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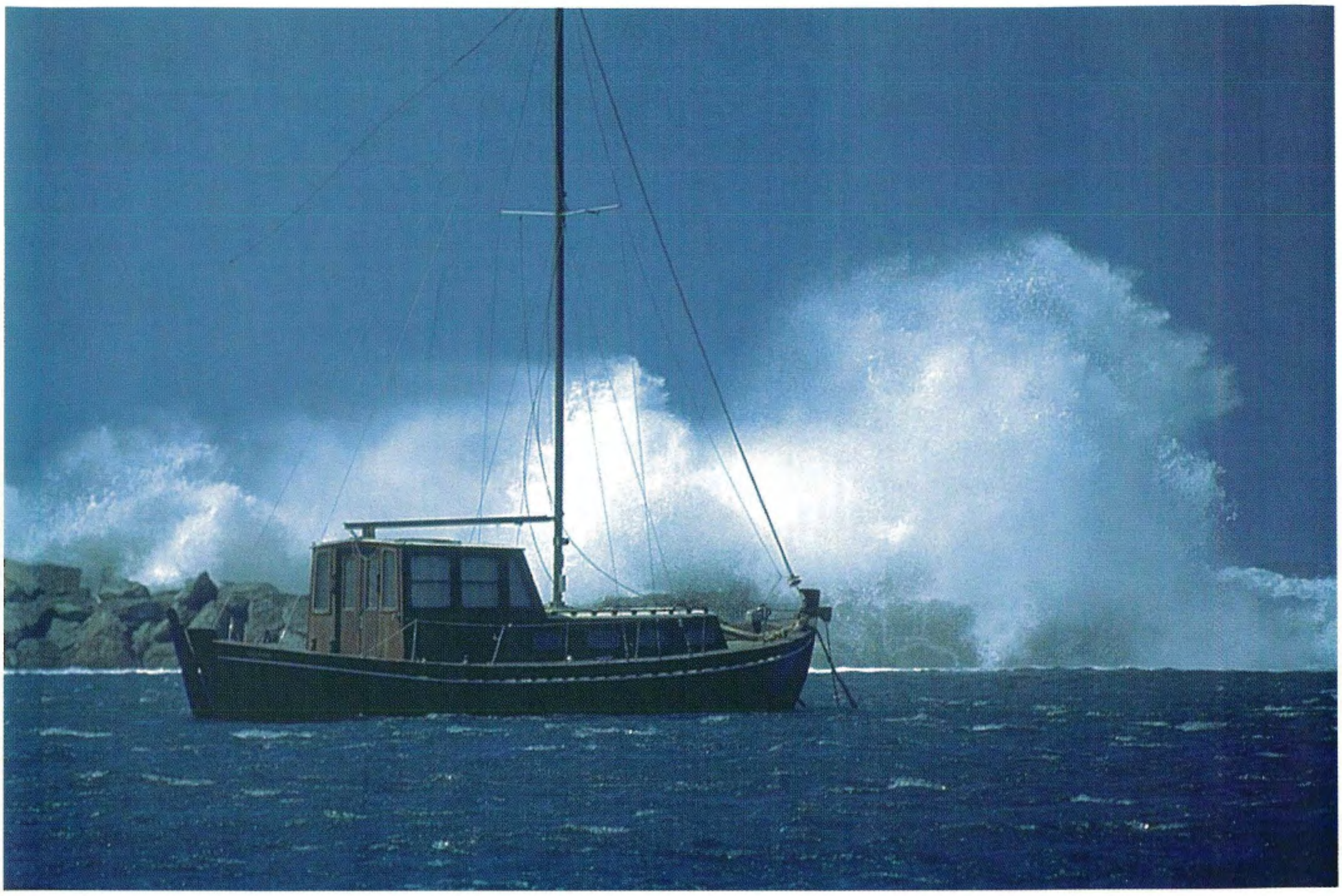

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Abstract/Sammandrag

The Swedish Regional Climate Modeling Program (SWECLIM) is a 6-year national research effort with the aim of providing the Swedish society with more detailed regional climate scenarios than typically available from international global climate model simulations. The background is the perceived further enhancement of the greenhouse effect that is projected to lead to global warming and other changes in the climate system. SWECLIM provides users within governmental organizations, businesses, political decision-making, as well as media and the general public with expertise and synthesis of climate change issues, science, results and the detailed regional climate scenarios, to further the understanding of the future changes, to facilitate planning and realization of mitigation and/or adaptation measures. This requires development and use of regionalization techniques, regional modeling tools and other studies of the relevant regional processes and collected data. Apart from hydrological interpretation done of the climate scenarios, SWECLIM does not perform impact studies. Additional concretization of the climate scenarios by external groups, who possess branch-specific impact assessment expertise, is supported and encouraged by SWECLIM.

This report describes the background of the SWECLIM-program, the work undertaken during program phase 1,lasting from 1997 to June 2000. The model development, the prepared regional climate and water resources scenarios, results from statistical downscaling and basic process studies and data analyses, as well as the interaction with users and media are covered. Finally, a brief introduction to the program phase 2 plans are provided.

Key words/sök-, nyckelord

Regional climate modeling, regional climate change, climate change, climate scenarios, climate model, dynamical downscaling, regionalization, climate change impacts

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Contents

Introduction

It has become clear in recent years that a changing composition of the atmosphere due to human activities may influence the climate system (see IPCC 1990, 1996). Emissions of greenhouse gases and their subsequent accumulation in the atmosphere can lead into an enhancement of the greenhouse effect, result in a global warming and other changes in the climate system. A warming at the Earth's surface since the 19^{th} Century (Jones et al. 1994+updates, Hansen et al. 1999, Vinnikov et al. 1990, Peterson et al. 1998a,b, Parker et al. 1995+updates, Quayle et al. 1999 and based on Reynolds et al. 1994; see also IPCC 1996) a fairly large cooling in the lower stratosphere during the past 40 years (cf. Chanin and Ramaswamy 1999), increase in the ocean heat content (Levitus et al. 2000) and changes in tropospheric temperatures (e.g. Hansen et al. 1998, Pielke Sr et al. 1998a,b, Bengtsson et al. 1999, Angell 2000, Santer et al. 2000) have been determined from observations. The annual global surface mean temperature increases since ~1880 are shown in Figure 1. The spatial patterns of the changes in principle agree well with climate model simulations. The time evolution during the past 100 years has also been reproduced in climate model simulations when man-made emissions of greenhouse gases and sulfate are included (Tett et al. 1999, Delworth and Knutson 2000). Uncertainties remain in the quantification of the future climate change (cf. Mahlman 1997, Rummukainen, 1999a) but the issue itself, that the climate change is real and that it will very likely affect us in the coming decades, is now well accepted.

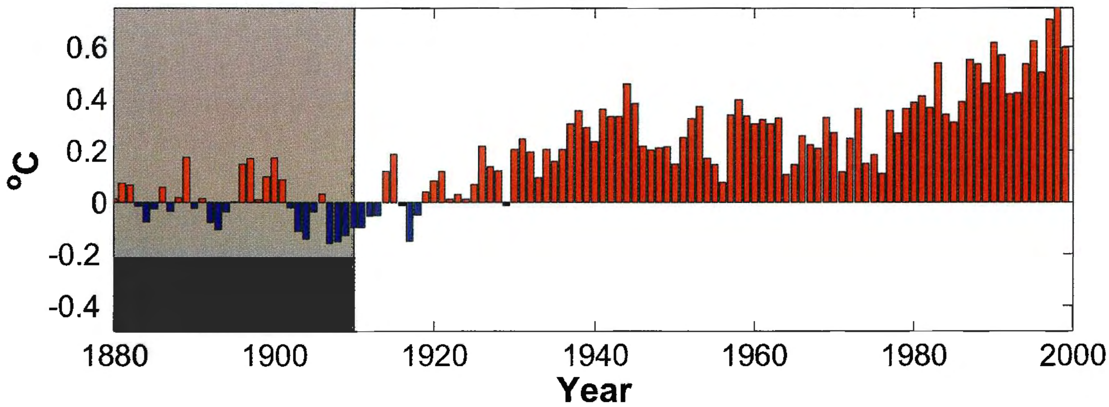

Figure 1. *Annual global surface mean temperature anomalies 1880-1999. The deviations refer to the global average surface temperature for 1880-1909, i.e. the first 30-year period in this record (see e.g. http://www.ncdc.noaa.gov). The 1880-1909 reference period is shaded for clarity.*

The continued emission of the greenhouse gases into the atmosphere may produce very substantial global climate changes in the future. If the emissions continue according to a "business-as-usual" scenario, i.e. without large effects on present trends in emissions, the atmospheric content of the man-made greenhouse gases likely doubles sometime between the middle and the end of the 21^{st} Century. Carbon dioxide is the most important directly man-influenced greenhouse gas. Methane, nitrous oxide and chlorofluorocarbons etc. are important too. Other anthropogenic activities that also affect climate are emission of sulfur and land-use changes. International negotiations may result in future reductions of emissions. One step on the way is the Kyoto Protocol from 1997. Nevertheless, an increase in the man-made climate- pollutants is likely to occur for several decades to come.

The global scale consequences of the projected climate change are notable. In the Second Assessment Report of the IPCC (1996), the global warming was projected to reach 1-3.5°C during the next 100 years. This is a large change, compared to the variations even on a multi-century-scale. This is illustrated in Figure 2. Recently, it has been made evident via media that the Third Assessment Report of the IPCC scheduled for publishing in 2100 will change the projected global mean warming range by 2100 to 1.5-6°C, mainly due to revisions of global emission scenarios.

