2006), as well as a number of differences to RCA2 in its radiation, turbulence and cloud parameterizations. Thanks to the new land surface scheme, RCA3 no longer use deep soil temperatures from a global model as was the case with RCA2. The two model versions are described in more detail in Kjellström et al. (2005).

In addition to the atmospheric model the Rossby Centre also operates a regional ocean model, the RCO (Meier et al., 1999; Meier et al., 2003). The relevant set-up of RCO is for the Baltic Sea including Kattegatt with a horizontal resolution of 6 nm (approximately 11 km). The coupled version of the RCA2 and the RCO constitutes the regional atmosphere-ocean model RCAO (Döscher et al., 2002; Döscher and Meier, 2004). The more recent model version RCA3 is not yet coupled to RCO for the Baltic Sea. In the following the two model set-ups are referred to as RCAO (coupled atmosphere-ocean regional climate model, including also the land surface, lakes and sea ice) and RCA3 (atmosphere/land surface regional climate model).

Both set-ups cover Europe with a rotated longitude-latitude grid with a horizontal resolution of 0.44^o (approximately 50 km) and 24 vertical levels in the atmosphere. The domain and grid are slightly different for the two model versions, but the same physiography data base is used for both models (see Figure 1). The time step in RCAO was 36 minutes while it was 30 minutes in RCA3. These differences are for most users not important in practice.

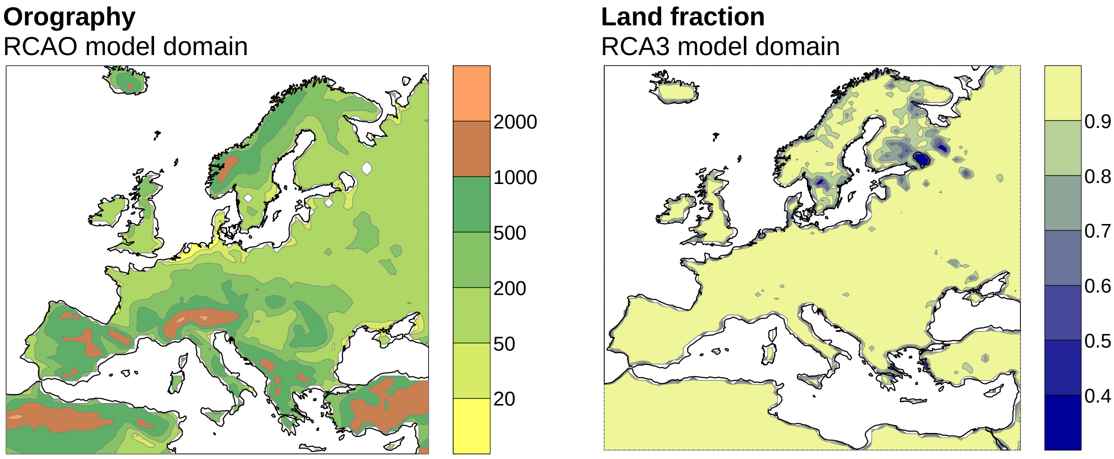

Figure 1. *Inner (neglecting the outer boundary relaxation zones of 8 grid points in all directions) model domain used in RCAO and RCA3. The orography (height of land surface, in m) and land fraction are the same in RCA3 and RCAO. The model domains are, however, slightly different because of practical reasons.*

2.2 Global climate models

We use driving data from three global climate models, HadAM3H, ECHAM4/OPYC3 and ECHAM5/MPI-OM. In addition to initial conditions, the driving data consists of lateral boundaries and sea ice/sea surface temperatures (and, in the case of the older regional model version also deep soil temperature). These fields are taken from the global model every six hours in the simulations. The downscaling simulations with RCAO and RCA3 of HadAM3H and ECHAM4/OPYC3 results has previously been described in Räisänen et al. (2003, 2004) and Kjellström et al. (2005) while the downscaling of ECHAM5/MPI-OM with RCA3 has not previously been documented. In the following are short descriptions of the three global models:

- HadAM3H is the atmospheric component of the Hadley Centre coupled atmosphere ocean GCM HadCM3 (Pope et al., 2000; Gordon et al., 2000) that can be run with higher resolution (1.875° longitude × 1.25° latitude). Because HadAM3H excludes the ocean, the simulations with this model used sea surface temperature (SST) and sea ice distributions derived from observations in the control period (1961-1990). For the future time period it used the same observed data plus the climate change signal from earlier, lower resolution HadCM3 experiments.

- ECHAM4/OPYC3 (Roeckner et al., 1999) is a coupled atmosphere-ocean GCM developed at DKRZ, the Deutsches Klimarechenzentrum GmbH, and the Max-Planck Institute for Meteorology in Hamburg. It was run at T42 spectral resolution corresponding to a horizontal grid spacing of 2.8° in the atmospheric part.

- ECHAM5/MPI-OM (Roeckner et al., 2006; Jungclaus et al., 2006) is the successor of ECHAM4/OPYC3. One of the improvements of the model compared to ECHAM4/OPYC3 is that it does not require a flux adjustment between the atmosphere and the ocean. The current simulation is one of the contributions to the IPCC AR4 work from the DKRZ and the Max-Planck Institute for Meteorology. In a comparison with observations ECHAM5/MPI-OM has been shown to perform well in terms of surface pressure patterns in west-central Europe indicating that the large-scale circulation over Europe is realistic (van Ulden and van Oldenborgh, 2006). The simulation was performed at T63 resolution (1.875° × 1.875°).

2.3 ERA40 data

In order to provide a realistic baseline regional climate, to which the climate projections based on global scenarios can be compared, we have performed re-analysis driven experiments with the RCA. The boundary conditions for these are taken from the European Centre for Medium range Weather Forecasts (ECMWF) ERA40 data set (Uppala et al., 2005), extended with operational analyses to cover the whole period from 1961 to 2005. These data were downloaded on a 2^o horizontal resolution and 60 vertical levels, and interpolated for use with the RCA grid. In terms of greenhouse gas forcing we have imposed a linear increase with time in carbon dioxide (CO_2) identical to that used for producing the ERA40 dataset (1.5 ppm_v per year). Since RCA accounts in a bulk fashion for other greenhouse gases on their present-day concentration levels, we do not change their effect with time. In climate change experiments, this is overcome imposing greenhouse gas changes in equivalent carbon dioxide terms (see Ch. 2.4).

2.4 Future emissions scenarios

The downscaling experiments make use of three different scenarios for the future. These are the B2, A1B and A2 emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000). HadAM3H and ECHAM4/OPYC3 were run with observed forcing conditions for the time period until 1990 and with these emissions scenarios after that. ECHAM5/MPI-OM was run with observed forcing conditions until the year 2000 before switching to the A1B emissions scenario.

The IPCC SRES scenarios include emissions of anthropogenic greenhouse gases and aerosol precursors and/or types. Corresponding atmospheric concentration projections are also made available, after running the emissions through carbon cycle models. Because of the simplicity of the RCA radiation code, the net effect of these changes was approximated by an “equivalent” increase in the CO_2 concentration. In the RCAO experiments the equivalent CO_2 concentrations were held constant for the whole 30-year periods. The control run value of 353 ppm_v (1961-1990) was raised in the B2 simulations to 822 ppm_v and in the A2 simulations to 1143 ppm_v representing the period 2071-2100. In the RCA3 simulations the equivalent CO_2 concentrations were allowed to change with time and the numbers for each year are interpolated linearly from the decadal values shown in Table 1.

Table 1. *The anthropogenic radiative forcing is taken from table II.3.11 in IPCC (2001) and includes the effect of greenhouse gases plus the indirect and direct effects of aerosols under the SRES B2, A1B and A2 emissions scenarios. The equivalent CO_2 concentration for a certain time is calculated using the radiative forcing ($F=5.35\ln(CO_2/CO_{2ref})$ where CO_{2ref} is the concentration in 1990 (expression taken from Table 6.2 in IPCC, 2001. The RCA radiation code enables the use of a variable CO_2 concentration (as well as water vapour), whereas other anthropogenic greenhouse gases are accounted at their present levels. This means that the historical equivalent CO_2 concentrations need to be lower than the ones inferred from the greenhouse gas concentrations in the atmosphere, to compensate for the constant methane etc. concentrations. The equivalent CO_2 concentration profiles in this case also include a net negative forcing contribution of atmospheric aerosols. (NA= Not Applicable).*

Year	**Radiative forcing (W/m^2)**			**Equivalent CO_2 concentration (ppm_v)**		
	B2	*A1B*	*A2*	*B2*	*A1B*	*A2*
1950	NA	NA	NA	NA	313	NA
1960	0.39	0.39	0.39	313	313	313
1970	0.41	0.41	0.41	314	314	314
1980	0.68	0.68	0.68	331	331	331
1990	1.03	1.03	1.03	353	353	353
2000	1.33	1.33	1.32	373	373	373
2010	1.82	1.65	1.74	409	396	403
2020	2.36	2.16	2.04	453	436	426
2030	2.81	2.84	2.56	492	495	470
2040	3.26	3.61	3.22	536	572	532
2050	3.7	4.16	3.89	581	634	602
2060	4.11	4.79	4.71	628	713	702
2070	4.52	5.28	5.56	678	781	823
2080	4.92	5.62	6.40	730	832	963
2090	5.32	5.86	7.22	787	871	1123
2100	5.71	6.05	8.07	847	902	1316

2.5 Climate scenarios

In this report we present results from seven different climate change experiments (Table 2). These are combinations of driving fields from different global climate models (Ch.2.1), different regional climate model set-ups (Ch.2.2), and different emissions scenarios (Ch.2.4).

The experiments with RCAO are so called time slice experiments in which the model was first run for a control period (CTRL) representing the recent climate and then subsequently for a future time period under a given emissions scenario. These experiments are described and discussed in more detail in Räisänen et al. (2003, 2004) and put in the context of other regional climate model simulations in the PRUDENCE project (e.g. Christensen and Christensen, 2007; Déqué et al., 2007; Jacob et al., 2007, Kjellström et al., 2007). The transient experiments with RCA3 are continuous for the whole time period including also the recent decades. For both types of simulations it should be stressed that the control period is representative for the actual time period only in a climatological sense and not in a sense of representing the actual weather at a specific point in time or even a specific year.

Table 2 also contains information on one simulation in which RCA3 was run with boundary conditions from ERA40 (See Ch.2.3).

Table 2. *Downscaling runs presented in this report.*

No	Abbreviation	GCM	RCM	Emissions scenario	Time period
1	RCAO-H-CTRL	HadAM3H	RCAO	CTRL	1961-1990
2	RCAO-E-CTRL	ECHAM4/OPYC3	RCAO	CTRL	1961-1990
3	RCAO-H-B2	HadAM3H	RCAO	B2	2071-2100
4	RCAO-H-A2	HadAM3H	RCAO	A2	2071-2100
5	RCAO-E-B2	ECHAM4/OPYC3	RCAO	B2	2071-2100
6	RCAO-E-A2	ECHAM4/OPYC3	RCAO	A2	2071-2100
7	RCA3-E-B2	ECHAM4/OPYC3	RCA3	B2	1961-2100
8	RCA3-E-A2	ECHAM4/OPYC3	RCA3	A2	1961-2100
9	RCA3-E5-A1B	ECHAM5/MPI-OM	RCA3	A1B	1951-2100
10	RCA3-ERA40	ERA40 (boundary conditions)	RCA3		1961-2005*

* see Ch. 2.3

As a final remark on the scenarios we note that differences between different GCMs depend both on differences in the formulation of the GCMs and on differences in initial conditions used in the GCMs in the different climate change experiments.

2.6 Evaluation of RCA

Both RCAO (RCA2) and RCA3 have been evaluated against present-day climate. Jones et al. (2004) discuss. Given appropriate boundary conditions these studies show that RCA is capable of reproducing many aspects of the observed climate, both in terms of means and variability. In the following we summarize their findings with focus on some aspects that are relevant to the climate change indices presented in this report.

- The temperature climate in RCA2 was shown to be well simulated by Jones et al. (2004) with two exceptions, both over central-southern Europe; a cold bias (~1-2^{o}C) in winter and a warm bias (~1-2^{o}C) in summer. Associated with the summertime warm bias, a dry bias in precipitation was found. Despite this it was found that the model captured a number of high-resolution features of the precipitation climate in all seasons and all areas. Notable problems with RCA2 were the representation of clear sky radiation (contributing to the biases in temperature), a tendency for too frequent weak precipitation events, and some problems related to the link between cloud amounts and simulated longwave radiation. Several of these aspects were considered in the development of RCA3.

- For RCA3 Kjellström et al. (2005) show that seasonal mean temperature errors were generally within ±1°C except during winter when two major biases were identified; a positive bias in the north-eastern parts of the model domain, and a negative bias in the Mediterranean region. The reasons for these biases were traced back to the cloud water content, the downward longwave radiation, and the clear-sky downward shortwave radiation. They all contribute to underestimations in the diurnal temperature range and the annual temperature range in many areas in the model. These underestimations are most pronounced in the extremes. In general RCA3 underestimates the 95th percentile T_2max (hot conditions) by some 0 to 6°C, with the exception of the Mediterranean region where instead the 95th percentile is overestimated by 0 to 6°C at many locations during spring, summer and fall. In the north-eastern part of the region the model consistently overestimates the very low temperatures (5th percentile T_2min), more so during autumn and winter. In many areas precipitation biases are smaller than in the corresponding reanalysis data used as boundary conditions, probably thanks to the higher resolution. Compared to the observational climatologies RCA3 tends, nevertheless, to overestimate precipitation in northern Europe during summer and underestimate it in the south-east. A parameterisation of wind gusts is evaluated against a climatology for Sweden showing encouragingly good results.

In general, RCA3 shows equally good, or better, correspondence to climatologies as compared to RCA2. Among other things there are improvements in the representation of the interannual variability in Mean Sea Level Pressure (MSLP) during all seasons. However, there remains a bias in the pressure pattern over the Mediterranean Sea during winter when the MSLP is too high, indicating a problem in cyclone formation in that area. The seasonal mean temperature errors in RCA3 are smaller than in earlier model versions for most areas with the exception of north-western Russia as mentioned above. The large summertime bias in south-eastern Europe as reported in RCA2 (and other RCMs) has been substantially improved. This is also the area and season where the only notable difference in the precipitation climate compared to RCA2 is found. RCA3 simulates more precipitation in better agreement to observations. Also the snow climate, evaluated against Swedish observations, shows an improvement compared to RCA2.

3. Climate indices

The climate is usually described in terms of basic variables such as temperature and precipitation. Furthermore, usually mean values and seasonal variations are given. Typical climate indices, some of which are presented in this report, are based on yearly, seasonal or monthly values (or sums). The climate is though not only represented by mean values and seasonal variations. Rare extreme events are also an integral part of the climate. Extremes of a short-lived nature (e.g. windstorms, heavy downpours, etc.) often have a rather local extent but extremes of a persistent nature (e.g. heat and cold spells) typically cover larger regions. For climate models to describe in particular transient extremes high spatial resolution is needed. The Rossby Centre regional climate models fulfil these demands. Therefore it is possible to analyse how the occurrence of different extreme events may change under different future scenarios.

There are many kinds of climate extremes. Some last only a short while, such as a heavy shower or a windstorm. Others are linked to the dominating weather situation, and can persist much longer, such as a heat wave or an unusually cold period, a period of drought or a sequence of rain events. Each day in such an event is not necessarily extreme in itself. Rather, it is the accumulated effect over a long period that becomes noticeable.

Climate extremes can be defined as climatologically rare events (infrequent) but also based on how they affect the society and the environment. There are climatologically rare (i.e. extreme) events that have little impact on society (e.g. high air pressure), and climatologically not so rare events that still may have considerable impacts (e.g. heavy snowfall, freezing rain, or windstorms). It is therefore important to know the limitations to ability for society and environment to cope with climate extremes without serious stress.

Examples of different kinds of climate extremes are:

- Maximum- and minimum-values (e.g. lowest temperature during the day in January).
- Number of times a special threshold value is exceeded or the conditions are below (e.g. number of days when it rains more than 25 mm)
- Longest period when a threshold values is exceeded or the conditions are below (e.g. longest summer drought)
- The first or last occurrence of a certain weather condition (e.g. last frost in spring)

3.1 Climate indices – earlier studies

A brief description is given here below on some recent initiatives that contribute to the development of climate indices. It is worth mentioning that the initiatives to some extent collaborate and even overlap. The result is that many indices are identical or similar despite different terminology. The development of definitions and refinement of calculation methods is an ongoing activity.

After some early European initiatives (Heino et al., 1999, Tuomenvirta et al., 2000, Frich et al., 2002) the European Climate Support Network (ECSN) initiated the European Climate Assessment & Dataset (ECA&D, <http://eca.knmi.nl/>) managed by KNMI and supported by the Network of European Meteorological Services (EUMETNET). A database with daily observations has been put together, mainly based on data delivered from the national meteorological institutes (Klein Tank et al., 2002). Within the project work is done to homogenise data to be able to calculate a number of climate indices in a consistent manner.

Within an EU-project, EMULATE, a selection of climate indices mainly based on temperatures has been studied for a European station network (Moberg et al., 2006).