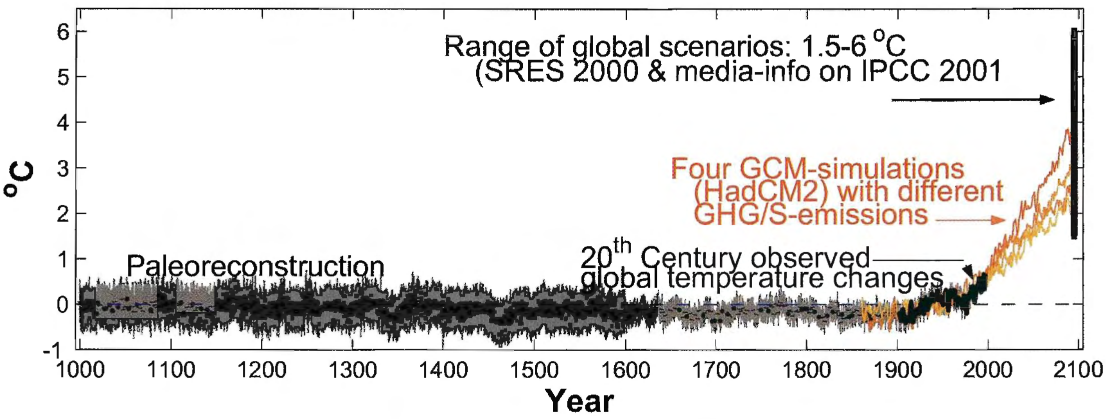

Figure 2. *Annual Northern Hemisphere surface mean temperature anomalies since 1000. The deviations are from the global mean surface temperature in 1902-1980. The paleodata-reconstruction with an estimate of accuracy (gray envelope) for 1000-1980 is from Mann et al. (1998; 1999). The heavy black line through the 20th Century the shows instrumental temperature observations in 1902-1998, sampled spatially to as the paleodata. The red and yellow lines show four UKMO HadCM2 GCM climate change runs with different greenhouse gas and sulfate emissions from the late 19th Century till year 2100 (cf. http://ipcc-ddc.cru.uea.ac.uk/). The range of GCM-estimates for global mean temperature change from the present day to 2100, additional 1.5-6°C, as compiled by IPCC (2001, see text), is drawn with the vertical bar to the right.*

The global accumulation of greenhouse gases in the atmosphere in the coming decades will lead into a significant change in the global climate. However, common to global climate scenarios is that they are difficult to put to practical use on a regional level. On regional scales, this may result in even much more pronounced climate changes. Quantitative progress on sub-global scales, in different regions and on a national level, is needed for planning more detailed response strategies; both for battling the climate change and adaptation to its likely evolution. The consequences of present and future emissions of greenhouse gases are studied and synthesized in the IPCC-process, for example, based on work by national and international research efforts.

Climate changes can impact the society in many ways. There will be direct weather- and climate-related effects (changes in mean climate, variability and extremes; e.g. storminess, energy-use, road clearing). Agriculture, forestry and infrastructure planning will be affected (dams, roads, harbors, coastal and along-river construction). How natural resources can be used is likely to change as well. The anticipated effects are large and will matter both globally (mainly negative consequences) and regionally (both negative and positive consequences). The scales and magnitude of the consequences translate into a need to combat climate change and a need to plan for adaptation. In both cases, improved knowledge of the global and regional issues of climate change is required for practical measures to be undertaken. This will directly impact the industrial and energy production, energy use and management of agriculture and forests. An example of possible effects of a climate change in the Nordic region is conditions for forestry and water resources in Sweden, as well as agriculture, other infrastructure planning etc. Almost all cultivable cereals and trees today have northerly limits of growth in Scandinavia. A change of climate can affect choices of types of trees or cereals for future cultivation. Other examples from a Swedish perspective, are fishing potential and the environmental state in the Baltic Sea, effects of road maintenance, uncertainty in the calculation of insurance policies, changed ice condition of importance for shipping, likelihood for rare species to survive, and so on. A common factor to these activities is that any plan of action relies heavily on reliable predictions of the timing and degree of a change in climate, together with a usable description of this future climate.

The main objective of SWECLIM, the Swedish Regional Climate Modeling Program, is to provide the Swedish society with more detailed and more reliable regional climate scenarios. SWECLIM aims to provide users within the national governmental organizations and businesses, political decision-making, and the general public with expertise and synthesis of global climate change science and more detailed regional climate scenarios. The aims are to develop regional modeling, to study some relevant climate processes and to create the regional scenarios. Apart from hydrological interpretation done of the climate scenarios, SWECLIM does not perform impact studies. Additional concretization of the climate scenarios is hoped from external groups, who possess branch-specific impact assessment expertise.

It is expected that the improved regional climate change assessments for Sweden will facilitate the planning of adaptation measures on activities with long planning horizons or activities that affect greenhouse gas emissions. In terms of Swedish competitiveness, it will be easier for the government to negotiate in international meetings on emission restriction measures, as well as for businesses to take into account the environmental issues, so to arrive at more environment-friendly practices. The latter is expected to improve their potential to compete nationally and internationally. At the same time, the SWECLIM-group builds up national expertise and educates young scientists in the field of climate modeling and climate change issues.

There is no doubt about the fact that the regional climate modeling and scenario analysis activities targeted in SWECLIM are highly noticed in the Swedish society. The recent report of Klimatkommittén (SOU 2000) makes an explicit note on the SWECLIM program and the need for a long-term consolidation of the program, when MISTRA funding period expires. This statement is made in conjunction with a perceived need to perform a risk analysis of future climate change impacts.

The question of climate change and its practical impacts will be important topics for a long time to come and certainly so beyond phase 2 of SWECLIM. It is foreseen that development of global climate models and greenhouse gas emission scenarios will improve the quality of climate scenarios that can be accomplished, thus increasing the usefulness of regional scenarios. In longer term, the impact of emission reductions like those targeted in the Kyoto Protocol will have to be evaluated. Additional negotiation rounds will certainly take place. Obviously, the Swedish participation should be backed up by established scientific research activities, access to climate scenarios and impact analysis on them. SWECLIM aims for, in the long-term, to secure climate change modeling and expertise in Sweden and to provide users with expert assessment on the issues, tools and results on climate change issues, and to support analyses of estimates of practical consequences.

This report describes the first phase of the SWECLIM program: how it came about, how the program is set up and what research has been pursued. In particular, the regional modeling approaches are described, examples of the produced regional climate scenarios are given and the impact studies so far performed are mentioned.

In the following, "Phase 1" means the first program phase of the SWECLIM-program. It extended from 1997 to June 2000. "Phase 2" refers to the second program phase that extends from July 2000 to June 2003. An introduction to the plans for program phase 2 is provided in the end of this report.

1 Part 1 – the road to SWECLIM

1.1 The initial program idea

The first ideas of a Swedish national effort in the field of regional climate change research were discussed already in 1993. A workshop held at the Royal Swedish Academy of Science formulated a proposal for strengthening of the climate modeling in Sweden (Documenta 1994). At that time Sweden was playing a prominent role in the international climate change assessment activities, in particular through Prof. Bert Bolin who chaired the Intergovernmental Panel on Climate Change (IPCC) process. In 1994 an initiative was taken by the Swedish Meteorological and Hydrological Institute (SMHI), asking Prof. Lennart Bengtsson at the Max Planck Institute for Meteorology in Hamburg to assess the possibilities to establish a research network in the area. This work led to a draft research proposal to the newly established Swedish Foundation for Strategic Environmental Research (MISTRA).

It is interesting to note that the establishment of MISTRA in 1994 in practice acted as a catalyst for the SWECLIM-program to come about. The background of MISTRA goes back to Swedish domestic politics and the former Employee Investment Funds. Article 1 of MISTRA's statutes provides the basis for the activities that MISTRA supports:

> *"The Foundation shall promote the development of strong research environments of the highest international class with importance for Sweden's future competitiveness. The research shall be of importance for finding solutions to important environmental problems and for a sustainable development of society. Opportunities for achieving industrial applications shall be taken advantage of."*

In addition to the basic requirement to offer scientific quality, the programs supported by MISTRA are characterized by targeting practical problems that relate to the environment, by the existence of identified user groups and by expecting concrete solutions/knowledge to arise. MISTRA requires a well-established program leadership and coordination, supports time-limited programs of typically up to some six years duration, conditional on the scientific merits evaluated at mid-term. The programs are also typically characterized by networking and cross-disciplinary activities and with links to user communities. There is room for some basic science in the programs, but weight is typically on applied science.

1.2 From the initial idea to submitting the application

Following a positive response from MISTRA in 1995 on the preliminary proposal, a group of scientists from university departments and SMHI, with Prof. Henning Rodhe from Stockholm University as chairman worked out a final proposal for a Swedish climate modeling program. A major component of the proposal was the establishment of a new core group of researchers at SMHI, the Rossby Centre. The application was sent to MISTRA in December 1995.

1.3 Final plan and negotiations

The plan was accepted after some revision. The main funding agencies became MISTRA (33 MSEK for phase 1 of the program) and SMHI (up to 10.5 MSEK for phase 1). Funding for phase 2 was made conditional on a mid-term evaluation, to be conducted at the end of the first period of three years. In addition, SWECLIM was obliged to secure other external funding from users, as a condition for MISTRA-funding for the second program phase. This requirement was later revised to include external research funding from e.g. EU.

From the outset it was clear that SMHI should be the central site for SWECLIM. The Rossby Centre would be part of the SMHI organization. SMHI would also become the program host and the university groups would receive funds from MISTRA via SMHI. A special contract arrangement between SMHI and the participating universities was negotiated. It was not straightforward for the participating university groups to agree on the terms laid out by MISTRA, i.e. in particular that decisions about the program are made by a board. Some university groups were of the opinion that when the budget for the program had been determined it was up to the university groups to decide how they would want to use the funds allocated. After discussions an agreement was reached, but as it turned out, one of the university groups left the program in 1998 due to disagreements on how decisions in the program are taken.

1.4 Building up the activities

The network, that came to be called the Swedish Regional Climate Modeling Program (SWECLIM), initially consisted of SMHI, groups at Stockholm University, Göteborg University and Uppsala University. [The Uppsala University group left the network during 1998.] The network base became the new research center at SMHI: the Rossby Center.

As SWECLIM was clearly a major research network initiative, consideration was dedicated to establish an efficient and balanced leadership and coordination structure. First the program board was setup of representatives from potential users, the university world and the SMHI. A representative of MISTRA was also included in the board though without a vote in decision making.

The program directorship went first to Prof. Erland Källén from Stockholm University who at that time was employed also by SMHI as the project leader of phase 3 of the international HIRLAM project on limited are weather forecasting. This was a good background for the appointed program director as the HIRLAM limited area model was taken as the development platform for the SWECLIM regional climate model. At the same time, the appointment gave credit to the expertise of the Department of Meteorology at Stockholm University (MISU) in climate research. The Rossby Centre leadership was assumed by Mr Lars Moen from SMHI which ensured balance between the network participants and was advantageous as the Rossby Centre was physically placed within SMHI, directly under the General Director Hans Sandebring (see Figure 3).

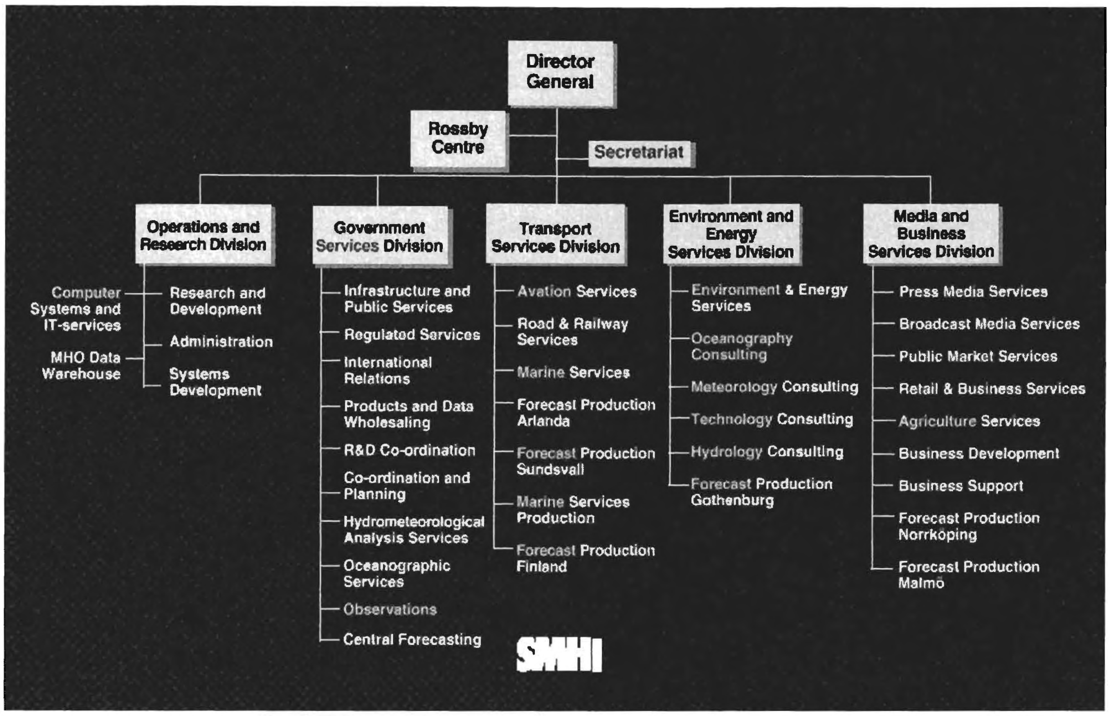

Figure 3. *The SMHI organization in 1997.*

The program activities formally started in January 1997 with the university groups started on their research tasks.

The Rossby Centre

The build-up of the Rossby Centre started in August 1997 as the first staff members started their work. The recruitment was finished first by mid-1998. The first year of activities was much a period of planning of the new major research area, solving practical and technical problems, building up a contact network and delivering the first results as committed in the SWECLIM plan.

The Rossby Centre has the following main tasks in SWECLIM:

- Establish, develop and maintain regional climate models for the atmosphere, the ocean and the land surface.
- Perform and analyze regional climate simulations.
- Provide an interface for interaction with users.
- Provide an overall information resource on climate modeling and climate change research.

The research group was recruited on a high scientific and technical level and attracted researchers from Sweden, Finland, Germany, the US and the UK, supported by system experts and a secretary. The competence covered all the three modeling areas of meteorology, oceanography and hydrology. An important factor behind the international interest on the positions was the possibility for SMHI to offer permanent positions.

From the start, the main responsibility for user interactions within SWECLIM was imposed on one of the researchers on a part-time basis. With a change in the staff in early 1999 this function was upgraded to a full time responsibility, to be handled by a senior meteorologist with experience from user contacts.

One important justification of locating the Rossby Centre to SMHI was the availability of the technical infrastructure. The cooperation between the National Supercomputer

Centre, NSC, at Linköping University and SMHI on the migration of the NWP production to the new parallel computer CRAY T3E made it possible for the Rossby Centre at an early stage to start regional climate modeling tests on this powerful platform. After some initial problems, the T3E was shown to be a very efficient platform for the planned climate simulations.

The internal computer facilities and service at SMHI has also been a necessary requirement for the work at the Rossby Centre. The SMHI infrastructure could however not immediately meet all the requirements. In spite of frequent upgrading of storage resources, limited disc space was a bottleneck most of the time and the costs for storage larger than anticipated.

It was also found that a more powerful local compute server for testing the model codes before running these on the T3E was needed. Such a facility was purchased jointly with the research section at SMHI (If) in July 1998.

Close contacts between the Rossby Centre and the If were established at an early stage. Researchers from If participated in workshops and informal working meetings. This cooperation, especially with the HIRLAM and BALTEX groups, has been extremely important. Within SWECLIM itself, cooperation has been continuously evolving between the Rossby Centre and the research groups in Stockholm and Gothenburg.

Active cooperation with researchers/research groups outside SWECLIM was also built up. Early on, contacts started with Hadley Centre (HC) in Bracknell, Max Planck Institute for Meteorology (MPI) in Hamburg, climate modelers and oceanographers in Denmark, Norway and Finland, the international HIRLAM project group, Southampton Oceanography Centre, Los Alamos National Laboratory, Institute of Marine Research in Kiel, Baltic Sea Research Institute in Warnemünde, forest researchers at SLU and visiting researchers at MISU (ocean modeling, glacier studies). Agreements were reached with HC and MPI for the availability of global climate simulations to be used as forcing of the regional simulations. This cooperation has significantly contributed to the fast development of the activities at the Rossby Centre.

The universities

Stockholm University: The SWECLIM research activities at the Department of Meteorology, Stockholm University (MISU) concentrate on the four main areas of:

- Aerosols and clouds
- Surface processes and turbulent exchange
- Large scale dynamics
- Oceanographic modeling

In the area of "aerosols and clouds" a PhD student became involved in SWECLIM at the start of the program. Her task is to estimate the effects of aerosols on clouds in regional climate simulations. This work builds on the expertise developed at MISU over a number of years in the area of aerosols and climate change. In particular sulfur aerosols are central to this research. Also some PhD student work in the areas of cirrus and stratocumulus modeling was directed towards SWECLIM interests. So far, two theses have been completed with part of the financing having come from SWECLIM. Future versions of the Rossby Centre regional model will incorporate some of the findings demonstrated in these theses.

Work on "surface processes and turbulent exchange" was initially planned at groups at Uppsala University. After their departure from the program, new expertise had to be recruited. A postdoc was recruited from Uppsala to MISU in 1999 to study surface exchange processes. Furthermore, a PhD student has become involved in studying the effects of turbulent processes on fronts. Much of the gain from increasing resolution in a climate model is the capability to better describe frontal structures. However, it must be ascertained that parameterizations of turbulent processes in the free atmosphere do not adversely affect the fronts. Simulations of strong winds and intense rain events are closely coupled with frontal structures.

The "large scale dynamics perspective" focuses on the possible effects of global climate change on regional circulation patterns. Previous research activities at MISU have investigated mechanisms that are responsible for the maintenance of persistent, large-scale circulation patterns. Now the attention has been turned to the possible effects that a change in the global climate may have on these patterns. There are many theories postulating that certain changes will take place, but it is not apparent from general circulation models that such changes actually would take place in a warmer climate. A PhD student has been employed for this work.

In the area of oceanographic modeling a newly formed research group at MISU has collaborated closely with the Rossby Centre. The common task has been to set up a numerical 3-D ocean model for the Baltic Sea. One senior researcher has been recruited to MISU for this purpose and collaboration with the Defense Research Institute (FOA) has been established. Also help with the basic technical work involved when setting up a parallelized ocean model code has been obtained via visiting scientists at MISU.

The International Meteorological Institute is an integral part of MISU and some of the visiting scientist resources have worked also with SWECLIM. In particular one visitor, J. Oerlemans, contributed with a new aspect of regional climate change modeling, namely a study of the impact of climate change on mountain glaciers. Using the first Rossby Centre climate change simulation results he could determine possible effects on mountain glaciers in the Nordic region.

Göteborg University: The SWECLIM research activities at Göteborg University (IGGU) concentrate on:

- Analysis of Baltic Sea ocean climate observations.
- Process-oriented Baltic Sea modeling and scenarios.
- Development and application of statistical downscaling on climate analysis and climate scenarios (formally this was started during Phase 1 rather than having been planned for originally).