Internationally coordinated work has been conducted within CC1/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI <http://www.clivar.org/organization/etccdi/etccdi.php>) (Karl et al., 1999, Petersen et al., 2001). Within this working group 27 Core Indices have been developed. A special software tool has been produced for standardised calculation of those indices (ClimDex, <http://cccma.seos.uvic.ca/ETCCDMI/index.shtml>). The indices proposed by ECA&D correspond to a large extent with the ETCCDI indices. Because these indices are designed to be independent on climatic zone some of them are somewhat involved.

Both ECA&D and ETCCDI focus on observational data. The EU-financed project consortium MICE, PRUDENCE and STARDEX focused on climate model data. Within MICE preliminary analyses of a large number of extreme indices were made focusing on different applications. Within PRUDENCE a number of indices were calculated from an ensemble of regional climate models. Within STARDEX it was examined how well a smaller number of indices, mainly from the ETCCDI's list, can be calculated by statistical downscaling from GCM data.

Several of the groups have delivered GCM scenario data for a selected number of extreme indices to IPCC Fourth Assessment Report, including attempts to describe the large scale climate development in more rich and versatile ways than before.

A selection of indices with special focus on Swedish conditions (1961-1990) is presented in Sveriges Nationalatlas (Vedin and Raab, 2004).

3.2 Climate indices – this study

In some sectors there is a high awareness regarding that specific weather conditions may play a major role in the present climate, but a rather limited knowledge regarding possible impacts of future climate change (Rummukainen et al., 2005). In our work, a new approach of formulating climate indices was implemented. The starting point was the suggestions by stakeholders, mainly different sector expert groups, on what climate extremes were important from their perspective. They expressed their needs of information in the context of vulnerability studies within the different sectors. The requests were typically of general nature and related to a broad problem where climate change were expected to become important and not formulated as specific requests for well-defined indices. The technical formulation was then made by the Rossby Centre, taking into account data availability and assessed data/index reliability. This led to a deletion of some of the more complicated indices combining different climate variables. Our climate indices are calculated from climate model output of 2m-temperature (mean, maximum and minimum), surface temperature, precipitation (also separated into rain and snow), snow on ground (water content, cover and depth), wind (mean and gust), cloudbase height, relative humidity, radiation (longwave and shortwave), evapotranspiration, runoff and lake ice. If more than 1% water over land, according to the landfraction-database, this is considered as lake area. For Sweden lake areas are classified as shallow (about 3 m depth), medium deep (about 7.5 m depth) and deep (≥10 m) according to a special database for Sweden. Outside Sweden all lakes are considered as 10 m deep in the model, except for the more specified lake Ladoga.

All indices are calculated as mean values of the annual index values during 30-year periods. Several indices are built around some threshold value that has to be exceeded (in either direction). There are basically three issues to consider when selecting such a threshold. Firstly, for indices relevant to some specific area of application, well established thresholds may exist, for other indices specified thresholds do not exist. Secondly, thresholds defined for gridcell data from regional climate models are not necessarily directly transferable to point measurements, i.e standard meteorological observations. The gridcell size of the regional climate model is in the present setup about 48 km x 48 km, thus the data is representative for some 2300 km^2. This is mainly an issue for small-scale processes like convective rainfall and wind. Thirdly, the climate model produces some systematic errors (biases) (see Ch. 2.6) that affect both mean climate and climate variability. The standard method of accounting for such biases is to analyse the difference in climate between a reference period (typically 1961-1990) and the relevant future period. This approach is also applicable to climate indices in general, but may not work well for indices including thresholds. The reason for this is that a threshold may introduce a strong nonlinearity. To fully account for these limitations is a complicated task that includes substantial research and development efforts. An alternative and in this context feasible approach is to empirically account for the limitations by adjusting the threshold.

Here follows a brief description of the considerations behind the selected threshold values. The total list of indices used in this study is found in Appendix 2.

Intensive precipitation

Intensive convective precipitation takes place at a spatial scale much smaller than the grid resolution. Thus, it is parameterised in the model and the resulting precipitation amount is then distributed over the whole gridcell area. The resulting amount, that is an average over the whole area, is much lower than what is actually produced locally over a small fraction of the gridcell. For example, if the model produces 10 mm of convective precipitation concentrated to 10 % of the gridcell then the local amount received would be 100 mm and, likewise, a simulated precipitation amount of 25 mm translates to 250 mm over 10 % of the gridcell area, which is a very high precipitation amount rarely observed in Sweden. In reality, the area of convective cells varies which complicates such translations. However, the thresholds 10 mm and 25 mm have previously been used to indicate what has become known as ‘heavy precipitation’ and ‘extreme precipitation’ (Christensen et al., 2001).

Wet periods

For assessments of extended wet periods maximum precipitation accumulated over 7 days, which is a period length towards the upper end of the synoptic timescale determined by the life-time of extra-tropical cyclones over the North Atlantic-European region. For longer timescales, wet conditions are also determined by the evapotranspiration, which is the reason why indices for longer periods (7, 14, 30, 60 days) instead make use of the effective precipitation (i.e. precipitation minus evapotranspiration) accumulated over selected time period.

Droughts

Droughts are complex phenomena that very much is defined by a combination of context and balance between water demand and availability (Hisdal and Tallaksen, 2000; Demuth and Stahl, 2001). Here, we focus on meteorological drought, i.e. low or lacking precipitation. When using standard equipment for precipitation measurements the lowest measurable amount is typically 0.1 mm, which thus provides a natural definition between dry and wet days. However, a climate model produces arbitrarily low precipitation amounts, and the threshold between dry and wet days depends on model and spatial resolution. To be comparable with observational data the threshold is typically higher than 0.1 mm (Bärring et al., 2006). Here we use 1.0 mm as threshold for delineating dry and wet days.

Snow cover

Snow cover is included as separate tiles of variable area in the land surface scheme (Samuelsson et al., 2006). Three snow tiles may be present, one for open, one for forest and one for ice areas. In each tile snow density and snow water equivalent is modelled. From these variables we calculate the snow cover depth and areal extent. The land and ice part of a grid cell can be snow covered. Snow cover for forest, open land and ice can be 1-95%, respectively. The working groups were particularly interested in possible changes to thin (>0-10 cm) and medium thick (>10-20 cm) snow depths. The decrease in thick (>20 cm) snowcover is more pronounced compared to the change of thin and medium thick snowcover, resulting in an increase in frequency of days having these thinner snow depths (Figure 2).

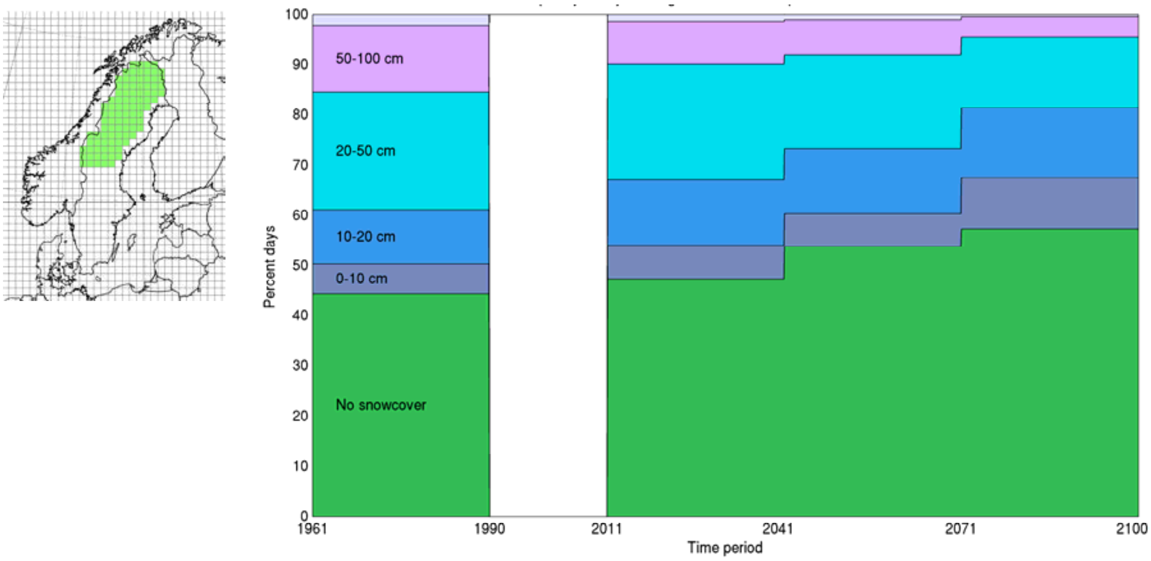

Figure 2. *Average frequency of annual days with different snowdepths within the area marked on the map. The large decrease is in days with thick (>20 cm) snowcover, which results in an increase in frequency of days with thin (>0-10 cm) and medium thick (>10-20 cm) snow cover.*

Extreme temperatures

In general, temperature conditions are well simulated by the model (see Ch. 2.6), but there is an increasing bias the more extreme the temperature becomes (Kjellström et al., 2005; Kjellström et al., 2007). Additionally, the diurnal temperature cycle is too small. This affects several indices devised to gauge changes in high temperature conditions, such as hot days and heat waves, 'tropical nights', 'hot summer days', cooling requirements for buildings, and so on. In Sweden the threshold 25 °C is commonly used for warm conditions, except for the standard threshold of 20 °C for tropical nights. To account for the biases, that in effect result in too low a frequency of days reaching above 25 °C and nights reaching above 20 °C, we changed the thresholds based on empirical tests to 20 °C for (17°C for tropical nights).

Growing season and vegetation period

The relationship between climate and vegetation in general is covered by several well established climate indices. Length of the growing season and start/end of the vegetation period are frequently used. They are all based on the concept growing degree days, which is the temperature sum above a threshold. For agricultural purposes the threshold is often taken to be +5 °C, and in forestry it is +2 °C because of the different plant physiological response to temperature. The start of the vegetation period is defined as the date (day number) of the fourth day of the first consecutive four-day period having daily mean temperature above the threshold (+5 °C or +2 °C). Similarly, the end of the vegetation period is defined as the date (day number) of the last day of the last consecutive four-day period having daily mean temperature above the threshold. The length of the growing season is then simply the number of days between the start and end of the vegetation period. In addition, a specialised index giving the degree-days above the threshold +8 °C during the growing season was calculated.

Cold conditions

The requested indices on cold conditions mainly focus on conditions close to the freezing/melting point, rather than cold extremes. Thus, the natural threshold of ±0 °C appears in several indices. One index focuses on freeze-thaw situations where both the 2m daily minimum temperature drops below the freezing point and the 2m daily maximum temperature reaches above the melting point. Two indices with threshold -7 °C was developed for studies on changes in insect survival.

Wind

Average wind conditions are well simulated by the regional models RCAO, and RCA3. But extreme winds are underestimated in RCAO. The main reason for this is that extreme wind speeds, i.e. wind gusts, involve small-scale processes that are not directly resolved at the gridcell scale. In RCA3 a specific wind gust parameterisation scheme (Brasseur et al., 2001; Nordström, 2005) is included. In this work the index showing frequency of windstorms is based on the gust wind simulated by the model and we follow the standard threshold for gale winds 21 m s^{-1}.

Low clouds

Low clouds are of importance for air traffic as they make flying according to visual flying rules impossible. Especially in the vicinity of airports they may be a hindrance for take off and landings. Low clouds are represented by clouds with a cloud base of at most 100 m in the present set of indices. It is required that at least half of the grid box is covered by clouds; this corresponds to cloud observations of at least four octas (4/8) according to SYNOP[2] and METAR[3].

Mould and freezing rain

Two specialised indices were requested to get some initial information on more complex specific weather conditions. One is related to the problem of excessive humid conditions causing mould in buildings. As a tentative first step an index was devised that counts the number of days with both 2m relative daily mean humidity exceeding 90% and 2m daily mean temperature over 10 °C. The other index was devised to capture conditions with risk for freezing rain by counting days with both 2m-maximum temperature not reaching above the melting point and more than 0.5 mm of rainfall (not general precipitation).

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[2] SYNOP (surface synoptic observations) is a numerical code used for reporting weather observations from a manual or automatic weather station.

[3] METAR (aviation routine weather report) is a format for reporting weather information and is predominantly used by pilots as part of a pre-flight weather briefing.

4. Web-application

There are several thousands of climate index maps available on the attached DVD (and made available on the Internet), based on 51 indices calculated with data from six regional climate scenarios and one ERA40-driven climate simulation (see Ch.2). The six climate scenarios are based on calculations with two emissions scenarios, two global models and two regional models. The downscaling runs are listed in table 2 and all are represented as indices on the DVD (and on the Internet), except the RCA3-E5-A1B.

To facilitate the use of the prepared climate index maps, an interactive web-application was made. It allows the user to choose an index and then compare the results across the different scenarios. There are two main categories of map provision; mean values for thirty-year periods ("Climate scenario maps") and differences between different thirty-year periods and the reference period of 1961-1990 ("Difference maps"). For practical reasons the maps are grouped in three parts named "Ut", "El" and "SGU" according to three different target groups.

Frequency distributions of wind speed at 70 m height above ground are available as difference maps (follow the link "Wind speed"). Both relative and absolute values for 25, 50 75, 90, 95 and 99 percentiles are available. A special application was made for wind directions, analyzed for 18 grid squares representing Swedish locations (the link "Wind direction" on the Internet). The wind directions are presented in the form of wind roses.

General information on the results, our models, data, indices, maps and denominations is also available along with references. Information on how to use the DVD and where the material is available on the Internet is found in Appendix 5.

4.1 Maps in frames

Seven different versions of the web-application exist: three Climate scenario maps (Ut, El, SGU), three Difference maps (Ut, El, SGU) and one Wind speed. The seven versions work in the same way.

The user first has to choose either Europe or Scandinavia as the geographical area. Thereafter the choice is between 44 indices (Ut), 14 (El) and 11 (SGU). The indices are called climate variables. Depending on choice of climate variable, different possible choices appear under "Frame". Different combinations of regional models and time periods are available. Depending on choice under "Frame", different choices appear under "Driver"; global model, emissions scenario or ERA40.

The wind speed application has only one geographical area (Nordic) and the climate variables to choose between are the 6 different percentiles expressed as absolute and relative values. For this application there are two climate scenarios available.

The maps in frames can be presented both for the web and for printing. The choice is between format A3 and A4. All maps can be enlarged by clicking on them and it is possible to print, store and send them individually. An example of how the application works is illustrated in Figures 3 and 4.

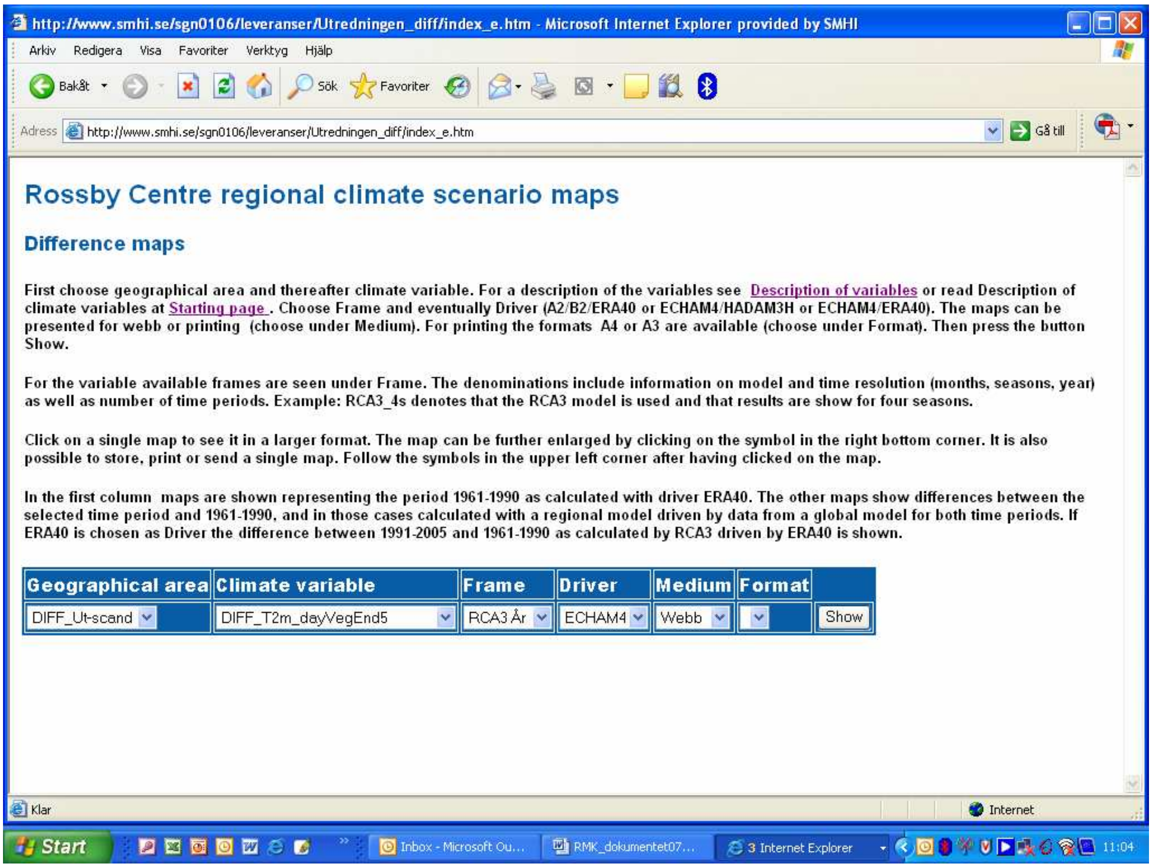

Figure 3. *An example of the web-application. In this case Difference maps-Ut has been chosen. The result is seen in figure 4.*

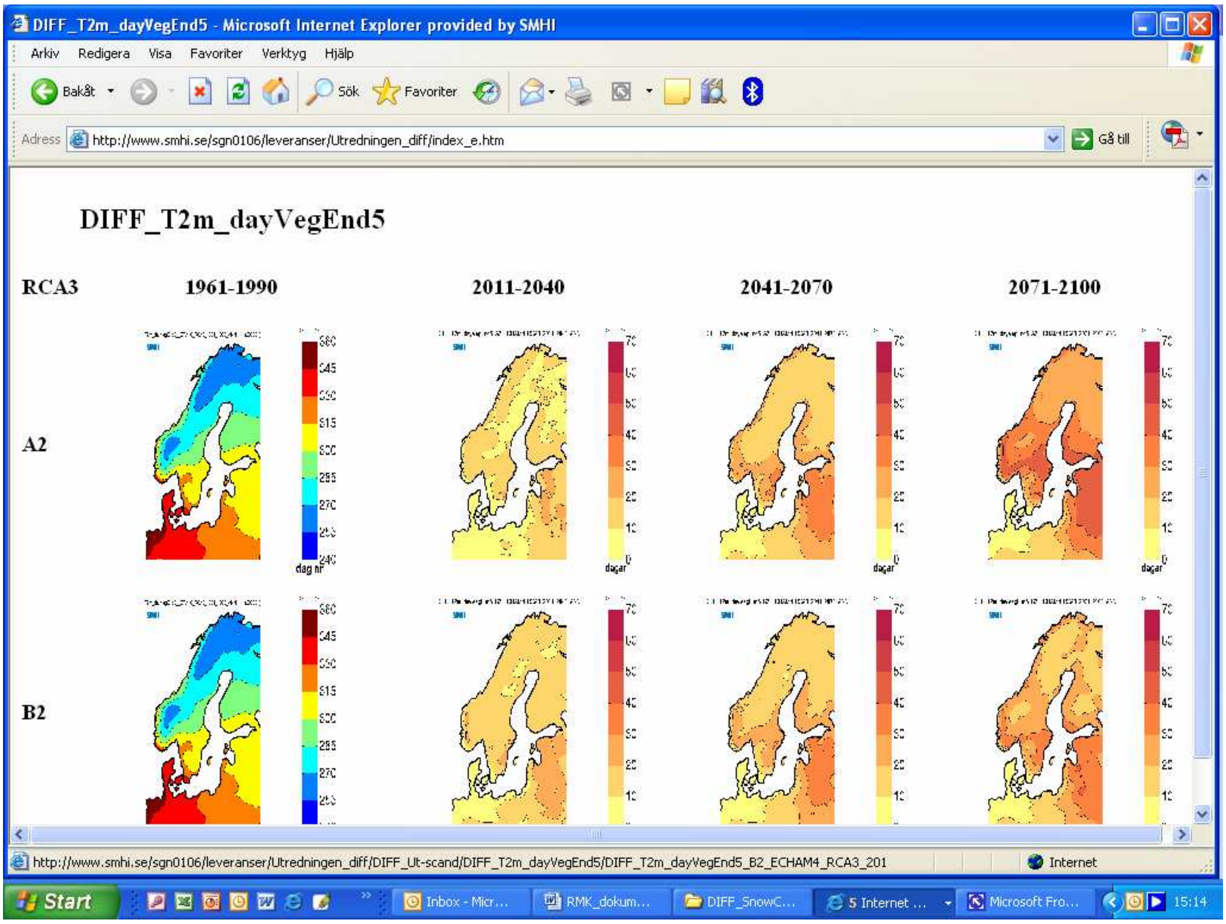

Figure 4. *The result of the choices made as shown in figure 3 is here presented as it appears on the screen. The presentation is adapted to printing on A4 format. The climate variable is "End of the growing season, with threshold 5 ºC" (T2m_dayVegEnd5) and the calculations are based on the two scenarios A2 and B2 as calculated with the regional climate model RCA3 with data from the global climate model ECHAM4/OPYC3. The reference period 1961-1990 is represented by calculations with RCA3 driven by ERA40-data. For the periods 2011-2040, 2041-2070 and 2071-2100 difference maps are shown.*

4.2 Wind roses

Wind directions, analyzed for 18 grid squares representing Swedish locations, are presented in the form of wind roses (the link Wind direction). They represent different seasons or annual values. In each figure, 30-year periods are shown with separate colours. The frequencies (%) of wind directions are specified in 10-degree intervals (0-10, 10-20, ..., 350-360 degrees). The calm days have been sorted out before calculating the frequencies. Calm days are defined as days when the wind speed is below 0.5 m/s. The frequencies of calm days are stated in the diagrams. Two climate scenarios are available.

All wind roses can be enlarged by clicking on them and it is possible to print, store and send them individually. An example on the wind roses application is seen in Figure 5. This application can only be found on the Internet (see Appendix 5).

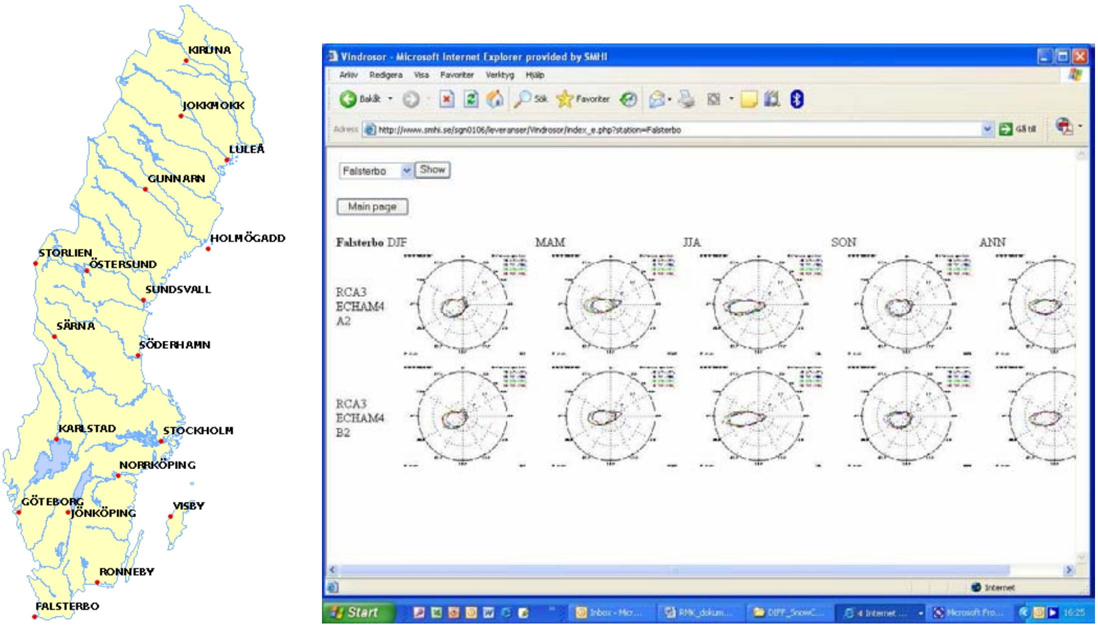

Figure 5. *The places representing the wind areas are marked on the map to the left. To the right an example of presentation of wind roses is seen.*

5. General results for Sweden from climate scenarios

As will be shown in this chapter, the climate scenarios for Sweden agree to a large extent with each other both in terms of the size of the climate change signal and in terms of its geographical patterns. By the end of the century, much of the climate change signal is determined by the emissions scenario. There are, however, also substantial differences between the scenarios that depend on choice of GCM. Such differences are seen in the regional climate change signal since it, to a large extent, is affected by changes in the large-scale circulation. In some cases a scenario with smaller emissions can even lead to a larger regional climate change signal than a scenario with larger emissions. Furthermore, climate variables also incorporate an effect of (simulated) natural variability, which might explain some of the apparent differences between the scenarios. These differences should lose in importance with time, when the climate change signal due to increased greenhouse gas concentrations grows but noticeable differences between different members also shows up by the end of the century (e.g. Pinto et al., 2007). An example of how different the evolution with time can be is shown in Figure 6 showing seasonal mean change in temperature in Sweden in RCA3-E-B2, RCA3-E-A2 and RCA3-E5-A1B. Note especially the absence of a strong trend during the first decades in the RCA3-E5-A1B scenario compared to the other two that show an early strong increase in temperature. By the end of the century these simulations are more in line with what would be expected given changes in the forcing with the strongest climate change signal in the A2-scenario. In Appendix 3 changes in temperature and precipitation for Sweden divided in a northern and a southern part is shown for these three simulations.

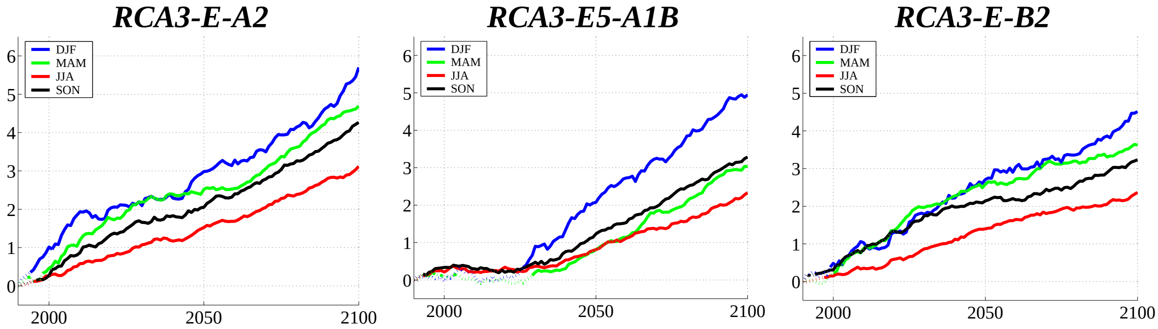

Figure 6. *Changes in seasonal and area averaged temperature for Sweden in the three transient simulations. Periods that are at the 95% level statistically different from the control period are denoted with a full line. Units are °C.*

Finally, the formulations of the RCM contribute to the climate change signal. Separate representation of different processes in the two model versions used here, RCA2 and RCA3, implies different sensitivities to a changing climate. Specifically, RCA3 is less sensitive to warming, both in winter and summer as discussed in Kjellström et al. (2005).

5.1 Temperature, snow and seasons

By 2071-2100, the Swedish annual mean temperature is projected to increase between 2.5 and 4.5 ºC, compared to the period 1961-1990. Despite the high variability between years the trend is clear. The projected changes are statistically significant[4)] already by the much earlier period of 2011-2040. More detailed studies reveal that the temperature changes are especially pronounced during winter, and reach between 2.8 and 5.5 ºC by 2071-2100. The larger increase during winter than in summer is connected to the snow cover reduction in a warmer climate. This affects the local and regional surface energy balance and near-surface atmospheric conditions leading to some enhancement of the basic warming. The largest increase during winter is expected along the coast of Norrland and in Svealand (the middle part of the country). These are the areas where the snowcover is decreased the most.

Projected changes in snow concern both its total cover and the length of the snow season. The part of the year with snowcover becomes shorter with at least one month by 2071-2100

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[4] With statistic significance is here meant that, given the simulated between year variability during the control period, there is at maximum 5 % risk that the climate change signal is by chance. A more elaborate description on how this is calculated can be found in Kjellström et al. (2005).

in all of the scenarios. In Skåne and along the coast of Götaland, the snow season is short already today and the snow more or less disappears in the scenarios. The largest changes are calculated for parts of Svealand and the coast of Norrland, and amount to between 2 and 4 month shortening of the snow season. At the same time as the snow season length and snowcover extension decreases, the maximum snow depth decreases all over the country. The areas with presently small amounts of snow are affected the most, but reductions are projected also in the mountain area.

The large change in temperature during winter affects not only the seasonal mean conditions. Projected changes are strikingly different for the coldest and for the mildest winter days. The coldest days are affected the most by up to more than twice the changes in the mean. The temperature during the mildest winter days changes as well, but by smaller amounts. This applies throughout the country. During the summer there is some similar uneven change between the warmer and the cooler days in the south, where also the seasonal mean temperature change is largest. The change is larger for the warmer days than for the mean temperatures as well as for the coolest summer days. In the rest of the country the temperature increase is expected to be more or less the same both during cool and warm summer days.

The projected warming brings about a movement of climate zones towards the north. This has been shown for one of the scenarios, RCAO-H-A2, by de Castro et al. (2007). The temperature climate has a large influence on society and nature. One example is the suitability of a certain region for specific plants. The temperature climate can be described with mean values, variability and extremes. In some cases, the frequencies of the number of days with temperatures in certain intervals are also of interest. One example is the growing season. In the scenarios described above it is determined as the part of the year when the daily mean temperature is above 5 ºC. With the projected warming, the growing season increases with 1-2 months except for the most southern parts where the increase can be up to 3 months. A longer summer with warmer conditions also leads to increased need for cooling. If we look at the whole energy need for the country this is probably more than compensated for by a decreased heating need between 10-30% in different parts of the country and depending on scenario.

5.2 Precipitation

The annual mean precipitation over Sweden is projected to increase during the century with a little less than 10% up to more than 20%. Precipitation shows a higher variation than temperature between years and decades. The projected increase is nevertheless clear. The precipitation increase is highest during winter. However, the projections based on the different global climate models also differ quite a lot in this respect. The simulations based on the German models are characterised by more forceful westerly winds over the Nordic area, leading to more winter precipitation. The simulation based on the British model does not indicate such changes in westerly winds, and there is even some decrease of precipitation in parts of western Scandinavia. There is nevertheless more precipitation east of the mountains, driven by more pronounced southeasterly regional circulation. During summer southern Sweden is expected to have less precipitation, together with the rest of Europe further south. This is common to all these scenarios that are in line with the larger ensemble of GCM-scenarios presented in the IPCC AR4 report (Christensen et al., 2007). In the most northern part of Sweden, precipitation is expected to increase slightly even during summer. The rate of change differs in the transient simulations based on ECHAM4 and ECHAM5 models respectively. The increase in Swedish precipitation in fall, winter and spring is statistically significant[4)] already by the period 2011-2040 in the ECHAM4 based simulations while it is not increasing as fast in the ECHAM5 based simulation (Figure App3-2).

In all scenarios extreme precipitation, expressed as 24-hourly precipitation, is projected to increase. This occurs both in regions where the total precipitation increases, and in regions where it decreases. For southern Sweden during summer it can be said that it will be drier and there will be rain less often, but when it rains it pours even more than before. In northern Sweden in summer and for the whole country during winter, precipitation will be more frequent and also the amounts will increase.

5.3 Wind

Wind conditions are only slightly affected during summer according to the different scenarios. During the rest of the year and especially during winter the changes depend on the choice of global model. In the calculations based on the ECHAM4 global model, the near-surface winds increase with 7-13% towards the end of the century over Sweden in the mean. Slightly higher increases are found over the Baltic Sea in winter, especially for the Bothnian Bay and the Bothnian Sea. This is caused by less sea ice cover which in turn leads to a more unstable stratification of the boundary layer and this promotes higher wind speeds. Similar relatively higher increases over those regions than over the adjacent land areas are seen in all scenarios independent of GCM. The regional projections based on the HadAM3H and the ECHAM5 global models show generally only small changes in the regional wind climate. A similar effect, with increased winds due to higher sea surface temperature, is seen in summer for calculations based on the HadAM3H model. The maximum wind speed is expected to increase about as much as the mean wind speed. Changes in the wind climate in the ECHAM4 and HadAM3-based simulations with RCAO are discussed in more detail in Meier et al., 2006 and Pryor et al., 2005.

5.4 The Baltic Sea

The global warming leads to a higher sea level due to thermal expansion of the water and the melting of land-based ice (glaciers). Globally the effects are currently estimated to result in a global mean sea level rise of 18-59 cm increase at the end of the century compared to the end of last century (AR4, IPCC 2007), with some uncertainty especially towards even higher values. At regional scales, the sea level rise will very possibly deviate some from the global mean changes. In the Baltic Sea region, for example, changes in wind need to be taken into account, where more westerly winds are expected to lead to higher water levels. The ongoing land uplift is a very important process counteracting the increased sea level in the northern parts of the region. For the southern parts of Sweden the land uplift is too small for that, however.

Rossby Centre regional climate models have been used for projections of regional changes for the Baltic Sea. The use of regional models is necessary as this regional sea cannot be represented realistically with the coarser resolution of today's global climate models. The results are clear on the fact that a regional warming affects even the Baltic Sea. Based on the made projections, the Baltic Sea surface warming is highest in the north during summer and in the south during winter and spring. On a yearly basis the sea surface warms by a little less than 3 ºC over the 20th century. During different seasons changes can reach up to 5 ºC in some parts of the basin. Circulation effects (upwelling and downwelling) cause large variations between different parts of the Baltic Sea. The regional warming leads to a strong decrease in occurence of sea ice in the Baltic Sea. In the projections, ice will towards the end of the century form during a normal year only in parts of the Bothnian Bay and far inside the Gulf of Finland.