During the first months of Phase 1, a formal "marine climate group" was formed at the Department of Oceanography in Göteborg University, in the context of the SWECLIM-program, building also on the expertise in climate studies collected at the department for a long time. The group to become involved in SWECLIM included three senior scientists and two PhD students. The funding from SWECLIM was used as complementary funding for some of the scientists involved. The work within SWECLIM has also benefited scientists outside the group and vice versa.

The focus of the scientific work at IGGU was in the beginning on analyses of the present-day ocean climate of the Baltic Sea. This included collecting relevant oceanographic data from different sources into archives of historical data. Process-oriented modeling of present and future climate of the Baltic Sea was also taken on, in close cooperation with other SWECLIM participants.

The educational activities in SWECLIM were also managed by the IGGU-group . A series of climate-related seminars were initiated at the onset of the program to support the execution of the program activities combining different disciplines and tasks. A number of PhD courses were also planned for and carried out together with the other university departments involved in the program. Students and teachers from the disciplines of hydrology, meteorology, oceanography and physical geography were involved. The motivation was to create a network among students and teachers with climate related interests.

The hydrology group at SMHI research unit

The hydrological modeling within SWECLIM has been carried out partly at the research unit (If) of the SMHI and partly at the Rossby Centre of the SMHI. The overall research unit has some 40 researchers in the fields of meteorology, climatology, oceanography and hydrology. The hydrology group has during recent years consisted of 6-7 persons working with different modeling and analysis aspects. The group has long experience in model development and applications of the hydrological HBV runoff model. It has been used for hydrological forecasting and design studies during many years and also for environmental studies of non-point source pollution and climate change impact studies (Saelthun et al. 1998). Main part of the group, with the emphasis on four researchers, has been involved in the modeling work during Phase 1. At the Rossby Centre, one researcher has been working with large-scale hydrological modeling.

The management structure

MISTRA provides a model for the management structure for the supported programs. The model includes a program board, a program director, a management group and project leaders. This model is followed in SWECLIM (see Figure 4). SMHI is the program host (economic and legal administration) with a contract with MISTRA and also with contracts with the other participants, the Stockholm and Göteborg Universities.

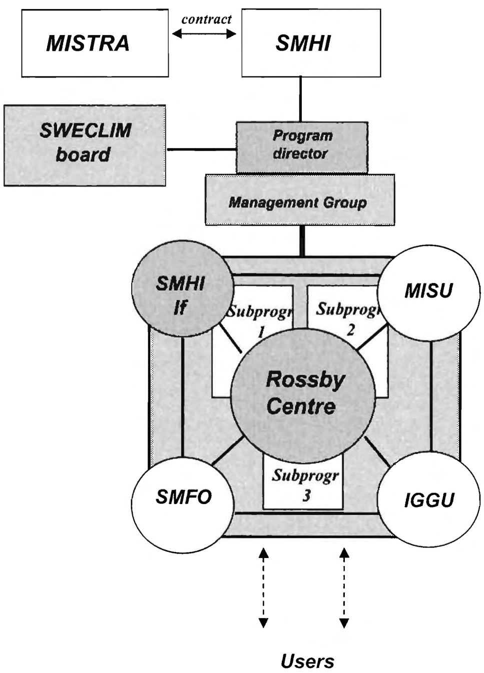

Figure 4. *The phase 1 program structure.*

The SWECLIM program board consists of representatives of user groups with interest in the climate change issue. The chairman is from SMHI, one member is from the universities, one represents forestry interests, one the Swedish Environmental Protection Agency (Naturvårdsverket) and one the electric power sector. Observers from MISTRA and the Rossby Centre are also included. The board has the overall responsibility for the allocation of resources within the program and for monitoring and reporting on the progress. The board links the program to the user aspects and distributes information. The board also appoints and instructs the program director.

The program director carries out the tasks specified by the board, reports to the board and has the executive duties and responsibilities of the scientific and administrative program management. The program director maintains and develops links between the program and external groups as well as within the projects in the program and chairs the management group.

The management group provides for more detailed supervision of the efforts within and between projects (in SWECLIM these are called subprograms). The members of the group are the subprogram leaders. The subprogram leaders are also responsible for an efficient dissemination of results, contribute and call for contributions to the SWECLIM Newsletter, workshops, conferences, meetings, scientific journals and the annual scientific and popular program reporting.

Subprograms. In Phase 1 of SWECLIM (1997--mid-2000), there were three subprograms: 1) "Regional climatological interpretation", 2) "Climate system processes - atmosphere/surface" and 3) "Climate system processes - ocean". The division reflected the intensive modeling development in each of the fields of meteorology, oceanography and hydrology. The subprograms create the practical frame for collaboration between the university groups and the Rossby Centre.

In Phase 2 (mid-2000--mid-2003), model development and scenario simulations will be continued targeting coupled (atmosphere-land surface/hydrology-lakes-Baltic Sea-ice) modeling of the regional climate system. Increasing emphasis will also be on the provision of climate scenarios to users. To reflect these priorities, the Phase 2 program organization includes four subprograms:

1) "Development of regional climate models" (covers the further development of the regional atmospheric, hydrological and ocean models)
2) "Computation of regional climate scenarios" (a sufficient set of long climate calculations and their basic interpretation is performed).
3) "User interaction and hydrological impacts" (covers user interaction and studies on climate change impacts on water resources).
4) "Theoretical and analytical studies of climate" (includes supporting studies on regional climate variability and interpretation of imported global climate model results).

International cooperation

Contacts and collaboration with other climate research institutes are vital for SWECLIM. The regional atmospheric and land surface modeling is based on the Nordic-Irish-Dutch-French-Spanish collaboration on short-range weather forecasting (the HIRLAM-project). Cooperation on regional ocean modeling is done with the Southampton Oceanographic Research Centre and the University of Kiel. The global model data needed to drive the regional climate models are obtained from the Hadley Centre in the UK and the Max-Planck-Institute for meteorology in Hamburg, Germany.

Early on in the program, visits by key staff members were made to other institutes. A Nordic cooperation agreement in the field of regional climate modeling was established between the meteorological services in Denmark (Danish Climate Center at DMI), Norway (RegClim-project run in part at DNMI), Finland (regional climate related activities at FMI) and Sweden (Rossby Centre at SMHI). A letter of intent was established between BALTEX and SWECLIM.

SWECLIM has participated in several international research meetings and workshops. The EU-supported MERCURE project on regional climate modeling has arranged workshops where also results from SWECLIM have been discussed. Presentations have been made in international conferences such as EGS- and IUGG-symposia. SWECLIM has also enabled an active Swedish participation in international research efforts such as CLIVAR, CMIP2 and contributions to the preparation of the IPCC Third Assessment Report.

SWECLIM is involved in two regional modeling intercomparison projects, the Project to Intercompare Regional Climate Simulations (PIRCS) and the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS). PIRCS is a community-based project, organized at the Iowa State University and manages intercomparison of regional climate models. So far, experiments have been made for hydrologically special periods in the US, following the GEWEX Numerical Experimentation Panel recommendations. PIRCS does not provide funds. PILPS is a World Climate Research Program project under the auspices of GEWEX and WCRP. It manages a series of experiments, designed to improve land surface parameterizations and the modeling of hydrological, energy, momentum and carbon exchanges with the atmosphere. SWECLIM will participate in the next PILPS modeling experiment (2e) conducted for the Torne river basin in northern Sweden.

International scientist participation in SWECLIM has been accomplished through a successful international recruitment to scientist positions at the Rossby Centre. Scientists from Germany, Finland, the United Kingdom and the United States are presently employed at the Rossby Centre. At MISU scientists have also been recruited internationally and in addition there have been visiting scientists participating in SWECLIM activities. Finally, SWECLIM PhD courses arranged through the University of Göteborg have included lecturers from the United States and students from other Nordic countries.

2 Part 2 – Phase 1 program activities; 1997–June 2000

2.0 The regional climate model tools: An overview

The SWECLIM regional climate model system is built around the main components illustrated in Figure 5: A regional atmospheric model including a land surface part and a model for inland lake systems (RCA and PROBE-lakes; see Rummukainen et al. 1998, 2000) and a process-oriented model (PROBE-Baltic) or a 3-D high resolution regional ocean model for the Baltic Sea (RCO; see Meier et al. 1999). The models are forced at the lateral boundaries by global climate models. Over the sea areas not covered by the regional ocean models, the global model sea surface properties (temperature, ice) are used. The atmospheric and oceanic models are coupled through fluxes of momentum, heat and water. The land surface acts as a link between the atmospheric and oceanic models through freshwater fluxes.

In addition, hydrological simulations for waterflow in rivers, soil moisture and snow are done with the HBV hydrological model (Bergström 1995, Lindström et al. 1997). Features of the HBV have also been introduced into the RCA model.

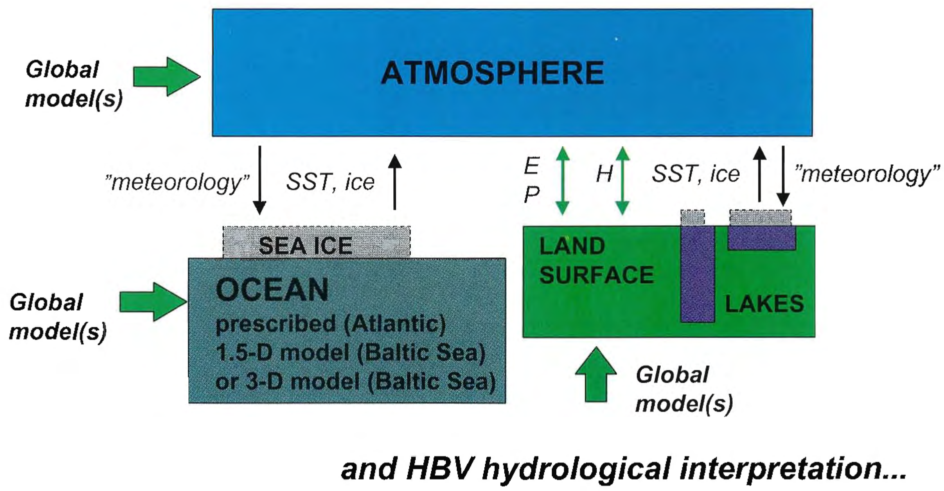

Figure 5. The SWECLIM regional climate modeling system; the atmospheric model with a land surface component (RCA), models for deep lakes and shallow lake systems and either 1.5-D process-oriented regional ocean model, or the 3-D RCO regional ocean model. The HBV-model is used for off-line hydrological interpretation of the results. The system is forced by data from GCM-simulations (or, in some applications, numerical meteorological analyses/forecasts/reanalyses such as the ECMWF ones). Coupling between the model system components is done either using fluxes (within RCA for the atmosphere and land surface: radiation, latent and sensible heat, wind stress) or by separate flux calculations in different components (in RCA for the atmospheric and lake/1.5-D Baltic Sea components). In the latter case, input data such as surface air temperature, moisture, wind, precipitation and cloudiness, SSTs or ice cover is passed between the components, as appropriate. The coupling of RCA and RCO is based on coupling using fluxes, via the so-called OASIS flux coupler tool.

The development of the regional model system is illustrated in Figure 6.

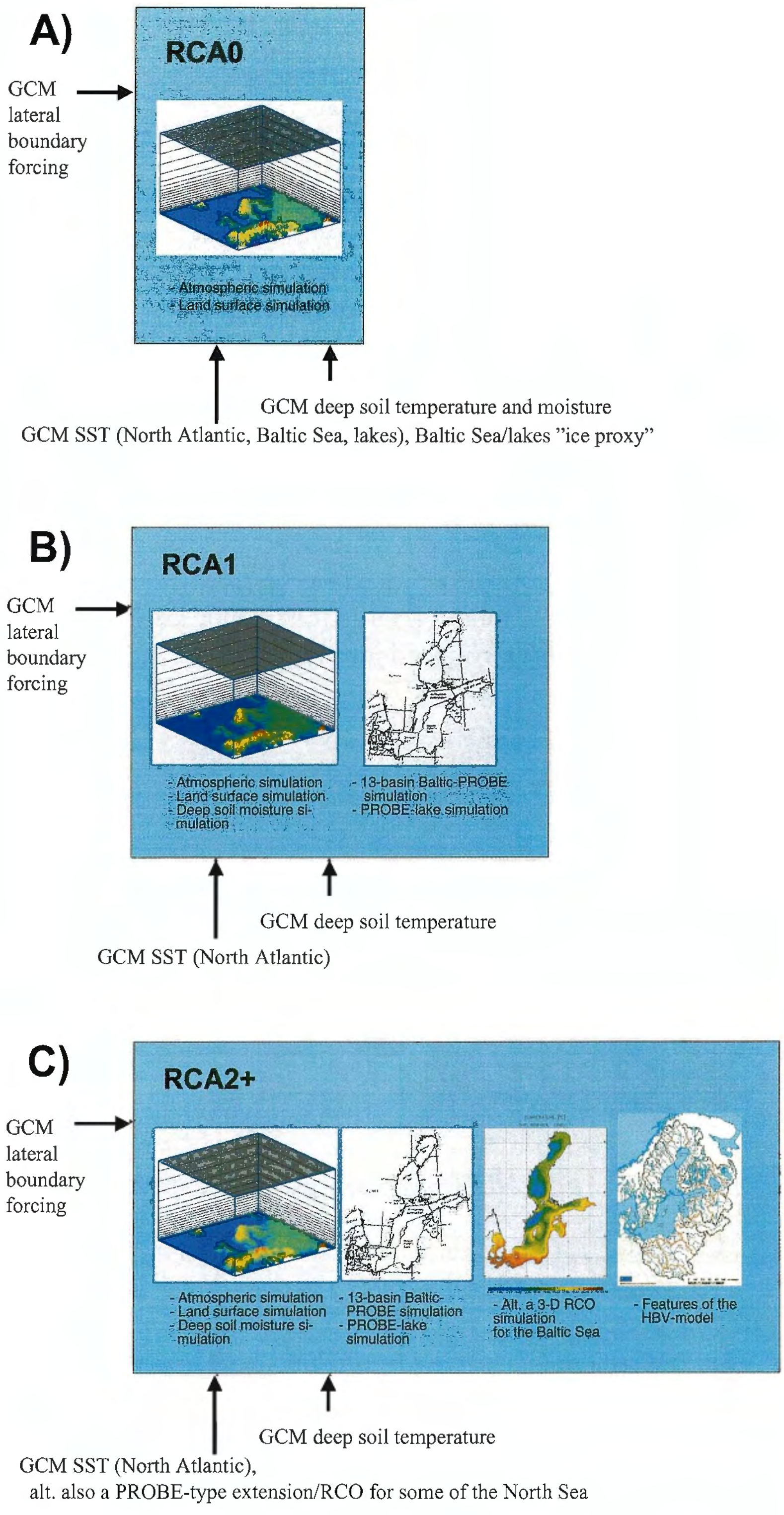

Figure 6. *Schematic illustration of the three major setups of the regional climate modeling system developed and used in SWECLIM.*

Of the three setups so far, the first (RCA0, panel A) was established for the first SWECLIM scenarios in 1998. It featured atmospheric and land surface simulation. The North Atlantic and Baltic Sea surface data were from global climate models (i.e., General Circulation Models, GCMs). Deep soil temperature and moisture were also prescribed from GCMs. The second setup (RCA1, panel B) from 1999 was used in the second set of scenarios. Instead of using GCM data for the Baltic Sea, the regional model was extended to include the Baltic Sea, using the 13-basin PROBE-Baltic model. Lakes were modeled similarly with the PROBE-concept. Due to advances in soil parameterization, soil moisture simulation was done without the deep soil forcing. Deep-soil forcing of soil temperature, from GCM data, was still done.

The third setup (RCA2+, panel C) is scheduled for autumn 2000. It includes the RCO as an alternative for describing the Baltic Sea in the regional modeling. The coupling between RCA and RCO is designed using the OASIS flux coupler tool (Terray et al 1999; Valcke et al. 2000). Additional features of the HBV model are incorporated into RCA, to describe river flow and to update the modeling of snow on land. A number of atmospheric (convection, condensation, cloud fraction, turbulence) and land surface parameterizations (vegetation temperature, surface physiography, surface resistances, rainfall interception) are to be considered.

To construct climate change scenarios the regional model systems are run in multi-year time slices. One simulation uses a time slice from a global model run representing present climate conditions ("control simulation"). The results can be compared with observations to assess how well the regional model manages to capture regional climate characteristics, not well described in global models. A second time slice is taken from the global model scenario period. This represents a future climate scenario. By computing differences between the control and the scenario run, measures of climate change signals in the mean characteristics as well as in higher order statistics are obtained. Thus the mean change can be tested for significance with respect to the characteristic variability within the sample period.

2.1 The model for the atmosphere, land surface, lakes and 1.5-D Baltic Sea: The RCA including two PROBE-type modules

RCA is based on the short-range weather forecasting limited area model HIRLAM (Källén 1996, Eerola et al. 1997). The later was originally based on a mid-1980's version of the ECMWF global weather prediction model. Rummukainen et al. (1998) describe the first RCA version, the RCA0 from 1997-98. The next model version, the RCA1 from 1999-2000 is described by Rummukainen et al. (2000), focusing on the surface/soil/snow scheme and the treatment of the Baltic Sea and inland lakes that were much modified.

RCA is a hydrostatic, primitive equation gridpoint model with Eulerian advection and a leapfrog semi-implicit time integration (Simmons and Burridge 1981). The prognostic variables are temperature, specific humidity, horizontal wind, cloud water and surface pressure. Cloud ice is diagnostic. Cloud water is transported by an upstream scheme. Advection of other variables is with second order centered finite difference approximations. Horizontal diffusion is done with a linear, fourth-order scheme. Up to the regional climate model version of RCA1, additional prognostic variables have been snow cover, soil temperature and soil moisture. To couple the driving large-scale data (e.g. ECMWF analyses or some GCM- results), a Davies-type (Davies 1976) boundary relaxation is applied on surface pressure, temperature, specific humidity, wind and cloud water, with a *tanh*-shape weight function in an 8-points wide boundary zone.

The HIRLAM physical parameterizations used still in RCA1 are the core of the radiation scheme (Savijärvi 1990, Sass et al. 1994), the convection scheme (Kuo 1965, 1974), the large-scale cloud and precipitation microphysics (Sundqvist et al. 1989, Sundqvist 1993) and the first-order vertical diffusion (Louis 1979, Geleyn 1987). These are targeted for modification or replacement in the next model version RCA2.

The RCA domain uses a spherical, rotated latitude/longitude Arakawa C grid. Typically, 19 vertical levels, a hybrid vertical coordinate (Simmons and Burridge 1981) and the model top at 10 hPa are used. Three different horizontal resolutions have been tried out: 88 km, 44 km and 22 km. Most of the scenarios made so far have been with the 44 km resolution. A typical RCA model domain is shown in Figure 7. How this compares with typical present-day global climate models is also illustrated.