The increased precipitation in large parts of the Baltic Basin leads to an increase of fresh water to the Baltic Sea. More fresh water may cause a dilution of its characteristic brackish waters. Alongside increased precipitation also increased westerly winds, as noted in some of the projections, may also contribute to increased amounts of fresh water in the sea, when the sea level rises and salt water intrusions from the North Sea become rarer. The temperature changes, as well as those in the wind, may influence both mixing and salt water intrusions and thus the stratification of the Baltic Sea. However, according to the calculations so far, neither the halocline nor the thermocline will change particularly much. Changed precipitation may influence the water quality also in other ways, when the runoff from the rivers around the Baltic Sea changes in different ways, such as increases in the less populated north and decreases in the south dominated by agricultural activities.

5.5 Variability and extremes

Regarding extreme events, the picture that evolves is of a future climate with changes both in frequencies and degrees of some extreme events in the region. The cold extremes reduce sharply during the winter half year. During the summer, some intensification of warm spells is projected, but the largest such changes are located further down south in Europe. It is only in the southernmost parts of Sweden that the temperature during the warmest days increases proportionally more than the summer mean temperature does. The precipitation climate seems to move towards wetter conditions both regarding the total amounts and also intensity. In southern Sweden summertime the total amount of rain decreases, but the intensity in showers does increase at the same time.

6. Results for Europe from climate scenario indices

In this chapter the climate scenario indices presented on the DVD are commented for the European scale. The descriptions on projected changes are based on results from the six A2 and B2 scenarios (No. 3-8 in Table 2). Statements in the text, including numbers and ranges, refer to all six scenarios at the end of the century (2071-2100) unless specifically noted. The RCA3-E5-A1B scenario is not included on the DVD and thus excluded in this chapter, with exception of wind speed at 70 m (W70 mean). Some projected changes (2071-2100) on the European scale regarding temperature, precipitation and snow as calculated including also RCA3-E5-A1B is found in Appendix 4.

The main features of the simulations in today's climate are summarized above (Ch. 2.6). A more detailed description of the indices, including weaknesses in them, is given in Ch. 3.2. Together with some further comments in the text below, this information gives some indications in relation to the different indices on how reliable the results are even if we have not performed a rigorous evaluation of all indices.

The climate change scenarios indicate a rapid increase in temperature in Europe in all seasons with some regional differences. The changes are most pronounced in southern Europe during summer and in north-eastern Europe during winter. The large response in temperature in these regions and seasons are due to positive feedback mechanisms in which the climate change signal is amplified, in summer due to drying of the soils and in winter due to reductions in the snow cover. Other aspects of the climate change signal are; increases in precipitation on an annual mean basis in northern Europe and decreases in the Mediterranean area and a wind climate that is very sensitive to how the large-scale atmospheric circulation given by the boundary data from the GCMs changes.

6.1 Temperature

The temperature increases in all future scenarios in all of Europe, not only the average temperature but also maximum and minimum temperatures. As a result of the increasing temperature, temperature indices are also increasing (or decreasing in the cases when they measure low temperatures). The vegetation period gets longer, warm days will be warmer and more frequent, the need for cooling will increase, cool days will be fewer and warmer and the need for heating will decrease. Temperature increase (in number of degrees) is largest in winter in northern Europe and in summer in southern Europe.

Mean temperature

T2m mean

The temperature increases until the year 2100 in all future scenarios. According to A2, winter temperatures increase with 3-4 ˚C in most of Europe by the end of the century, but almost twice as much in north eastern Europe and about 1 ˚C less on the British Isles. The pattern is the same in spring but as spring turns into summer the temperature increase in Scandinavia is less dramatic, 2-4 ˚C, while temperatures in southern Europe increases with up to, or even more than, 7 ˚C. In autumn, temperatures increase with 4-5 ˚C in most of Europe by the end of the century. The pattern is very similar in scenario B2, but with approximately 2 ˚C smaller amplitude.

The changes in the annual mean temperature is relatively uniform over the continent as the difference between summer and winter changes in the north and south are almost balancing. In A2 the mean annual temperature in 2071-2100 is 4-5 ˚C in northern and central Europe, and 5-7 ˚C in southwestern Europe. RCAO-H-A2 is a bit colder, 3-4 ˚C in northern Europe and 4-5 ˚C in southern Europe in 2071-2100. In the B2 scenarios the changes in annual mean temperature is about 1 ˚C less than in the corresponding A2-scenarios.

Maximum temperature

T2max mean

Maximum winter temperature increase by 1-3 ˚C in 2011-2040 and by 3-7 ˚C in 2071-2100 in northern Europe. In southern Europe the corresponding increases are 1-2 ˚C in 2011-2040 and 3-5 ˚C in 2071-2100. In spring and autumn the maximum temperature increases with 1-3 ˚C in 2011-2040 and 2-5 ˚C in 2071-2100 in most of southern Europe, with maximum increase with up to 7 ˚C on the Iberian Peninsula, and 2-4 ˚C in northern Europe. In summer 1-4 ˚C in southern Europe and 0-2 ˚C in northern Europe in 2011-2040, and more than 5 ˚C in southern and central Europe and 1-5 ˚C in northern Europe by 2071-2100.

The annual mean of the maximum temperature is increasing with 1-4 ˚C in Scandinavia and Britain, 2-5 ˚C in central Europe and 3-6 ˚C on the Iberian Peninsula.

Minimum temperature

T2min mean

The average minimum temperature in winter is -5 - -15 ˚C in northern Europe, 0- -10 ˚C in central Europe and 0-5 ˚C in southern and western Europe in the present climate. In the same regions temperature minimum increase with 3-7 ˚C in northern Europe, 3-5 ˚C in central Europe and 2-3 ˚C in southern and western Europe until the end of the century.

In the beginning of spring the average minimum temperature is still below zero in northern Europe and the temperature is changing in the same way as in winter. Later in spring, when the average temperature is higher the change is smaller. The minimum temperature increases with 3-5 ˚C from 0-10 ˚C. The situation is opposite in southern Europe, the minimum temperature increases later in spring, with at least 3 ˚C and as much as 7 ˚C in parts of the Iberian Peninsula from 5-15 ˚C.

In summer the minimum temperature is 5-15 ˚C in northern Europe and 10-20 ˚C in southern Europe in the present climate. By the end of the century the minimum temperature increases with 3-5 ˚C in northern Europe and with at least 5 ˚C in southern Europe. In autumn the minimum temperature is between 0-10 ˚C in most of Europe and it increases with 2-4 ˚C in the scenarios.

The annual average of the minimum temperature is changing most in the northern and southern parts of Europe. By 2071-2100 the minimum temperature is increasing with 3-5 ˚C in central Europe and with 3-6 ˚C in the north and the south of Europe. RCAO gives about the same numbers but the difference between the northern, central and southern parts is not as distinct.

Cooling degree days

T2max CDD20

The number of degree days for maximum temperature over 20 ˚C (CDD20) is naturally low in winter even in a warmer climate. But CDD20 is starting to occur in February at the southern tip of the Iberian Peninsula in the period 2011-2040, which is about one month earlier than in the present climate. In April CDD20 will occur in most of the Peninsula, from 0-20 days today to more than 90 days in almost the whole region. CDD20 will then occur further north as summer approaches and more and more in later time periods. Maximum is reached in July and August when almost all of continental Europe has CDD20 over 90 days and southern Sweden has CDD20 around 30 days.

Warm days

T2max nGT20

The number of days with maximum temperature over 20˚C is more than 120 in southern Europe. North, of that, the number of days rapidly decreases to around 15 in southern Scandinavia. The number of warm days increases until 2071-2100. In southern Europe the increase is 50-60 days, and in southern Scandinavia 20-40 days. It is, of course, unrealistic that the number of days with maximum temperature over 20˚C is only about 15 in Scandinavia, Great Britain and Ireland in the present climate. This is due to model problems described in Ch. 2.6 and 3.2.

Heat wave

T2max maxHWaveGT20

The longest period of consecutive days with maximum temperature over 20 ˚C is more than 24 days in southern Europe. North, of that, the number of days rapidly decreases to around 5 in southern Scandinavia. The longest heat waves as defined by this index increases until 2071-2100. In southern Europe the longest heat wave gets more than 1.5 month longer and in southern Scandinavia 1-2 weeks longer than present. It is, of course, unrealistic that the longest period of consecutive days with maximum temperature over 20 ˚C is only about one week long at the most in Scandinavia, Great Britain and Ireland in the present climate. This is due to model problems described in Ch. 2.6 and 3.2.

Degree days over 20 ˚C

T2m DDGT20

The number of degree days for daily mean temperatures over 20 ˚C is over 100 around the Mediterranean, 10-40 in central Europe and 0-10 elsewhere as an average during 1961-

1990. DDGT20 increases in the future; with more than 300 in southern Europe, 30-240 in central Europe, 0-120 on the British Isles and 0-10 in Iceland and Scandinavia except the south west coast of Sweden according to scenario A2 where DDGT20 increases with 30-60.

Tropical Nights

T2m nTropNight

Tropical nights occur from more than 20 days/year in southern Europe to 0-2 days/year in northern Europe in the control climate. The number of tropical nights increases with up to 60 in southern Europe, 20-50 in central Europe and 5-30 in southern Sweden and Finland. In northern Scandinavia the change is small. Tropical nights will be rare even in 2071-2100. In the model output tropical nights are defined as days with minimum temperature exceeding 17 ˚C instead of the standard 20 ˚C. This is due to model problems described in chapter 2.6 and 3.2.

Cold days

T2max nLTminus7

The number of days with maximum temperature below -7 ˚C is zero, or just above zero, for the whole of Europe except the Alps, Iceland, northern Scandinavia and north eastern Europe. In these areas the number of days is somewhere between 10 and 60. The number of days with surface temperature below -7 ˚C will decrease in future to zero for practically the whole of Europe. The northern tip of Scandinavia and parts of the mountain regions in Norway and Iceland will still have days with maximum temperature below -7 ˚C, but they will occur much more seldom, not more than 30 days/year compared to 60-70 days/year in today's climate. In RCAO the area with surface temperature below -7 ˚C is at present conditions somewhat larger than in RCA3. Even in 2071-2100 days with surface temperature below -7 ˚C still occur in northern Scandinavia and Iceland according to RCAO.

Heating degree days

T2m HDD17

The number of heating degree days for daily mean temperatures below 17 ˚C is naturally high in winter in northern Europe and low in southern Europe. The number decreases in summer and increases again when autumn comes. The number of HDD17 is reduced in a future warmer climate. The reduction is largest in winter in Scandinavia, Iceland and the Alps; the areas where the number of HDD17 is large. HDD17 will be reduced with 60-100 in 2011-2040, and with 160-200 in 2071-2100 from a present value of more than 600. The pattern is similar in spring and autumn, but with lower present HDD17. In summer HDD17 is very low in most of Europe. Iceland and northern Scandinavia are the areas with highest value of HDD17, 100-300. In these areas HDD17 is reduced with 60-100 in 2071-2100. In southern Europe the change in HDD17 is small, since the value cannot go below zero.

Start of growing season (vegetation period)

T2m dayVegStart2

The start of the growing season (based on four consecutive days over 2 ˚C) occurs on day number 15-60 of the year in central Europe, 60-120 in Scandinavia and the Alps and 120-150 in the Scandinavian mountains and Iceland. In western and southern Europe the growing season as represented by this index is ongoing the whole year round.

The growing season will start earlier in a future warmer climate. Already in 2041-2070 the growing season will cover the whole year in all of Continental Europe except the Alps, and also southern Scandinavia by 2071-2100. In the areas where the growing season still has a start by the end of the century, it will occur 0-60 days earlier.

T2m dayVegStart5

The start of the growing season (based on four consecutive days over 5 ˚C) occurs on day number 30-75 of the year in central Europe, 75-135 in Scandinavia and the Alps and 135-180 in the Scandinavian mountains and Iceland. In western and southern Europe the growing season starts on day number 15-30, except for the coastline where it is ongoing the whole year.

The growing season will start earlier in a future warmer climate. Already in 2041-2070 the growing season covers the whole year in all of western and central Europe except the Alps. In Scandinavia, north eastern Europe and Iceland the start of the growing season will occur 0-50 days earlier in 2071-2100 compared to today's situation.

End of growing season (vegetation period)

T2m dayVegEnd5

The growing season ends in the present climate at day number 315-345 in central Europe; 285-315 in the Alps, southern Scandinavia and eastern Europe; and 255-285 in northern Scandinavia and Iceland. In southern and western Europe the growing season as defined here is ongoing the whole year. The growing season will be prolonged in a future warmer climate. By the end of the century the growing season will continue all year with the exception of Iceland, northern Scandinavia, north eastern Europe and the Alps. In these areas the end of the growing season will be delayed with about one month. In RCAO, and especially RCAO-H, the change is slightly smaller.

Length of growing season (vegetation period)

T2m nVegPeriod2

The growing season (based on days over 2 ˚C) is 330-360 days long in western and southern Europe. The period is shorter further north and for northern Scandinavia about 120-180 days. In the projected future the growing season is longer. In 2071-2100 the period is shorter than 300 days only in northern Scandinavia, the Alps and Iceland.

T2m nVegPeriod5

The growing season (based on days over 5 ˚C) is 330-360 days long in western and southern Europe. The period is shorter further north and for northern Scandinavia about 90-150 days. A longer growing season is projected for the future. In 2071-2100 the period is shorter than 300 days only in northern Scandinavia, eastern Europe, the Alps and Iceland.

Degree days in growing season (vegetation period)

DDGT8VegPeriod5

The number of degree days within the growing season over 8 ˚C is around 360 in western Europe and around the Mediterranean, 240-330 in central and eastern Europe and 90-240 in Scandinavia and Iceland. As both the length of the growing season and the temperature during it increases the number of degree days is expected to increase. The increase is rapid with up to more than 300 in all of Europe except northern Scandinavia and Iceland in 2071-2100.

Last Spring Frost

T2m lastSpringFrost

The last spring frost occurs in the present climate at day number 15-75 along the European south and west coast, 75-105 in central Europe and the British Isles and 105-165 in Scandinavia and Iceland. By the end of the century the last spring frost is occurring almost one month earlier in Scandinavia and eastern Europe and almost two months earlier in western and south western Europe.

“Slipperiness” index

T2m nZeroCross

A day with zero crossing is defined as a day with temperature both below and above zero (i.e. Tmax > 0 ˚C and Tmin < 0 ˚C). In winter the number of days with zero crossings is large (around 30) in most of southern and central Europe. By the end of the century the number of zero crossings will be reduced with 15-20 in this area.

In northern Scandinavia, on the other hand, the number of days with zero crossing will increase; from around 10 in the present climate to around 30 by the end of the century. In this area the number of zero crossings presently is low in winter since the temperature is far below zero, but in a warmer climate temperatures close to zero will be more common in winter.

In spring the number of zero crossings is large (around 30) in Scandinavia, Iceland and the Alps. In these areas the number of zero crossings will decrease with 15-20 by 2071-2100. In summer there are almost no zero crossings at all. In autumn there are around 20 days zero crossings in Scandinavia, Iceland and the Alps. By the end of the century they will be reduced to around 5 days.

Surface temperature below -7˚C

Tsurf nLTminus7

The number of days with surface temperature below -7 ˚C is zero, or just above zero, for the whole of Europe except Iceland, northern Scandinavia and north eastern Europe. In these areas the number of days is between 10-60 days. The number of days with surface temperature below -7 ˚C will decrease in future to zero for practically the whole of Europe. In RCAO the area with surface temperature below -7 ˚C is at present conditions somewhat larger than in RCA3. Even in 2071-2100 there will still occur days with surface temperature below -7 ˚C in northern Scandinavia and Iceland.

6.2 Sun and radiation

Long wave radiation

LWdown mean

The incoming long wave radiation varies between the seasons, from 250-300 W/m^2 in winter to 325-375 W/m^2 in summer. The change in radiation with time is on the other hand almost the same for all seasons. Radiation increases with 5-15 W/m^2 in 2011-2040, with 10-20 W/m^2 in 2041-2070 and with 20-30 W/m^2 in 2071-2100.

Shortwave radiation

SWdown mean

The average short wave radiation is large in summer, from 125 W/m^2 in northern Europe up to 300 W/m^2 around the Mediterranean and small in winter, from 0 W/m^2 in northern Europe to more than 100 W/m^2 at the southern tip of the Iberian Peninsula.

The shortwave radiation in winter and autumn is relatively unchanged with time in the future scenarios. In spring the shortwave radiation is decreasing in Scandinavia. It continues to decrease over the century and the area of decreasing radiation spreads southwards. In summer the short wave radiation is only decreasing in northern Scandinavia while most of Europe remains relatively unchanged.

Sunshine hours

SunH sum

The sum of sunshine hours has a maximum in summer with 300-400 hours/month in Europe as a whole and a minimum in summer with 0-100 hours/month in the northern parts and 100-200 hours/month in the southern parts of Europe. Small changes are expected in the future scenarios. In winter and autumn the number of sunshine hours is reduced with 10-30 h/month in northern Europe and with more than 40 h/month in eastern Europe. In spring and summer the number of sunshine hours is decreasing with 20-50 h/month in northern Scandinavia and Iceland, while the change in sunshine hours is small in the rest of Europe.

6.3 Cloudiness

Cloudy days

Cloud base nLT100

The number of days with cloud base below 100 m is changing very little. There is a tendency towards fewer days with low clouds in central Europe but only with a couple of days.

6.4 Air humidity

“Mould” index

Rh T2m nGT90GT10

Days with high relative humidity and mild temperatures are favourable for growth of mould. In this study a relative humidity over 90% in combination with temperatures above 10°C was chosen (see Ch. 3.2). These days occur in winter in Portugal and western France with up to around two weeks. In spring mould days occur in most of Europe with around 5 days, in summer the occurrence is high in Scandinavia, Britain and the Alps (around three weeks) and low around the Mediterranean (almost no days). The maximum number of “mould days” in autumn occurs in Great Britain and Ireland.

The number of “mould days” is only changing with a few days until 2011-2040. By 2071-2100 “mould days” are slightly more increasing. In winter the number of days is increasing in western Europe with 5-20. In spring the number of days is increasing in central Europe and southern Scandinavia with 5-10. In summer the number of days is increasing in northern Scandinavia with 10-30 and up to 40 in parts of Norway. In autumn the number of days is increasing in Scandinavia with 10-20.

6.5 Evapotranspiration

Evapotranspiration is the sum of all evaporation including the transpiration and is also called total evaporation. Evaporation increases with increasing temperature provided that there is enough water available at the surface (including open water bodies, soil water, snow and water intercepted on the vegetation).

Evap sum

The pattern of mean annual evapotranspiration shows a gradient from south to north with 400-900 mm/year to 200-600 mm/year. The evapotranspiration is depending on the altitude. The highest evapotranspiration is found during summer in today’s climate as well as in future climate scenarios.

The annual mean value is increasing in northern Europe with around 100 mm in A2 and around 75 mm in B2 by 2071-2100. RCAO projects slightly lower values: around 75 mm in A2 and around 50 mm in B2 by 2071-2100.

A pattern gradually evolves with increasing evapotranspiration in the northern parts especially in spring. At the same time evapotranspiration decreases in the southern parts especially in spring and summer. The influence of altitude is though clearly seen. In winter an increased evapotranspiration is mostly pronounced in central Europe.

6.6 Precipitation

The pattern of precipitation change gets more and more pronounced in the future scenarios and generally dry gets drier and wet gets wetter. What is wet and what is dry is, however, different in different seasons. Basically precipitation is increasing in winter in western and northern Europe and decreasing in all of Europe apart from the northernmost parts of Scandinavia and Finland during summer. The precipitation decrease in southern Europe may seem to be small in absolute numbers, but these areas are dry already now and thus a small change may have a large impact.

Summed precipitation

Precip sum

The winter precipitation is increasing in Scandinavia and over the British Isles with up to 50 mm/month. There is a strong gradient across Europe to the Mediterranean where precipitation decreases with as much as 50 mm/month. The winter precipitation in RCAO-H-B2 areas also increases but less than in the other scenarios. In that scenario winter precipitation is also increasing in parts of central Europe and in Italy and Greece.

In summer the drought is shifted northwards to central Europe and southern Scandinavia. Most of Europe will experience less summer precipitation in the future. Down to 50 mm/month less rain at the end of the century. Around the Mediterranean the decrease in precipitation is less in summer than in winter. However, the amount of precipitation in summer in these areas is small already now, so even if the absolute changes are small the relative changes can be large. And, obviously, if precipitation decreases to 0 mm/month, then it cannot decrease any further.

The patterns of precipitation change in spring and autumn reflects the transition between the more pronounced patterns of summer and winter. Precipitation change is quite similar in both A2 and B2 scenarios, but changes in A2 are a bit larger than in B2.

The change in annual precipitation shows a clear, strong north-southerly gradient. This pattern is evident already in the period 2011-2040 and in both future scenarios, and the gradient gets stronger in later time periods. Precipitation is projected to increase with around 50 mm/month in northern Europe and decrease with around 30 mm/month in southern Europe. In RCAO-H the gradient is not as distinct as in the other scenarios. In scenario B2 precipitation is increasing in south eastern Europe, and the only distinct precipitation increase is in south western Europe. Precipitation is also decreasing in parts of (A2) or the whole (B2) of Great Britain and Ireland. In the other scenarios most of the British Isles receive more precipitation.

Rainfall

Rainfall sum

In winter the sum of rainfall is low in northern and northeastern Europe, 0-100 mm/season, and high in parts of the British Isles and southern Europe with over 300 mm/season. In the scenarios rainfall sum is increasing the most in Iceland, Scandinavia and the Baltic States. Increases of up to 100-150 mm/season are projected by 2071-2100. Rainfall in winter is decreasing in the same period in southern Europe with 0-75 mm/season.

The sum of rainfall in spring and autumn is highest in the Alps (700-800 mm/season) and other mountainous regions (around 400 mm/season). For the most of the remaining Europe the sum of rainfall is 100-200 mm/season. At the end of the century rainfall is decreasing with 25-75 mm/season in the south while it is increasing in northern Europe. Maximum increase in this area is in western Scandinavia and Iceland with more than 150 mm/season in some parts in some scenarios. The boundary between increasing and decreasing rainfall cuts through the British Isles.

In summer rainfall is over 600 mm/season in western Scandinavia and the Alps. In the rest of northern Europe rainfall is around 200 mm/season; along the coastlines in southern Europe rainfall is below 100 mm/season. In 2071-2100 rainfall sum is decreasing the most (50-75 mm/season) in Ireland and Great Britain, central Europe and southern Scandinavia. In southern Europe rainfall is decreasing 0-25 mm/season. Rainfall increases only in northern Scandinavia and parts of Iceland, 0-50 mm/season.

The annual rainfall sum is highest in mountainous regions, 1000-1500 mm/year (and in the Alps as much as 2500 mm/year). Rainfall sum is in the rest of Europe around 500 mm/year. At the end of the century rainfall is increasing, with as much as 500 mm/year in western Scandinavia and Iceland, in the north and decreasing with 0-100 mm/year in the south. The boundary between increasing and decreasing rainfall goes from Britain in south easterly direction to Turkey. In scenario A2 it goes through central England, in scenario B2 a bit further south. In scenario RCAO-H-B2 the area of decreasing rainfall is restricted to the western part of Europe, i.e. the British Isles, France and the Iberian Peninsula.

Snowfall

Snowfall sum

In winter snow is falling with more than 50 mm/season in Iceland, Scandinavia, north eastern Europe and the Alps; in the mountainous regions with up to 400 mm/season. Snowfall is decreasing in all of Europe, except the northern tip of Scandinavia where snowfall increases with 0-10 mm/season. Snowfall is decreasing the most (50-60 mm/season) in areas with large amount of snowfall, and less in areas with little snow. In spring and autumn snow is falling with more than 50 mm/season in Iceland, the Scandinavian Mountains and the Alps. In the end of the century snowfall is decreasing in all regions with up to 60 mm/season. In summer no snow is falling.

The annual sum of snowfall is more than 100 mm/year in Iceland, northern Scandinavia and the Alps. In 2071-2100 snowfall is decreasing with at least 50 mm/season and up to 150 mm/season.

7-day maximum precipitation

Precip maxRunSum7

The maximum amount of precipitation during 7 days increases in winter in northern Europe, with 0-10 mm/7days in 2011-2040 and with 10-20 mm/7days in 2071-2100. The signal is not distinct in southern Europe; in some areas precipitation is increasing in one period and decreasing in another. A general tendency, though, are decreases in the Mediterranean area, except in the RCAO-H-B2 scenario.

Maximum 7-day precipitation increases also in spring in Scandinavia, but less than during winter. In central Europe the change is rather small, but in southern Europe a clear decrease is seen during spring. In 2071-2100 the precipitation has decreased with at least 5 mm/7days in most parts of Portugal, Spain, France, Italy and Greece.

In summer the change in the 7-day maximum precipitation is ambiguous for the first time periods, with areas of increasing and decreasing precipitation scattered over Europe. In the last time period, however, the precipitation is decreasing with 5-10 mm/7days for most part of Europe in scenario A2, except in northern Scandinavia where a small increase is seen. In the B2 scenario the geographical pattern is similar to that in the A2 scenario but not as distinct.

In autumn precipitation is increasing in Scandinavia and Britain and decreasing on the Iberian Peninsula in scenario A2 and at least parts of it in scenario B2.

Heavy precipitation

Precip nGT10

In winter the number of days/season with more than 10 mm precipitation is 0-6 days in most of Europe. Mountainous regions and coastal regions may have up to 30 days. The number of days is especially increasing in western Europe with up to 8 days. The situation is similar in spring, but the rain days are increasing only in western Scandinavia and Iceland and decreasing with one or two days in southern Europe. Britain is divided by the line of which precipitation increases on the north side and decreases on the south side.

In summer the number of days is increasing in western and central Europe. The number of days is not changing much in southern Europe, possibly because the number of days already is low. Interesting to note is that there is no decrease even if the total precipitation decreases. This finding is in line with Christensen and Christensen (2003). In autumn the number of days increases with 2-8 in northern Europe and decreases with one or two days in southern Europe.

Extreme precipitation

Precip nGT25

The number of days/year with more than 25 mm precipitation is 0-3 days in most of Europe. Mountainous regions and coastal regions may have up to 10 days. The number of days is especially increasing in western Scandinavia, Iceland and the northern parts of Great Britain and Ireland with up to 8 days in 2071-2100. RCAO-H projects a change in days with much precipitation of ±1 in most of Europe, except the south western tip of Norway where the number of days increases with up to 8 days.

Maximum precipitation intensity

Precmax max

The most extreme maxima of precipitation intensity are 5-8 mm/h found in coastal areas around the Mediterranean. For the rest of Europe maximum precipitation intensity is 3-5 mm/h except in northern Scandinavia where it is 2-3 mm/h. Maximum precipitation intensity is increasing with at least 1.0 mm/h, and in many places up to 1.8 mm/h, in Europe, excluding northern Scandinavia, the Iberian Peninsula and south eastern Europe where precipitation increases with 0.2-0.8 mm/h.

DrySpell

Precip maxDrySpell1

The longest period with no rain is relatively unchanged in winter. The largest projected change is 3-6 days shorter dry period in Scandinavia and eastern Europe. In spring and especially summer most of Europe gets longer dry periods. Around the Mediterranean the signal is a bit unclear. Some places alter between shorter and longer dry periods, but in other and larger areas the longest dry period will be more than two weeks longer than today in the last time period in scenario A2. In B2 the increase is less pronounced and smaller; 6-9 days longer dry period by 2071-2100.

The general trend is, however, that Europe will get much drier than today. RCAO predicts, with both drivers and both scenarios, even drier conditions by the end of the century than RCA3, with a two weeks longer dry period for most parts of southern and central Europe. This difference between the two models is a result of a deeper soil layer that can hold more water in RCA3 compared to RCA2 (Kjellström et al., 2005). Autumn shows about the same signal as spring. Southern and central Europe will get increasingly drier, while northern Europe will get a little shorter dry periods.

Number of dry days

Precip nDryDay1

The number of days with less than 1 mm precipitation is in winter decreasing with 1-5 days/month in 2071-2100 from a present value of around 20 days/month in northern Europe and increasing with 1-5 days/month in 2071-2100 from a present value of around 20 days/month in southern Europe. The pattern in spring is about the same, but the area of increasing numbers of dry days is more widespread.

In summer the number of dry days is increasing in the whole of Europe except northern Scandinavia, where the number of dry days decreases with 0-3 days/month. The number of dry days in summer is increasing with more than 3 days/month in large parts of central Europe. Around the Mediterranean the increase is smaller, but the number of dry days is approaching 30 days/month. In autumn the number of dry days is starting to decrease again in northern Europe. In southern Europe the number of dry days is still increasing and is close to 30 days/month in the southern half of the Iberian Peninsula even in autumn in 2071-2100.

As with other precipitation indices RCAO-H behaves partially different. The number of dry days in winter decreases also in large parts of southern Europe including the Mediterranean area where the other scenarios show drier conditions. Otherwise the change in dry days is similar to the other scenarios.

Freezing rain

FreezeRain GT05LE0

Freezing rain occurs especially in mountainous regions, such as Iceland, the Alps and western Scandinavia, with 20-30 days/year. In the rest of Scandinavia, Finland, parts of Russia and the Baltic states there are 5-15 days/year. From this area the number of days decreases towards the south and southwest so that less than 3 days/year occur in the British Isles, central western Europe and Mediterranean area. The future change is determined by changes both in precipitation and temperature. The number of days with freezing rain decreases with a few days in all parts of Europe where freezing rain occurs in the present climate already in 2011-2040. The only exception to this is the far north (northernmost Scandinavia, the Kola Peninsula and parts of northern Russia) where there is instead a small increase as the climate gets milder and temperatures closer to 0°C gets more common. By 2071-2100 freezing rain virtually only occurs in Iceland, northern Scandinavia, Finland, northern Russia and to some extent in the Alps.

Effective precipitation

Effective precipitation is precipitation minus evapotranspiration (see Ch.6.5).

P-E maxRunSum7

The maximum effective precipitation during 7 days is largest along the coasts of western Europe, the west coasts in the Mediterranean Sea and in mountainous regions. In these areas the maximum accumulated effective precipitation during 7 days is 80-100 mm. In the rest of Europe the maximum is in the range 30-60 mm/7 days.

The maximum weekly effective precipitation is increasing in the north and decreasing in the south, by the end of the century is it increasing with 15-25 mm/7 days in western

Europe, and with more than 25 mm/7 days in western Norway. In the rest of northern Europe it is increasing with 0-15 mm/7 days. In southern Europe maximum weekly effective precipitation is decreasing with 0-10 mm/7 days. RCAO-H gives a different result with generally a weaker signal than in the other scenarios. Effective precipitation is changing with 0-10 mm/7 days in most of Europe. The only areas with decreases, of 0-10 mm/7 days, can be found in parts of southern Europe and also along parts of the Scandinavian west coast. The only areas with an increase of over 20 mm/7 days are the south western tip of Norway and parts of the Alps. The different pattern of change in the Scandinavian region between the RCAO-H scenarios and the ECHAM-forced scenarios reflect the different changes in atmospheric circulation in the two global models, as discussed in Ch. 5.2.

P-E maxRunSum14

The maximum effective precipitation during 14 days is largest along the coasts of western Europe, the west coasts in the Mediterranean Sea and in mountainous regions. In these areas the maximum accumulated effective precipitation is 100-120 mm/14 days. In the rest of Europe the maximum is 40-80 mm/14 days.

The maximum two-weekly effective precipitation is increasing in the north and decreasing in the south, by the end of the century it is increasing with 30-50 mm/14 days on the west coast, and with more than 50 mm/14 days in western Norway. In the rest of northern Europe it is increasing with 0-15 mm/14 days. In southern Europe maximum accumulated effective precipitation is decreasing with 5-10 mm/14 days. RCAO-H gives a different result with generally a weaker signal than in the other scenarios. Maximum effective precipitation is increasing with 0-15 mm/14 days in most of Europe. The only areas with decreases, of 0-10 mm/14 days, can be found in parts of southern Europe and also along parts of the Scandinavian west coast. The only areas with an increase of over 30 mm/14 days are the south western tip of Norway and parts of the Alps. The different pattern of change in the Scandinavian region between the RCAO-H scenarios and the ECHAM-forced scenarios reflect the different changes in atmospheric circulation in the two global models, as discussed in Ch. 5.2.

P-E maxRunSum30

The maximum effective precipitation during 30 days is largest along the coasts of western Europe, the west coasts in the Mediterranean Sea and in mountainous regions. In these areas the maximum effective monthly precipitation is 160-200 mm. In the rest of Europe the maximum is 60-120 mm/30 days.

The maximum monthly effective precipitation is increasing in the north and decreasing in the south, by the end of the century it is increasing with 40-80 mm/30 days on the west coast, and with more than 90 mm/30 days in western Norway. In the rest of northern Europe it is increasing with 0-30 mm/30 days. In southern Europe maximum monthly effective precipitation is decreasing with 0-10 mm/30 days. RCAO-H gives a different result with generally a weaker signal than in the other scenarios. Effective precipitation is changing with 0-30 mm/30 days in most of Europe. The only areas with decreases, of 0-10 mm/30 days, can be found in parts of southern Europe and also along parts of the Scandinavian west coast. The only areas with an increase of over 50 mm/30 days are the south western tip of Norway and parts of the Alps. The different pattern of change in the Scandinavian region between the RCAO-H scenarios and the ECHAM-forced scenarios reflect the different changes in atmospheric circulation in the two global models, as discussed in Ch. 5.2.

P-E maxRunSum60

The maximum effective precipitation during 60 days is largest in mountainous regions. In these areas the effective precipitation is more than 350 mm/60 days. In the rest of Europe the effective precipitation is 100-200 mm/60 days. Maximum two-monthly effective precipitation is increasing in the north and decreasing in the south, by the end of the century it is increasing with 80-100 mm/60 days on the west coast, and with more than 100 mm/60 days in western Norway. In the rest of northern Europe it is increasing with 0-50 mm/60 days. In southern Europe maximum effective two-monthly precipitation is decreasing with 0-10 mm/60 days. RCAO-H gives a different result with generally a weaker signal than in the other scenarios. Maximum effective precipitation is changing with 0-40 mm/60 days in most of Europe. The only areas with decreases, of 0-10 mm/60 days, can be found in parts of southern Europe and also along parts of the Scandinavian west coast. The only area with an increase of over 70 mm/60 days is the southern tip of Norway. The different pattern of change in the Scandinavian region between the RCAO-H scenarios and the ECHAM-forced scenarios reflect the different changes in atmospheric circulation in the two global models, as discussed in Ch. 5.2.