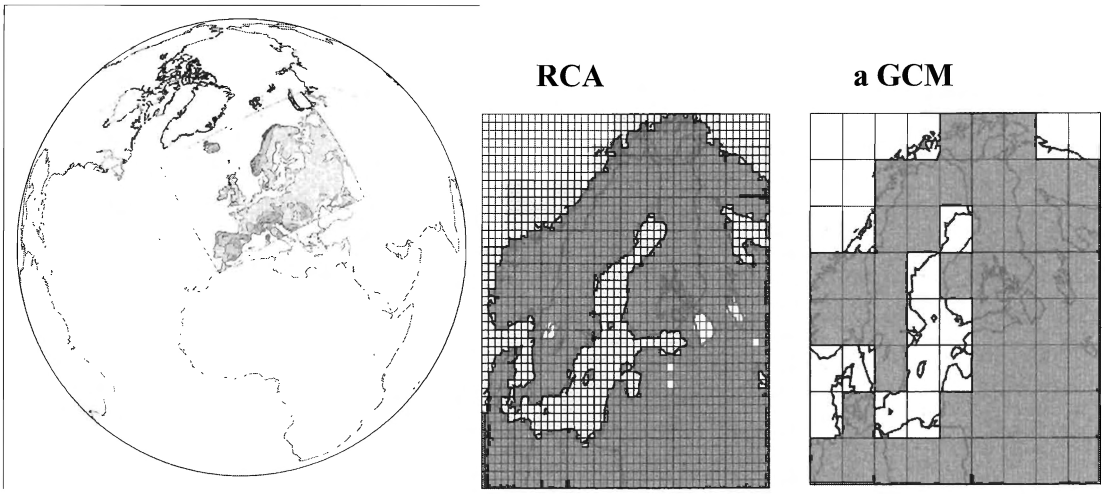

Figure 7. *(Left:) The typical RCA horizontal model domain and (right:) The Nordic part of a typical 44 km used in RCA and a typical grid (roughly 300 km resolution) in global climate models presently in use.*

Throughout the development of RCA, the aim has been to develop the process descriptions simultaneously, so that a proper balance in complexity and in model climate is maintained. New schemes have only been implemented after making sure that they lead to improved results. As model development is a continuous process, there is often a time lag between an identification of a problem and its solution. Scenarios are therefore sometimes simulated with a system including even known problems. It is, however, important that schemes not sufficiently tested are not used; so unexpected problems are avoided. Below, the treatment of the radiation processes, moist physics, the land surface-snow-hydrology system and the accounting for inland lake systems and the Baltic Sea is outlined as they developed in Phase 1.

The radiation scheme. The radiation scheme from HIRLAM has two spectral ranges, one for solar radiation and one for the longwave radiation. Its radiative transfer depends on the water vapor and cloud fields. The roles of CO_2, ozone and background aerosol are incorporated as constants without an easy allowance for a changing CO_2. This fixed-CO_2 treatment seems a limitation in climate applications. At least regarding the temperature climate, however, the CO_2 concentration in RCA is relatively unimportant, because the forcing by the driving GCM is strong, from the lateral boundaries, by the Atlantic SSTs and the deep soil temperature. RCA has also been run with a modified radiation scheme that allows for varying CO_2 (Räisänen et al. 2000c). This was implemented in RCA1 by early 2000, in time for the final Phase 1 regional scenarios and will also be used also in RCA2.

The moist physics and turbulence schemes originally in the RCA model have been completely replaced by schemes more appropriate for the model resolutions utilized in

SWECLIM (10-50 km). There has also been the desire for a more sophisticated moist physics description, such as a microphysics scheme retaining information on the droplet size distribution, as this would allow more explicit links with the radiation scheme. The new package consists of the Kain-Fritsch convection scheme (Kain and Fritsch 1990), the Rasch-Kristjánsson condensation/cloud scheme (Rasch and Kristjánsson 1999) and the CBR turbulence scheme (Cuxart et al. 2000). The primary motivation for making these changes lay in the need to parameterize convection appropriately for mesoscale resolutions. The CBR turbulence scheme was shown to perform better than the earlier vertical diffusion scheme (Louis 1979) in HIRLAM tests. This and the fact that new convection scheme required TKE as a closure term, led to the natural incorporation of this parameterization as the subgrid scale vertical mixing scheme in the RCA. This new package of moist physics and turbulence is presently being evaluated in the HIRLAM group, with the aim of it becoming the reference package for the next HIRLAM model. A brief description of the schemes follows.

Turbulence. It proved desirable to package the new moist physics with a new turbulence scheme to facilitate a closer coupling between convection, vertical turbulent mixing and cloud formation. The turbulence scheme is the CBR boundary-layer turbulence parameterization (Cuxart 1997, Calvo and Cuxart 1997, Cuxart et al. 2000, see also Kållberg and Ivarsson 1998) with a prognostic equation for the turbulent kinetic energy (TKE) and an analytical mixing length to close the system (Bougeault and Lacarrère 1989). The latter is proportional to the distance that an air parcel can travel vertically from a given level before being stopped by buoyancy, while consuming its TKE; this represents the size of the turbulent eddies. The exchange coefficients are proportional to the TKE and the mixing length. Stability functions are derived from the complete system of equations without *ad hoc* assumptions and modulate the turbulent exchange, depending on the buoyancy. Presently the scheme uses dry variables, but a new version utilizing moist conservative variables (liquid-water potential temperature and total-water mixing ratio) will be worked on.

Convection. At 10-50 km resolutions, the parameterization of convection requires a different approach to that often used in lower resolution models. For example, the Kuo scheme, originally in use in RCA, relates convective heating/drying to the predicted resolved-scale moisture convergence in a column. It also attempts to parameterize the heating/moistening associated both with active convective updraughts and downdraughts, and mesoscale convectively forced circulations. As the resolution of the model increases beyond 50km, these mesoscale circulations and cloud systems associated with convection progressively become explicitly resolved. There is a danger, therefore, of double counting the effect of these circulations in the context of the heat and moisture budget of the model atmosphere. The convective parameterization should now only describe the thermodynamics of the active convective turrets, since the forced mesoscale circulations become resolved in the model. The closure assumptions relating convective processes to the large-scale model atmosphere when parameterizing active convection of this type, at higher resolutions, differ greatly from those used at low-resolution. Observations suggest that on scales below 50 km, the local Convective Available Potential Energy (CAPE) is a more appropriate closure variable than moisture convergence. The KF scheme has been found to perform particularly well in the SWECLIM target resolution range (cf. Kuo et al. 1996, Wang and Seaman 1997). The KF scheme became the starting point for the new moist physics. The basic closure for deep convection is removal of grid-column CAPE in a representative time period. For shallow convection the closure is based on the TKE of the turbulence scheme. There is thus a strong coupling between the model convection and turbulence schemes.

Large scale clouds and precipitation. The RK condensation scheme is based on Sundqvist (1989) that RCA first inherited from HIRLAM. In RK, the conversion of water vapor to/from condensate closely follows Sundqvist but the conversion from condensate to precipitation is somewhat different. A more explicit determination of the various physical processes contributing to precipitation release is made. This allows for easier diagnosis of the water budget and a larger degree of freedom through which the resolution dependency of the model hydrological cycle can be explored. In RK, cloud liquid water is prognostic. Cloud ice is diagnosed as a function of temperature. Cloud cover is diagnostic and is presently a function of relative humidity via the Slingo scheme (Slingo 1987). A version of the cloud fraction calculation that utilizes both cloud water and relative humidity due to Xu and Randall (1996) has been implemented as an option and will be investigated in the future.

The three schemes (CBR, KF, RK) act in RCA in the following manner. The CBR is called first for sub-grid scale turbulent mixing. The predicted TKE is passed to the KF. The KF is called to determine points with deep or shallow convection. Convective heating/drying rates are calculated and a convective precipitation rate is calculated. Cloud water, heat and moisture are detrained from the convective plumes into the environment to modify the tendencies of temperature, specific humidity and cloud water prior to calling the RK. This is a direct coupling between the convection and large-scale condensation and means convection and large-scale condensation can occur simultaneously in a grid box. The diagnostic convective and large-scale cloud fraction is then calculated. The large-scale cloud fraction is passed to RK and used to govern the location of condensation and evaporation of cloud water. Finally, tendencies due to large-scale condensation are calculated and the large-scale precipitation predicted. A combined total cloud field is used in the next call to the radiation scheme.

These new schemes are extensively tested already with the RCA1-2 framework using ERA data as the large-scale forcing and comparing to available precipitation and cloud observations/analyses. Overall, the new package performs well. Systematic biases appear small and the model runs in a stable manner without having to use very short time steps as earlier in RCA0-1 with the original moist physics. The RCA1-2 containing these new schemes contributed to the PIRCS 1b intercomparison for a major flood event over the American Mid-West in 1993. The RCA precipitation fields proved to be the most accurate of all 12 participating models. Also the seasonal and diurnal precipitation and cloudiness cycles appeared well simulated. Future work will concentrate on the following areas, in cooperation with other groups:

- Cloud fraction onset and development.
- A thorough evaluation of the seasonal and diurnal cycle of cloudiness and the vertical distribution of cloudiness.
- Improving the performance of the new moist physics at 10-25 km resolution.
- Coupling the new moist physics to the semi-Lagrangian dynamical scheme to allow longer model timesteps.

The land surface-snow-hydrology. In the surface parameterization imported from HIRLAM, there was no vegetation-dependent control on evaporation and the soil thermal and hydraulic properties were invariant in space and soil moisture. In addition, the soil temperature and moisture evolution was constrained by a relaxation to prescribed, "climatological" deep-soil fields. This was maintained in RCA0 and used in the very first scenario simulations in 1998. The deep-soil forcing on moisture meant that in principle there was considerable loss of soil moisture without explicit accounting for it in the runoff variable. The loss came about as the simulated soil moisture was relaxed to monthly fields that obviously were in the mean drier than the soil moisture simulated closer to the surface in RCA0. Furthermore, the simulation of snow included a large empirical correction. Only surface runoff took place, instead of a more physical vertically-routed transport of soil moisture (cf. Graham and Bergström 2000).

In RCA0 (Rummukainen et al. 1998), hydraulic and thermal diffusivities were made to vary with soil texture type and soil moisture (Clapp and Hornberger 1978, McCumber and Pielke 1981). In retrospect, the distinction between different soil types was probably of small importance compared to the action of vegetation that was not addressed yet. Only some minor improvement in the surface climate simulations could be observed.