P-E sum

The sum of effective precipitation in winter and autumn is 50-200 mm/season in most of Europe. In mountainous regions the effective precipitation is more than 350 mm/season. In summer and spring the effective precipitation is positive (0-350 mm/season) in northern Europe and negative in southern Europe (-150-0 mm/season).

By 2071-2100 effective precipitation in winter will increase with 40-80 mm/season in northern Europe and decrease with 0-80 mm/season in southern Europe. In spring effective precipitation increases with 60-80 mm/season in western Europe and with 0-80 in the rest of central and southern Europe. Effective precipitation is increasing with more than 60 mm/season in western Scandinavia, northern Britain and Iceland. In summer effective precipitation is decreasing with 40-80 mm/season in western and central Europe and southern Scandinavia. Effective precipitation is increasing in southern Europe and northern Scandinavia. In autumn effective precipitation is increasing with 20-80 mm/season in Scandinavia, Iceland and the northern part of Great Britain. In southern Europe effective precipitation is decreasing with 0-80 mm/season. RCAO-H projects similar changes with one exception; effective precipitation along the Scandinavian west coast is decreasing in winter and increasing in summer, opposite to what is described above, again due to the differences in the global models (see Ch 5.2).

The annual mean of the sum of the effective precipitation is 0-400 mm/year in most of Europe. In mountainous regions the effective precipitation is higher, over 800 mm/year. In parts of southern Europe effective precipitation is negative, -200-0 mm/year.

By the end of the century the annual effective precipitation is decreasing in most of Europe with 0-100 mm/year. Effective precipitation increases in northeastern Europe, northern Scandinavia, Iceland and the northern part of Britain. In Iceland and on the Scandinavian west coast effective precipitation increases with more than 300 mm/year. RCAO-H gives the same pattern but with lower amplitude in the precipitation increase: not more than 100 mm/year in any region.

6.7 Snow

As temperatures increase the amount of snow will generally be less in a changing climate. But, there is also a possibility that an increase in snowfall may be larger than the increased melting due to the higher temperatures. This may lead to increases in snow depth at some locations. Elsewhere, the snow cover will be thinner and the extension of the snow cover is expected to decrease everywhere. Some of the snow indices describing snow depth are actually increasing in some regions. This can occur in regions with a relatively thick snow cover in today's climate. Consequently, when the snow cover gets thinner there will be more days that fit in a certain range. This means that the number of days with a thinner layer may increase while number of days with a thicker layer decreases (see Ch. 3.2).

Snow period

nSnowcover

The period with snow cover will shorten during the coming 100 years. Iceland, Scandinavia, the Alps and eastern Europe are most affected, since these areas currently have long periods of snow cover. In these areas the period of snow cover will be 30-40 days shorter in 2011-2040 and 60-70 days shorter in 2071-2100. In some places, especially as projected by scenario A2, the period will decrease with around 100 days until 2100. At that time there will only be snow cover in Iceland, northern Scandinavia and parts of the Alps.

Period with 'thin' snow layer

Snow depth n0to10

The number of days with snow depth in the range 1-10 cm is large (around two months) in southern Sweden and central/eastern Europe. North of that the snow cover is usually thicker, and south of that the snow cover is usually non-existent. The change in days with snow depth of 1-10 cm is in absolute values largest where the number of days is large. Already in 2011-2040 the number of days has decreased with 10-30 days. In the next period the number has decreased a bit more and the number of days with snow cover of 1-10 cm is reduced to 0 in all of central Europe except the Alps. In the last period the number of days is reduced to 0 also in southern Sweden in scenario A2. At the same time the number of days with snow cover of 1-10 cm is increasing in Iceland, northern Scandinavia and Russia, areas that all have more snow in today's climate.

Period with 'medium deep' snow layer

Snow depth n10to20

The number of days with snow depth of 10-20 cm is large (around two months) in Sweden, Finland, Russia and most parts of Iceland. The largest changes in snow cover of 10-20 cm are in these areas, the period will be 1-2 months shorter in 2071-2100. In relative values the decrease in snow cover is 100% in most parts of continental Europe and southern Sweden, by the end of the century a snow cover of 10-20 cm hardly occur.

The number of days is increasing in northern Scandinavia. This implies that the snow cover gets thinner. The number of days with snow cover of 10-20 cm is low at present since the snow cover usually is thicker.

Maximum snow water content

SnowWeq max

The annual maximum of water content in snow is more than 50 mm in Scandinavia, eastern Europe, Iceland and the Alps, in the mountainous regions water content is more than 300mm. A gradual decrease is seen at all locations where there is snow today. Relatively, the decrease is smallest, or even absent in the 2011-2040 period, in the interior of the Scandinavian mountains. In that area the high altitude may still provide a sufficiently cold climate to get more snow on the ground due to the increased winter precipitation. As the model resolution, and thereby topography, is relatively coarse it is very likely that high-altitude locations in the real terrain will see an increase in snow cover for some time period if the temperature and precipitation changes according to the scenarios presented here. By the end of the century water content has decreased with at least 50 mm, and up to 100 mm in regions with currently large water content.

6.8 Runoff

Runoff is the deep drainage calculated by the land surface scheme. It depends on the supply of water at the surface and the water holding capacity of the soil that in turn is determined by the heterogeneity and soil properties of the grid boxes. It is not possible to compare runoff to the effective precipitation (P-E) as runoff is only calculated in the land area fraction of the grid boxes while evaporation is a grid box average (including open water bodies). This implies that P-E is often smaller than the runoff as evaporation over lakes can be large.

Runoff sum

Maxima in runoff are found in mountainous regions where locally fluxes of several hundreds of mm/month are simulated. Elsewhere, runoff to a large degree follows the effective precipitation discussed above with largest numbers in northern Europe and small, or even zero, runoff in the south particularly during summer.

In spring (April and May) runoff is decreasing with 0-10 mm/month for most of Europe, except the Alps and northern Scandinavia where runoff is decreasing with more than 30 mm/month and in April the Scandinavian mountains where runoff is increasing with up to 50 mm/month.

In summer and September the change in runoff is rather small in most of Europe. The change is larger in southern Scandinavia and Britain with a decrease of 10-20 mm/month. This area of decreasing runoff is expanding in the later time periods. In September runoff is increasing in the Scandinavian mountains and on Iceland. The large changes in runoff can be noted in areas where the runoff is large, so the basic pattern remains relatively unchanged until year 2100 although the differences between dry and wet conditions are amplified.

6.9 Wind

The simulated changes in wind speed are very sensitive to the choice of boundary conditions, a feature also note by Chen and Aschberger (2006). They compared changes in the geostrophic wind speed over the Baltic Sea in 17 different GCMs at the time of CO_2 doubling. In that study they show that some models project increases in seasonal mean wind speed while others project decreases. Based on their model results they could not find a statistically significant change in the wind speed in this area. The ECHAM4 used here also show a general increase in westerlies over northern Europe, see also Ch 5. HadAM3, on the other hand, does not show such an increase.

Mean wind speed and direction

W10 mean

The change in absolute wind speed is small, ±0.2 m/s in most of Europe. Only in the two last time periods in scenario A2 there is more change in larger areas; wind speed increases with 0.2-0.4 m/s in parts of Scandinavia and Scotland. The same is true for RCAO, but the area with increasing wind speed of 0.2-0.4 m/s is a little larger in RCAO-E-A2. The absolute numbers may seem small but in the ECHAM4-based A2 scenario it corresponds to an increase with about 10%.

W70 mean

The change in wind at 70m is discussed in Hovsenius and Kjellström (2007). Based on the three simulations with RCA3 forced by ECHAM4/OPYC3 and ECHAM5/MPI-OM discussed in their report they find that the energy density of the wind may increase with 5-20% in about 20-30 years from now. But, as they state, such a change may also be due to natural variability in the climate. They do not discuss long-term changes until the end of the century.

Wind direction

The wind direction is determined by the large-scale pressure pattern in combination with local topographic effects. Changes in the large-scale circulation may alter the wind direction. Wind roses have been calculated for 18 selected locations in Sweden for three time periods in the two RCA3-E driven simulations. The results show higher frequencies of south-westerly to westerly winds at many of the stations.

Maximum gust wind

Gustmax max

An increase in maximum gust speed is evident for large parts of northern Europe, mainly over the North Sea, the Norwegian Sea and the Baltic Sea, but also over adjacent land areas. The increases are of the order of 1-2 m s^{-1} in large parts of those areas. The change is rapid and clear already at the first time period considered (2011-2040) but after that it does not change much. In other regions the maximum gust speed can be increasing in one time period and decreasing in another. Here, it should be noted that the index is only calculated for the ECHAM4-based RCA3 scenarios. As gustiness was not calculated in RCAO we can not judge whether a similar increase would be the case also for the scenarios based on HadAM3H even though this is not likely given the small changes in mean wind speed.

Number of days with gust winds

Gustmax nGT21

The number of days with wind gusts above 21 m/s is changing considerably in Britain, along the North Sea coast and in western Norway. In these areas the number of days with wind gusts above 21 m/s is increasing with 3-9 days from 6-14 days/year. In Iceland the number of days is increasing with 0-6 days in 2011-2040 and decreasing with 0-9 days in 2071-2100. In all other areas the changes are small.

6.10 Lake ice

Ice covered lakes exist in Scandinavia and in continental Europe on the coast of the Baltic Sea. The number of days with ice cover and the thickness of the ice cover will be reduced in all these regions.

Lake ice days

Lake ice nGT15

The number of days with ice cover thicker than 15 cm is decreasing on the whole. In 2071-2100 lakes with ice cover thicker than 15 cm will only be the case for parts of northern Scandinavia, and the period with ice cover thicker than 15 cm is decreased with 1.5-3 months.

Day when ice breaks up

Lake ice dayBreakUp

Ice break up occurs from day number 40-70 along the south coast of the Baltic to day number 150-160 in northernmost Scandinavia in the 1961-1990 period. The change is largest in southern lakes. Already in 2011-2040 ice break up will occur around one month earlier, while ice break up at higher latitudes will occur only 5-10 days earlier. In this period there are almost no ice covered lakes in northern Germany and Denmark. In the period 2071-2100 ice covered lakes exist in Scandinavia and the Baltic countries, but in scenario A2 only in parts of southern Sweden. By this time ice break up occurs 50-60 days earlier in southern Sweden and the Baltic countries and 10-30 or 10-20 days earlier in northern Scandinavia in scenarios A2 and B2 respectively.

7. Discussion and conclusions

The regional climate scenarios described in this report show many similarities with previous scenarios in terms of general evolution and amplitude of future European climate change (cf. Christensen and Christensen, 2007; Räisänen et al., 2004; Kjellström et al., 2005). The broad picture, mostly determined by the forcing GCMs, is that of a gradually warmer climate, particularly in the northeastern part of Europe during winter and in the south during summer. Precipitation is projected to increase in the north in all seasons and in winter in the south while there is a decrease in precipitation in southern and central Europe during summer.

These broad average features are manifested in the climate indices derived here as increases in warm and decreases in cold indices. Likewise changes related to the water budget are represented as increases in "wet" indices in the north and "dry" indices in the south. In addition to reproducing the general features of average change, the indices provide information about changing extreme conditions. This is true both on a high temporal resolution, such as increasing intensity of heavy precipitation, changes in gust winds, etc. but also in a longer time perspective such as changing amounts of weekly integrated precipitation, increasing length of dry spells, etc. Also, more complex features of change can be studied by the aid of indices. This includes combinations of several variables, relation to certain thresholds etc.

Evaluations of the Rossby Centre regional climate models have been presented in Räisänen et al. (2003) and Kjellström et al. (2005). Many of the indices presented here focus on extreme conditions, and several of them involve specific thresholds, or are derived from a combination of two or more basic variables. All these factors make the indices sensitive to comparatively small systematic biases. Basic quality control measures have been taken, but a thorough control and evaluation is not possible to achieve because of the total volume of the material produced (51 indices calculated for 2-4 different time periods and different GCM/RCM/SRES emissions scenarios). In addition, it is not clear how best to evaluate the performance of the indices. While it would be possible to calculate the same indices for observational data, the fundamental difference between gridcell data and point observations makes any such comparison non-trivial.

By involving the Commission working groups and other stakeholders in the selection and definition of the climate indices an important and fruitful dialogue ensued. We found that this process increased our understanding of the different sectors, their problems, tools and information needs. At the same time, the knowledge of climate change, use of climate modelling data etc. increased among the stakeholders. Our own experience based on subsequent contacts with stakeholders and requests for climate model data is that the awareness of climate impact and vulnerability and adaptation also increased significantly in different sectors.

The picture of climate change that emerges in this extensive material is comprehensive in that it is both general and detailed. As many of the indices have been developed in dialogue with stakeholders and end users there is a focus on impact related questions even if the impacts are not described per se. Despite the extensive nature of the material, it does not cover all aspects of climate change and possible impacts, nor does it cover the full spread of existing climate change scenarios that in turn does not cover the full range of possible climate change.

The technical formulation of the climate indices and the production of the final results was a tedious process involving generalisation of complex and very specific weather conditions and also reconciling different and partly contradictory needs. For specific purposes the indices presented here only serves as first order attempts at gleaning some insight into possible future climate impacts. In many cases, targeted and more sophisticated climate indices could be developed based on deeper understanding of the underlying processes. One example of such indices related to insect damage to forests is presented by Jönsson et al. (2007). The ultimate level of sophistication is that the climate indices become independent process-based models using climate model data as input. Examples of this are the comprehensive and complex ecosystem model (Koca et al., 2006) and forest production model (Berg et al., 2005) used for providing scenarios of future vegetation and forest production to the Commission working groups. However, such more sophisticated climate indices and complex models require substantial research and development time and resources. In comparison, the indices presented here provide a rough and ready estimate that can be used for initial assessments.

The decision to make the material freely available on the Internet raises some thoughts. On the one hand, we find it important that the material is easily available. The need for information and results on climate change is immense. We hope that by making this material available, including supporting information and examples, provides at least some answers. A risk with a broad distribution of such extensive material is, of course, that it will be used for many years (maybe decades) as THE result. This is something we have experienced from the earlier Sweclim programme which ended in 2003, and is still referred to. We foresee continued efforts and updates of the results presented in this report, not least over the web-application.

The following conclusions can be drawn on the working process:

- The stakeholder communication process is important, and adds value to both the Research & Development process, and the use of results.
- Climate indices can be used to describe complex relations better than basic climate data.
- To practically manage such an extensive data set and interpret the vast amount of information therein involves substantial efforts both for the scientist (producer) and the stakeholder (user).

The work on the regional climate scenarios and analyse, including further development of indices as well as producing a firmer foundation of climate scenarios continues. We look forward to a continued interactive process with stakeholders. Finally, we note that researchers within other disciplines have already found the material. It is now used as inspiration and background for further climate change studies. We believe that this unique material is well suited for further analysis and impact studies on the Scandinavian and European scale.

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Appendix 1. Abbreviations

Abbreviation	Explanation
GCM	A General Circulation Model (also referred to as Global Climate Model)
AOGCM	A coupled Atmosphere-Ocean GCM
RCM	A Regional Climate Model
RCA	Rossby Centre Atmosphere model
RCA2	Rossby Centre Atmosphere model version 2
RCA3	Rossby Centre Atmosphere model version 3
RCO	Rossby Centre Ocean model
RCAO	Rossby Centre Atmosphere and Ocean model. RCAO is the coupled version of RCA and RCO.
PROBE	A lake model (PROgram for Boundary layers in the Environment)
HadAM3H	A global climate model from Hadley Centre at the Meteorological Office, UK. <http://www.metoffice.gov.uk/research/hadleycentre/index.html>
ECHAM4/OPYC3	An AOGCM from DKRZ and MPI-met.
ECHAM5/MPI-OM	An AOGCM from DKRZ and MPI-met. Successor of ECHAM4/OPYC3.
DKRZ	Deutsches Klimarechenzentrum GmbH <http://www.dkrz.de>
MPI-met	The Max-Planck Institute for Meteorology in Hamburg <http://www.mpimet.mpg.de/en/home.html>
ECMWF	European Centre for Medium range Weather Forecast <http://www.ecmwf.int>
ERA40	ECMWF 40-year reanalysis (1961-2002).
PRUDENCE	A European research project (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) <http://prudence.dmi.dk>
IPCC	Intergovernmental Panel on Climate Change <http://www.ipcc.ch>
SRES	Special Report on Emissions Scenarios, IPCC, 2000.

Appendix 2. Climate indices

Climate index	**Description**	**Unit**	**Time period**
Cloudbase_nLT100	Number of days with lowest cloud base below 100m	days	season
Evap_sum	Evapotranspiration, summed up	mm	month season year
FreezRain_GT05LE0	Number of days during the year when the maximum temperature is below 0 ºC and the precipitation is greater than 0.5 mm. The index represents "days with freezing rain"	days	year
Gustmax_max	Maximum gust wind (yearly highest)	m/s	year
Gustmax_nGT21	Number of days with gust winds >21 m/s	days	year
LakeIce_dayBreakup	Daynumber when ice on lakes break up. (For definition of lakes see Ch. 3.2)	Daynumber	year
LakeIce_nGT15	Number of days with ice thickness on lakes >15 cm	days	year
Lwdown_mean	Mean value of incoming longwave radiation (heat radiation)	W/m^2	season
PminusE_sum	Effective precipitation (i.e precipita-tion minus evapotranspiration), summed up	mm	season year
PminusE_maxRunSum7	Highest effective precipitation during a continuous 7-day period	mm	year
PminusE_maxRunSum14	Highest effective precipitation during a continuous 14-day period	mm	year
PminusE_maxRunSum30	Highest effective precipitation during a continuous 30-day period	mm	year
PminusE_maxRunSum60	Highest effective precipitation during a continuous 60-day period	mm	year
Precip_maxDrySpell1	Longest continuous period with preci-pitation <1 mm/day ("dry period")	days	season
Precip_maxRunSum7	Maximum precipitation during 7 continuous days	mm	season
Precip_nDryDay1	Number of days with precipitation <1 mm ("number of dry days")	days	month
Precip_nGT10	Number of days with precipitation >10 mm ("heavy precipitation")	days	season year

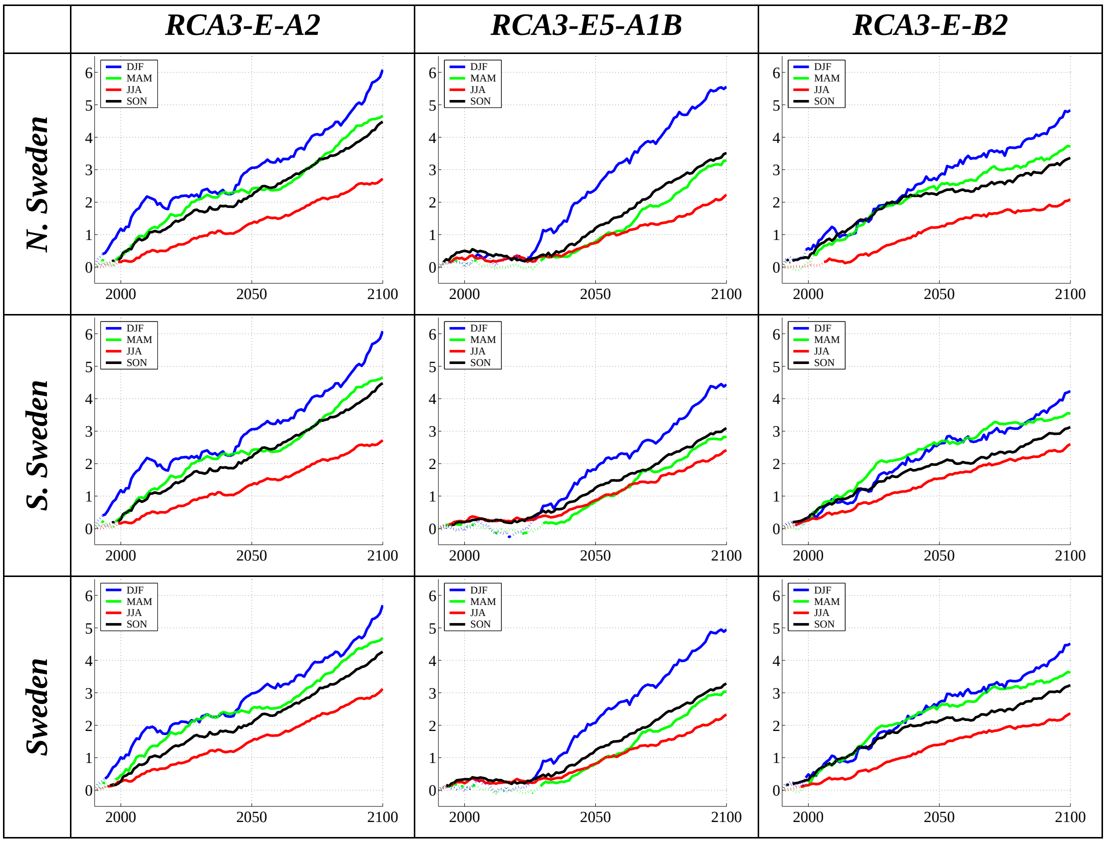
Climate index	Description	Unit	Time period
Precip_nGT25	Number of days with precipitation >25 mm ("extreme precipitation")	days	season year
Precip_sum	Precipitation, summed up	mm	month season year
Precmax_max	Maximum precipitation intensity (yearly maximum)	mm/h	year
Rainfall_sum	Amount of rainfall, summed up	mm	season year
RhT2m_nGT90GT10	Number of days when the relative humidity (daily mean) is above 90% and T2m > 10 ºC	days	season
Runoff_sum	Net runoff, summed up	mm	month (April-September)
SnowCover_nSnowCover	Number of days with snow cover	days	year
SnowDepth_n1to10	Number of days with snow depth 0-10 cm	days	year
SnowDepth_n10to20	Number of days with snow depth 10-20 cm	days	year
Snowfall_sum	Amount of snowfall (expressed as mm water), summed up	mm	season year
SnowWeq_max	Water content in snow, yearly maximum value	mm	year
SunH_sum	Sun hours, summed up	hours	month
Swdown_mean	Mean value of incoming short wave radiation (global radiation)	W/m^2	season
T2max_CDD20	CDD (cooling degree days), number of degree days when daily maximum temperature exceeds 20 ºC (model adjusted threshold value)	CDD	month year
T2max_maxHWaveGT20	Longest continuous period with daily maximum temperature >20 ºC	days	year
T2max_mean	Daily maximum temperature at 2 m height, mean value	ºC	month season year
T2max_nGT20	Number of days with daily maximum temperature > 20 ºC	days	season year
T2max_nLTminus7	Number of days with daily maximum temperature < -7 ºC	days	year
T2m_dayVegEnd5	"End of the growing season (5 ºC)", daynumber for the end of the last continuous 4-day period with T2m >5 ºC	daynumber	year

Climate index	**Description**	**Unit**	**Time period**
T2m_dayVegStart2	"Start of the growing season (2 ºC)", daynumber at the end of the first continuous 4-day period with T2m >2 ºC	daynumber	year
T2m_dayVegStart5	"Start of the growing season (5 ºC)", daynumber at the end of the first continuous 4-day period with T2m >5 ºC	daynumber	year
T2m_DDGT20	Number of degree days for daily mean temperatures>20 ºC	degree days	year
T2m_DDGT8VegPeriod5	Number of degree days for mean temperatures above 8 ºC during the growing season (5 ºC)	degree days	year
T2m_HDD17	HDD (heating degree days), number of degree days for daily mean temperatures above 17 ºC	HDD	month year
T2min_mean	Daily minimum temperature at 2 m height, mean value	ºC	month season year
T2min_lastSpringFrost	Daynumber when last spring frost occurs, daily minimum temperature <0 ºC	daynumber	year
T2min_nFrostDays	Number of days when daily minimum temperatures <0 ºC ("frost days")	days	season
T2min_nTropNight	Number of days when daily minimum temperatures >17 ºC, (model adjusted threshold value, not the general definition for tropical nights, see text)	days	year
T2m_mean	Mean temperature at 2m height	ºC	month season year
T2m_nVegPeriod2	"Length of growing season (2 ºC)", number of days between the end of the first continuous 4-day period with T2m >2 ºC and the end of the last continuous 4-day period with T2m >2 ºC	days	year
T2m_nVegPeriod5	"Length of growing season (5 ºC)", number of days between the end of the first continuous 4-day period with T2m >5 ºC and the end of the last continuous 4-day period with T2m >5 ºC	days	year

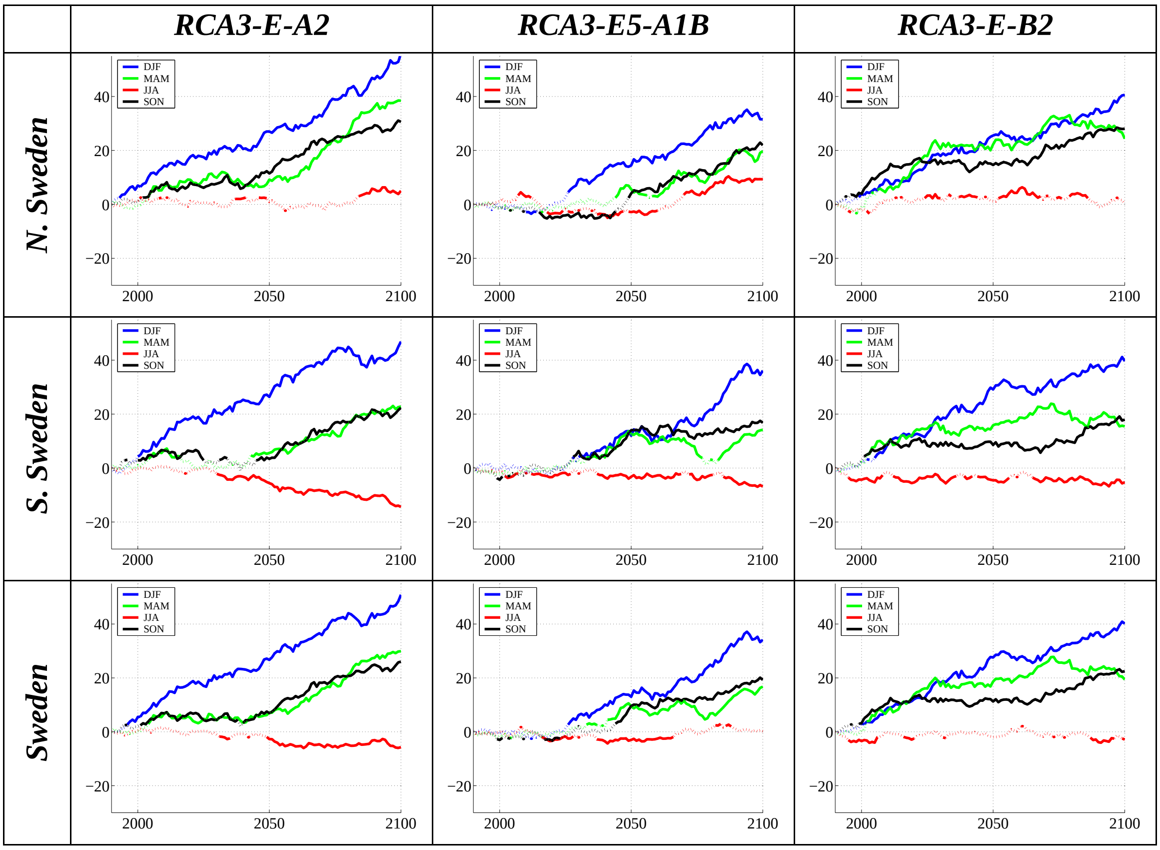
Climate index	**Description**	**Unit**	**Time period**
T2m_nZeroCross	Number of days when the temperature at 2 m height has been both above and below 0 ºC (T2max >0 ºC and T2min < 0ºC)	days	season
Tsurf_nLTminus7	Number of days when the surface temperature (daily mean) is <-7 ºC	days	year
W10m_mean	Daily mean wind speed	m/s	season year

Appendix 3. Examples of climate change trends in Sweden

Temperature and precipitation trends in three transient scenarios as calculated with the regional climate model RCA3 driven with data from the global models ECHAM4/OPYC3 (E) and ECHAM5/MPI-OM (E5) under emissions scenarios SRES A2, A1B and B2 respectively. The trends are shown individually for the four nominal seasons (DJF, MAM, JJA and SON). Plotted in the diagrams are average changes calculated consecutive 30-year periods as compared to 1961-1990. Indicated in the graphs is also information about the statistical significance of the change as compared to the reference period. This significance is calculated taking into account the interannual variability during the respective 30-year period. This method is described in more detail in Kjellström et al. (2005).



__App3-1.__ Seasonal mean temperature development (°C) averaged over 30-year intervals for northern Sweden, southern Sweden and as a total for the country. The climate change signal is compared to the 1961-1990 time period. Full line means that the calculated climate change signal is statistically significant given the interannual variability of the data sets. Blue= winter (DJF), green = spring (MAM), red=summer(JJA) and black=autumn (SON).



App3-2. *Seasonal mean precipitation development (%) averaged over 30-year intervals for northern Sweden, southern Sweden and as a total for the country. The climate change signal is calculated as percentage change compared to the 1961-1990 time period. Full line means that the calculated climate change signal is statistically significant given the interannual variability of the data sets. Blue= winter (DJF), green = spring (MAM), red=summer(JJA) and black=autumn (SON).*

Appendix 4. Examples of climate scenario maps for Europe

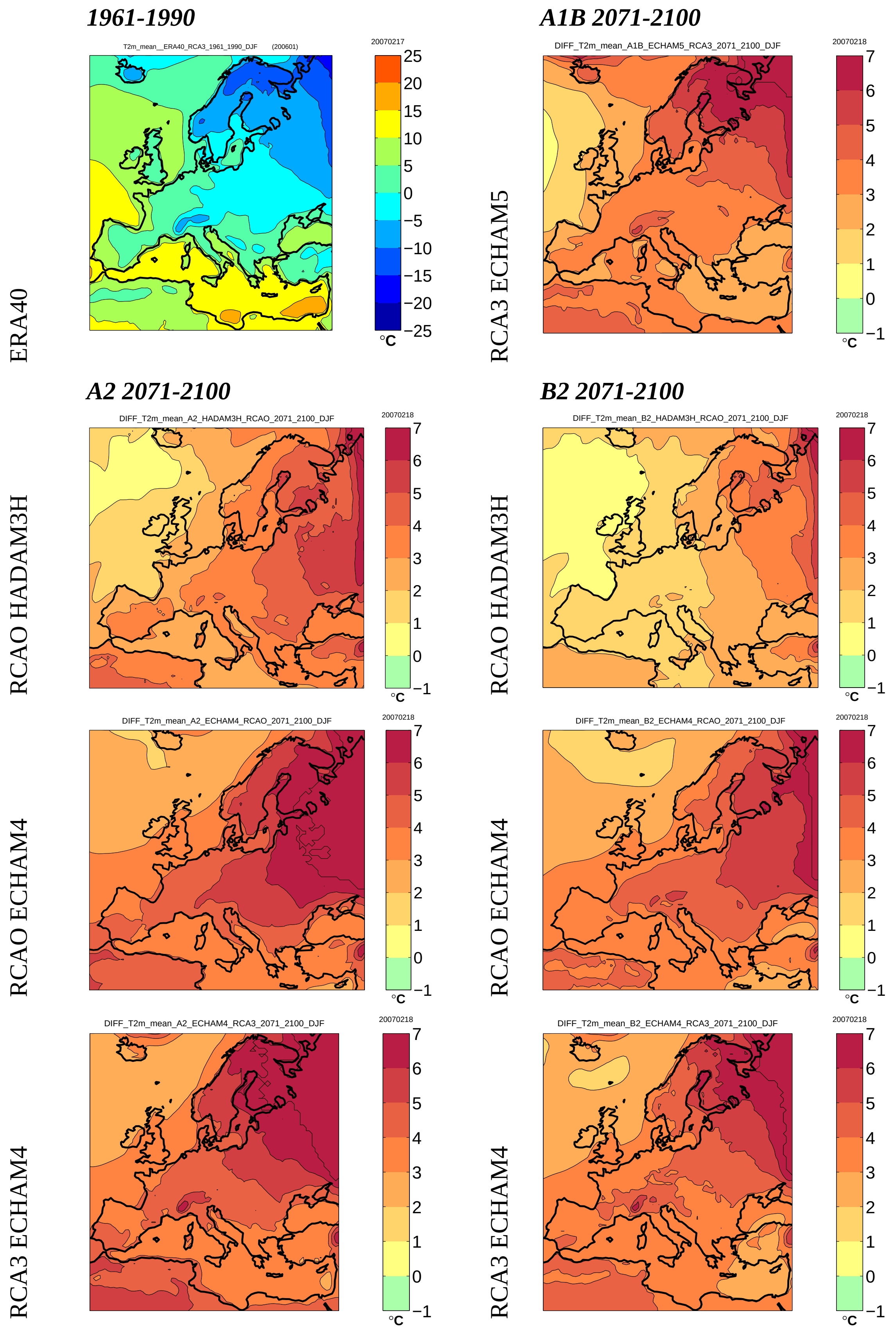
The climate scenario maps are available on the DVD (see Appendix 5). Here we present some of the climate indices most frequently asked for. The maps in Appendix 4 show projections on the European scale. Maps for the Scandinavia as well as Europe are available on the DVD. Results from different scenarios on differences between 2071-2100 to 1961-1990 are presented together with mean values for 1961-1990. The latter are as calculated with the regional climate model RCA3 forced with ERA-40 data.