In RCA1, several improvements on the land surface parameterizations were added. The earlier practice of soil moisture relaxation was discarded. Two prognostic soil moisture layers (7.2 and 80 cm thick with a total soil column water holding capacity equal to 242 mm) were defined. The deep soil temperature relaxation to deep-soil data from the driving global model was retained (two prognostic soil temperature layers, 7.2 and 43.2 cm thick, and a third layer for the prescribed deep-soil values). The top layer accommodates even the snow cover. In the second soil temperature layer, a scheme for soil freezing from Viterbo et al. (1999) is used to better simulate the soil in autumn/spring when freezing/melting of the soil affects the soil evolution. Surface forcing on soil is achieved by vertical fluxes of heat and snowmelt energy, precipitation, snowmelt and evapotranspiration. Soil moisture loss from the surface includes transpiration via vegetation using features of Noilhan and Planton (1989). The actual evapotranspiration is calculated as a fraction of potential evapotranspiration, depending on air temperature and soil water stress. The actual evapotranspiration is divided into a no-transpiration part (dries the top layer) and a transpiration part (dries the second soil layer). Heat diffusion operates between the soil temperature layers. Soil moisture layers are coupled with moisture diffusion (~capillary forces, cf. Rummukainen 1999b) and a vertically-routed runoff through the soil column, using a formulation from the HBV hydrological model (Bergström and Graham 1998, Bringfelt 1999, Bringfelt et al. 1999). Drainage from the top layer to the second layer and runoff from the second layer operate when there is precipitation or snowmelt. The partitioning between moistening the soil and runoff depends on the soil moisture content already present. When soil moisture is high (low), runoff for a given precipitation and/or snowmelt is large (small) and soil moisture increases by a small (large) amount.

The water content of snow is the prognostic snow variable. It is accumulated by snowfall and depleted by snowmelt and evaporation. An empirical snowmelt correction as in HIRLAM is used in RCA1. The monthly snow density and the albedo of snow-covered surfaces is fixed which underestimates the in reality very dynamic evolution of snow properties.

For the upcoming version of the regional climate model, the RCA2 (Bringfelt and Räisänen 2000), the snow scheme is extensively revisited to introduce subgridscale orography related features in snowmelt (Lindström and Gardelin 1999). Rainfall interception on vegetation is added. It reduces the amount of rainfall reaching the ground and introduces a new temporary water storage at the surface, easily to be evaporated back to the atmosphere. Surface resistance to transpiration is made a function of additional environmental parameters now comprising also photosynthetically active radiation and air water vapor pressure deficit. Additional topics worked on include a prognostic canopy temperature, mainly based on Sellers et al. 1996, a separate snow temperature and snow density (van der Hurk et al. 2000, Douville et al. 1995) and a new parameterization to better resolve processes related to the depth of snow cover and to allow for liquid water in the snowpack, from snowmelt and susceptible to refreezing.

There is some lack of suitable field data to guide the parameterization development process. For example, the diurnal evapotranspiration dynamics and winter evaporation nature have been difficult to obtain constraints for. In the future, data from programs such as NOPEX (Halldin et al. 1999) and WINTEX will hopefully be available.

Inland lake systems and the Baltic Sea. Regional climate models must also often deal with parts of the global ocean, regional oceans and lakes. As an aspect particular to the Nordic region is the abundance of lakes and the presence of the Baltic Sea, this is so with RCA.

To include such water bodies in RCA, data for the sea surface temperature (SST) and sea ice could be taken from the driving GCM. This would reduce the interaction between ocean/lakes and atmosphere to a set of surface boundary conditions in the regional model. For a large-scale ocean basin such as the North Atlantic, this can be acceptable. When it comes to regional seas and lakes with geography well below the representative resolution of present-day GCMs, the validity of using GCM fields for regional ocean/lake surface forcing is more uncertain (cf. Rummukainen et al. 1999a,b). In spite of this, only few regional climate models consider anything like an interactive ocean, sea ice or lake components.

The Nordic lakes are numerous. They cover ~10% of the land area of Sweden and Finland. Both shallow lakes and deep lakes exist. Ice forms on most lakes every year. The first-order effect of the lake systems is to moderate the seasonal climate during the warm part of the year. In contrast, the effect of an ice-covered lake in mid-winter does not differ much from that of snow-covered land surface. More contrast develops in the spring, as solar radiation increases and the surface albedo matters more (e.g. snow on ice vs. snow-free ice). Most work on coupled atmosphere-lake modeling is, however, concentrated on large lakes and is thus not well suited for a Northern-Europe application (cf. Hostetler et al. 1993, Hostetler et al. 1994, Bates et al. 1995, Small et al. 1999, see also Giorgi 1995).

As the Baltic Sea (area ~420,000 km^2) belongs to the marginal ice zone, there is considerable interannual variability in its wintertime ice cover. The annual maximum ice coverage varies between 12% and almost 100% of the total Baltic Sea area. The Baltic Sea surface thermal climate is predominantly forced by the atmosphere (large-scale circulation, temperature, wind-driven mixing), whereas the salinity is forced by precipitation, evaporation, river runoff and infrequent deep-water exchanges with the North Sea. The Baltic Sea is a part of the regional climate system as demonstrated by Omstedt and Nyberg (1996), Haapala and Leppäranta (1997), Ljungemyr et al. (1996) and Omstedt (1999), showing considerable sensitivity of the ocean climate to atmospheric climate. In addition, off-line oceanographic modeling for the Baltic Sea has been performed by a number of groups (cf. e.g. Meier et al. 1999 for an overview). Some coupled modeling applications for the Baltic Sea region are by Gustafsson et al. (1998) and Hagedorn et al. (2000), demonstrating, for example, that regional energy and water budget consistency requires coupled model systems. How large the sensitivity of regional climate and climate change simulations, from the atmospheric and land area viewpoint, are to the detail used to describe the state and evolution of the Baltic Sea is an unanswered question. However, observed cases clearly point to the importance of the state of the Baltic Sea to the development of dramatic coastal snowfall episodes (refs) in the winter. The state of the Baltic Sea is important from the viewpoint of environmental protection, traffic, fishery etc. as well.

GCMs (typical resolution of 200-300 km) distinguish the Baltic Sea by few grid points only and cannot be expected to properly resolve its geometry. Likewise, the complicate Nordic inland lake systems are not modeled in GCMs. In the first attempts at longer RCA simulations, the surface state of the Baltic Sea and the regional lake systems had to be prescribed, somehow, from the GCM-results. Data from the nearest GCM sea points were taken for the latter. The imported (too) warm GCM Baltic Sea description created a large warm and moist bias in RCA0 in winter. The local monthly mean temperature bias exceeded 10°C in mid-winter.

In a separated sensitivity study, the lakes were entirely removed from the regional model. This led to more than half of the warm bias to be removed over the land areas. A warm bias remained over the Baltic Sea and its coasts, however (Figure 8).

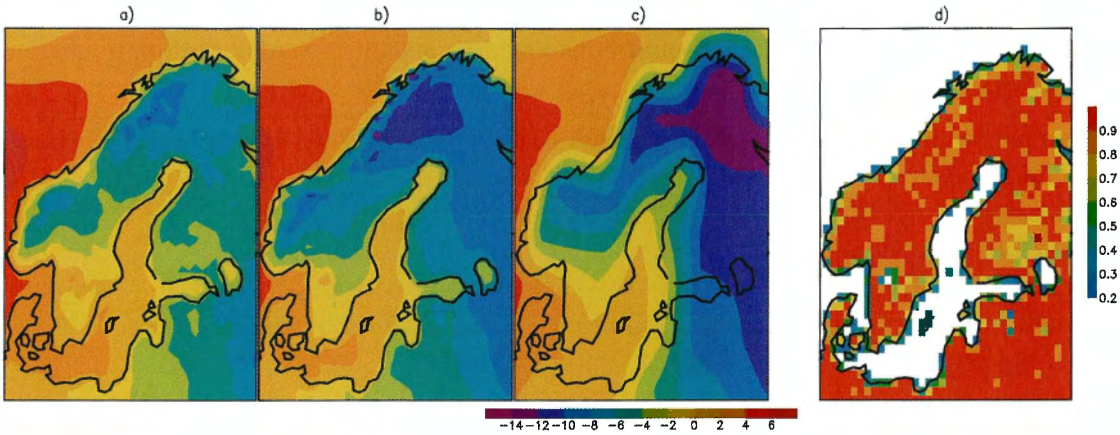

Figure 8. *Downscaled surface air temperature for an "average" winter (DJF) in the Nordic region from the 10-year control run time slice of HadCM2: a) RCA with the original HadCM2 SSTs on the Baltic Sea and extrapolated onto lakes, b) RCA with the original HadCM2 SSTs on the Baltic Sea, but the lakes made into land by rewriting the land sea mask, c) the original HadCM2 simulation results and d) the fraction of land per grid square in RCA. The "average winter" is chosen from the 10-year HadCM2 control run time slice as the one with monthly mean surface temperature best matching the 10-year mean season.*

It would have been undesired to remove the inland lake systems altogether from the simulations and it would not even have been enough to compensate for the warm GCM SSTs. To remedy the problem provisionally, "ice proxy" was designed. This was done by matching present-day Baltic Sea ice cover climate with deep soil temperatures in the HadCM2 present-climate data, thus mimicking a time-lag in the ice climate with respect to surface temperature climate. A threshold deep soil temperature close to the Baltic Sea points for existence of ice was determined. A similar ice proxy though with a slightly different time lag was designed for the lakes. The use of the ice proxies largely removed the problem with the warm winter SSTs and while not interacting directly with the RCA0 simulation, provided a realistic ice cover as a lower boundary condition for the RCA0. The proxies proved quite successful for the downscaling of the control run time slice from HadCM2 (Figure 9).