The chosen climate indices are:
App4-1: Winter mean temperatures
App4-2: Summer mean temperatures
App4-3: Winter precipitation
App4-4: Summer precipitation
App4-5: Length of snow season

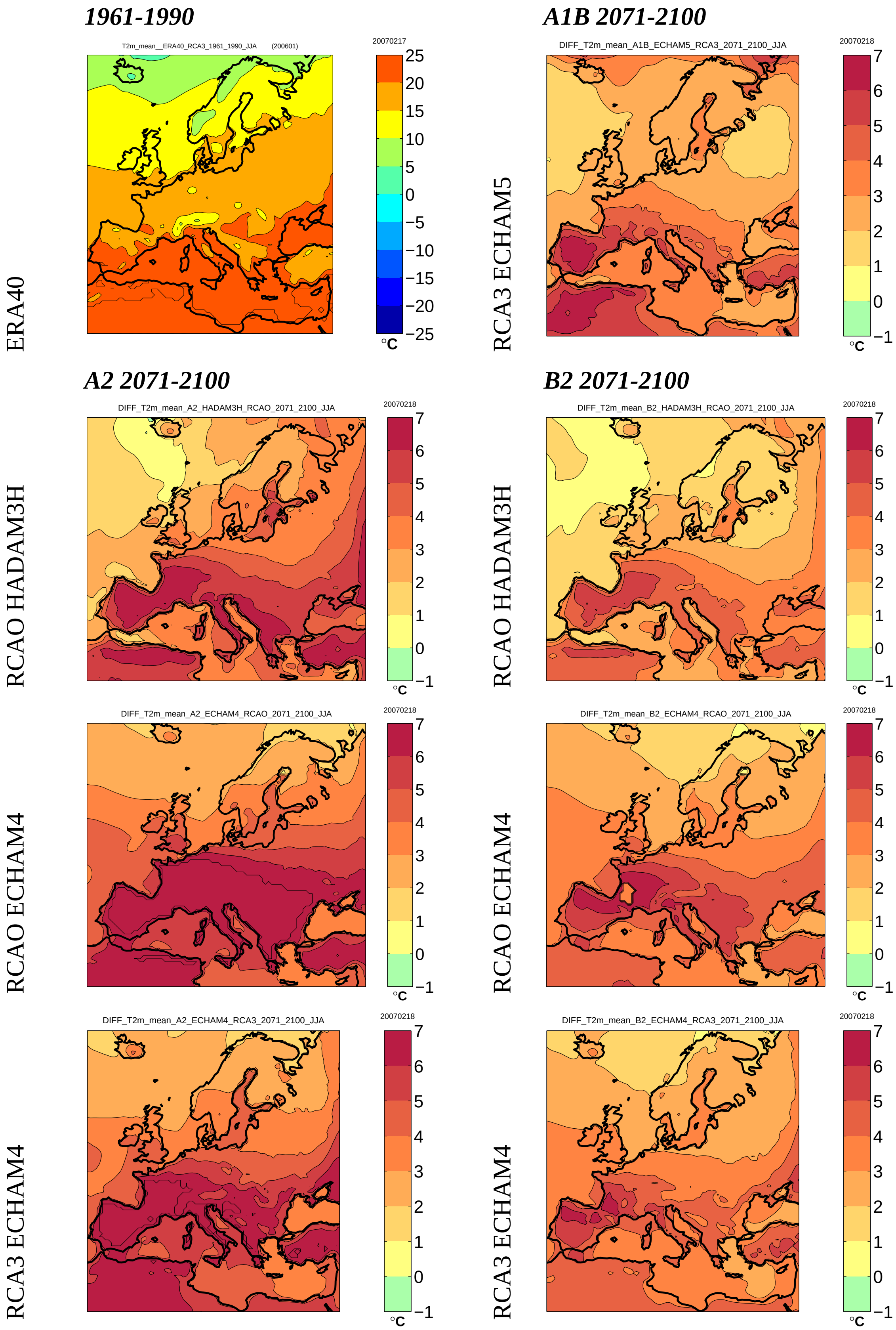
The scenarios are as follow:

Regional climate model	**Global climate model**	**Emissions scenario**	
RCA3	ECHAM5	A1B	*N.B! Not available on the DVD*
RCAO	HADAM3H	A2	
RCAO	HADAM3H	B2	
RCAO	ECHAM4/OPYC3	A2	
RCAO	ECHAM4/OPYC3	B2	
RCA3	ECHAM4/OPYC3	A2	
RCA3	ECHAM4/OPYC3	B2	

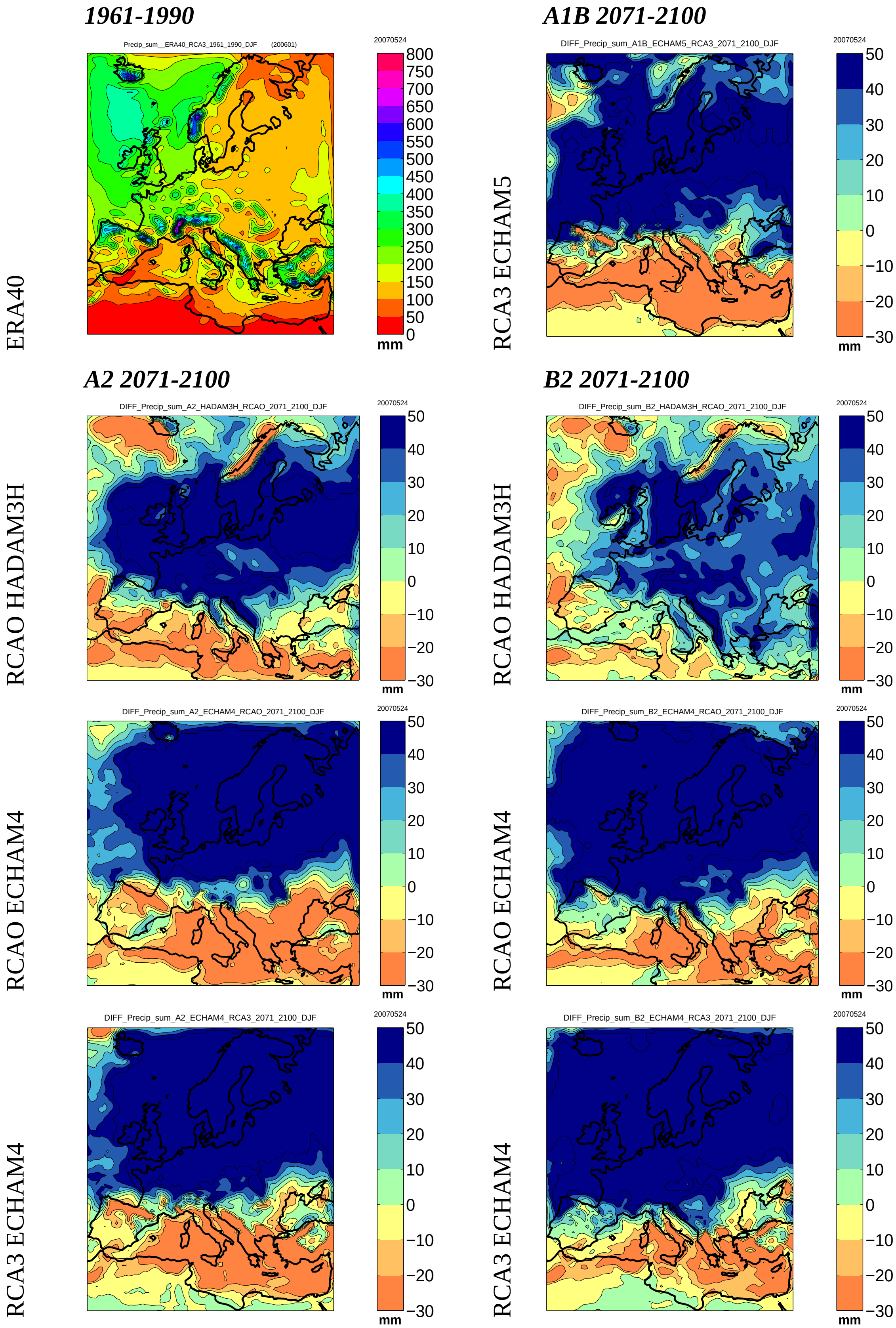
The two regional model domains slightly differ which is seen in the maps (see also Figure 1).



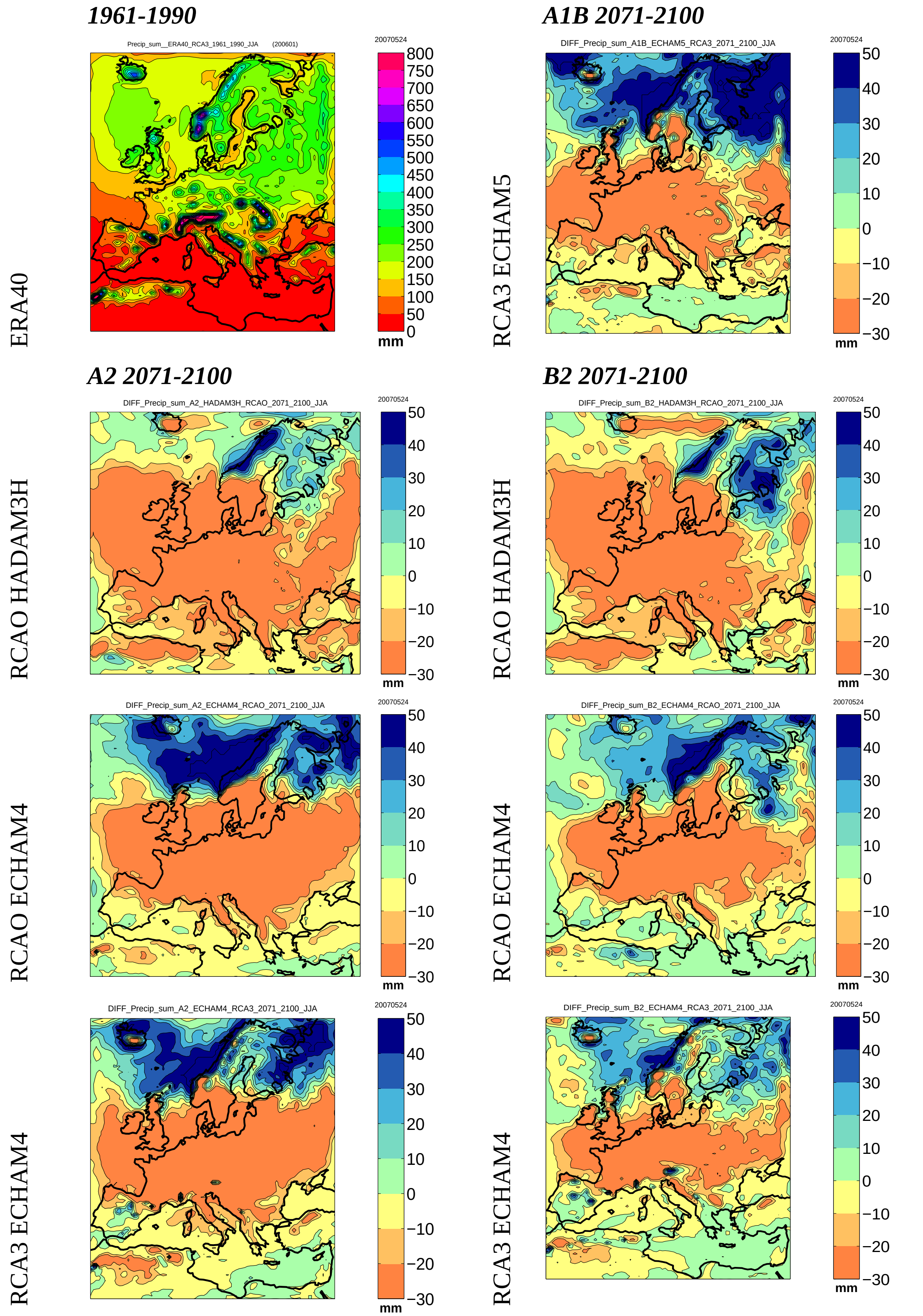
App4-1. *Projected changes in winter (DJF) mean 2m-temperatures (˚C) in 2071-2100 relative to 1961-1990 according to different scenarios. Top left shows the winter mean temperature 1961-1990 according to RCA3/ERA40.*



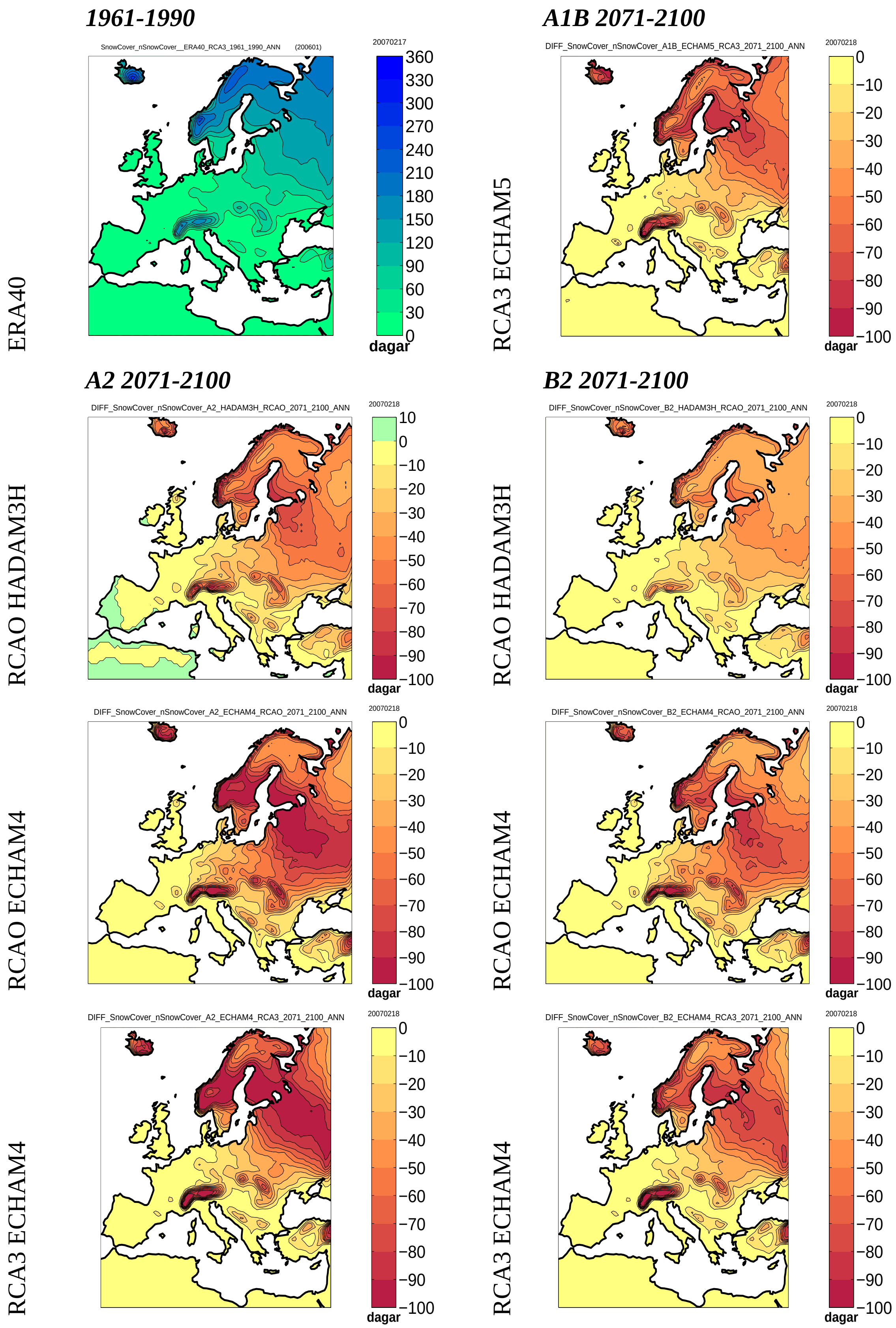
App4-2. *Projected changes in summer (JJA) mean 2m-temperatures (˚C) in 2071-2100 relative to 1961-1990 according to different scenarios. Top left shows the summer mean temperature 1961-1990 according to RCA3/ERA40.*



App4-3. *Projected changes in winter (DJF) precipitation (mm) in 2071-2100 relative to 1961-1990 according to different scenarios. Top left shows the winter precipitation 1961-1990 according to RCA3/ERA40.*



App4-4. *Projected changes in summer (JJA) precipitation (mm) in 2071-2100 relative to 1961-1990 according to different scenarios. Top left shows the summer precipitation 1961-1990 according to RCA3/ERA40.*



App4-5. *Projected changes in length of snow season (days) in 2071-2100 relative to 1961-1990 according to different scenarios. Top left shows length of snow season 1961-1990 according to RCA3/ERA40.*

Appendix 5. DVD – Rossby Centre climate scenario maps

The climate scenario maps described in this report are available on the DVD distributed together with the report. A web-application, also available on the DVD, makes it possible to study the material collected in frames as specified by the user (see also Chapter 4).

The maps show mean values for 30-year periods (Climate scenario maps) or the difference between a 30-year period and the reference period 1961-1990 (Difference maps). The maps are grouped in Ut, El and SGU as a result of different co-operations and thus different target groups. Frequency distributions of wind speed are available as difference maps (the link Wind speed).

A brief description of the climate variables (-indices) is also available together with some description of the maps and some general results (follow the link ”Information”). The material has been subjected to quality control, but as it is so extensive, some errors might still remain in the produced maps.

When using the DVD start by clicking on the start-file. Thereafter choose the English or the Swedish version by clicking on respective flags.

The material is also available on the Internet via:

the English version: http://www.smhi.se/sgn0106/leveranser/mallar_e.htm

the Swedish version: http://www.smhi.se/cmp/jsp/polopoly.jsp?d=8783&l=sv

A special application was made for wind roses analyzed for 18 grid squares (the link Wind direction). This application is, for technical reasons, only available on the Internet.

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