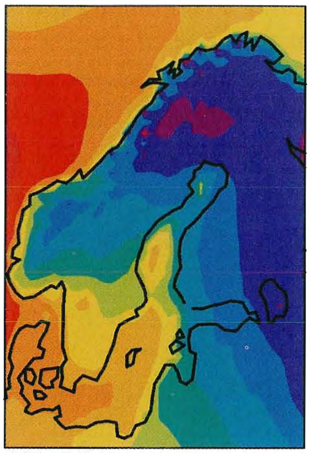

Figure 9. *Downscaled surface air temperature for the "average" winter (DJF) in the Nordic region from the 10-year control run time slice of HadCM2: RCA with the original HadCM2 SSTs on the Baltic Sea and extrapolated onto lakes, but now with the forced ice cover climate. The color scale is as in Figure 8.*

The downscaling of the scenario time slice from HadCM2 was also problematic at first. The GCM had warmed so much by the scenario time slice that the ice proxies hardly ever activated. The future state of the Baltic Sea is of course unknown and the ice-cover might change, even dramatically, with climate warming. It was still felt, however, that the scenario SSTs of HadCM2 (cf. its overly warm control climate winter SSTs) were too large over the Baltic Sea area and consequently that the simulated climate change was likely overestimated here.

To manage these issues, work was directed to couple RCA with more physically-based modeling of the Baltic Sea and inland lakes. The ultimate goal is to couple RCA with the Rossby Centre 3-D ocean model (see sections 2.3 and 3.1) in Phase 2 of SWECLIM. Meanwhile a less computationally demanding alternative is adopted for RCA1, coupling it with the PROBE-based (Svensson 1998) lake models of Ljungemyr et al. (1996) and Omstedt (1999) and with the 1.5-D Baltic Sea and Skagerrak model of Omstedt and Nyberg (1996), also called the PROBE-Baltic model.

In the lake models, the Nordic lakes are categorized into four basic types. Three are for shallow lakes (depth <10 m). Each of these types is defined in terms of a certain mean depth and surface area and the shallow lakes are then modeled as a slab. The fourth category is for the deep lakes; these retain their respective mean depth and surface area and are modeled with a 1-D column model.

The PROBE-Baltic fractional 1.5-dimension refers to the division of the Baltic Sea into 13 sub-basins (Figure 10). Between these, horizontal exchanges are calculated, using geometrical and dynamic constraints of sounds, sills and fronts. Each sub-basin is resolved vertically, with up to 100 layers for the deepest basins. The layer depths vary from 1 m close to the surface to 10 m close to the bottom. Inflows and outflows between the basins drive vertical advection. The water temperature, the salinity, the water volume, momentum and ice are modeled in PROBE-Baltic (see Omstedt and Nyberg 1996). Down to Ekman depth, vertical diffusivity is calculated with a buoyancy-extended two-equation turbulence model is included. One equation is for the turbulent kinetic energy (k) and the other for its dissipation rate (e). The deep water mixing below the thermocline or the halocline is parameterized according to Stigebrandt (1987). As shown by Omstedt and Axell (1998), the seasonal, interannual and longer-term variation of salinity and temperature and the large-scale vertical circulation can be realistically simulated with the PROBE-Baltic.

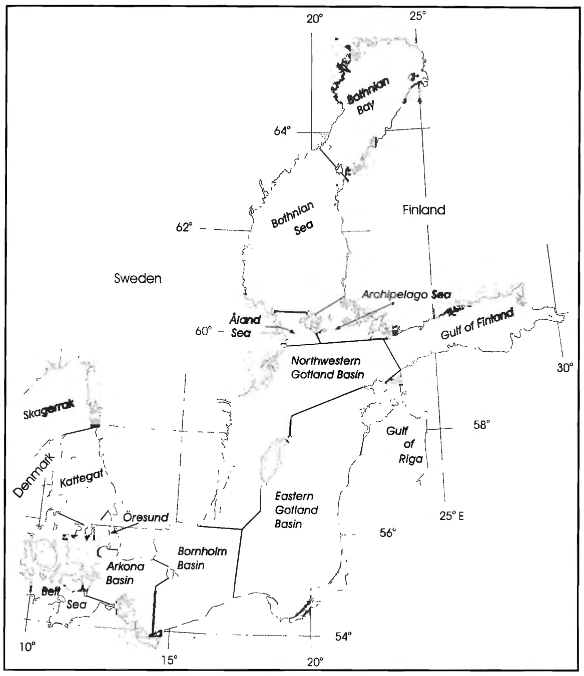

Figure 10. *The division of the Baltic Sea and Skagerrak into 13 sub-basins in the 1.5-D ocean model.*

The Baltic Sea and lake ice component has the thermodynamics of ice, ridging, and horizontal drift. Horizontal ice transport and ridging is not done on shallow lakes. In the case of initial ice growth or melting ice, strong wind and waves are allowed to break up the ice. In the case of columnar ice, the insulating effect of ice and snow are roughly taken into account. Only a very simple snow treatment is maintained over ice in these PROBE-based water body models. The surface albedo for the ice-covered region is tuned to achieve a reasonable melting of the ice.

The coupling between the lake and ocean models and RCA is interactive but so far not with fluxes. Atmospheric forcing on the waters is by near-surface temperature, relative humidity, wind, addition cloudiness and precipitation. The water body models use these to calculate the input fluxes. In addition, river runoff and the water level in the Kattegat also force the Baltic Sea model. The SSTs and the ice cover are subsequently returned to RCA to be used as lower boundary conditions. Initialization of the lake and regional ocean model is done as a 12-month off-line integration of the water body models, fed with gridded multiyear weather data. This is sufficient to cover the thermodynamic memory in the lake and Baltic Sea system (Omstedt and Rutgersson 2000), which is of the order of one year. A considerably longer integration is needed if the ocean salinity climate should be simulated in more detail, due to the longer Baltic Sea salinity stratification spin-up (Omstedt and Axell 1998). However, as shown by Omstedt et al. (2000), some ongoing salinity spin-up is likely not detrimental to the regional atmospheric simulations, i.e. the SSTs do not seem to be severely affected.

Coupling RCA1 with the lake and the 1.5-D ocean model proves to be a useful concept. The additional computational overhead is small, and the seasonal ice climate can be simulated in a realistic, although spatially coarse manner. The improvement of surface air temperature simulation from the inclusion of the Baltic Sea and the lakes in RCA is illustrated in Figure 11 that should be compared to the Figures 8-9.

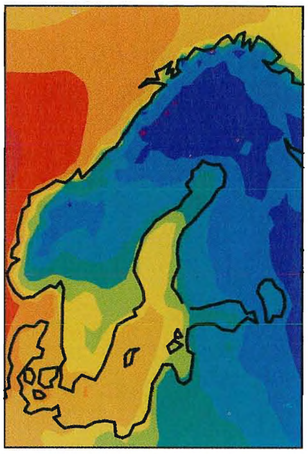

Figure 11. Downscaled surface air temperature for the "average" winter (DJF) in the Nordic region from the 10-year control run time slice of HadCM2: RCA with the 1.5-D Baltic Sea model and lake models included. The color scale is as in Figure 8.

2.2 The regional ocean model: The RCO

As mentioned earlier, the next improvement in the SWECLIM regional climate modeling tool is to include even a high-resolution 3-D Baltic Sea model component; the Rossby Centre regional Ocean model (RCO). It is an adaptation of the global ocean OCCAM code that can be traced back to the Bryan-Cox-Semtner model, one of the most widely used general circulation models of the ocean (Bryan 1969, Semtner 1974, Cox 1984). The starting point for RCO was the multiprocessor version of the code for the global ocean from Webb et al. (1997).

As the RCO Baltic Sea model domain is limited with open boundaries in the northern Kattegat, open boundary conditions by Stevens (1990, 1991) for the Bryan-Cox-Semtner model have been implemented. In case of inflow, temperature and salinity values at the boundaries are nudged towards climatological profiles. In case of outflow, a modified radiation condition is utilized. The bathymetry is based on realistic bottom topography data (Seifert and Kayser 1995), making use of 41 vertical levels with layer thicknesses from 3 m close to the surface to 12 m near the bottom. The maximum depth in RCO is 250 m. So far, two different horizontal resolutions have been used: 2 and 6 nautical miles.

In RCO a two-equation turbulence closure, the "k-e" model (Svensson 1978, Rodi 1993), is embedded. Two prognostic equations for turbulent kinetic energy (k) and for dissipation (e) of k are solved. The effect of breaking surface gravity waves is taken into account. The k-e model is further extended to include a parameterization for breaking internal waves (Stigebrandt 1987). In addition to turbulent vertical transports, the divergence of absorbed intensity of the penetrated shortwave radiation is heating the water column and included in the model.

In off-line RCO simulations, sea level elevation at the boundaries are prescribed from hourly tide gauge data, monthly river runoff data is prescribed from Bergström and Carlsson (1994) and three hourly surface fluxes are calculated with standard bulk formulae from gridded atmospheric observations (Lars Meuller, SMHI, pers. comm.).

The RCO is coupled with a Hibler-type (Hibler 1979) two-level (open water and ice) dynamic-thermodynamic sea ice model, applying an extension of the widely used viscous-plastic rheology with an elastic component (Hunke and Dukowicz 1997, Hunke and Zhang 1999). This leads to a fully explicit numerical scheme that improves computational efficiency on high resolution grids and is suited for parallel computing.

The ice thermodynamics are based on layer models from Semtner (1976) for thick ice/snow (multiple layers) and thin ice/snow using characteristic discrimination thicknesses for ice and snow. In RCO thick ice consists of one or two ice layers and thick snow consists of one snow layer. The reason for the discrimination between thick and thin ice/snow is numerical stability. The thin ice/snow models are based on simple heat budgets.

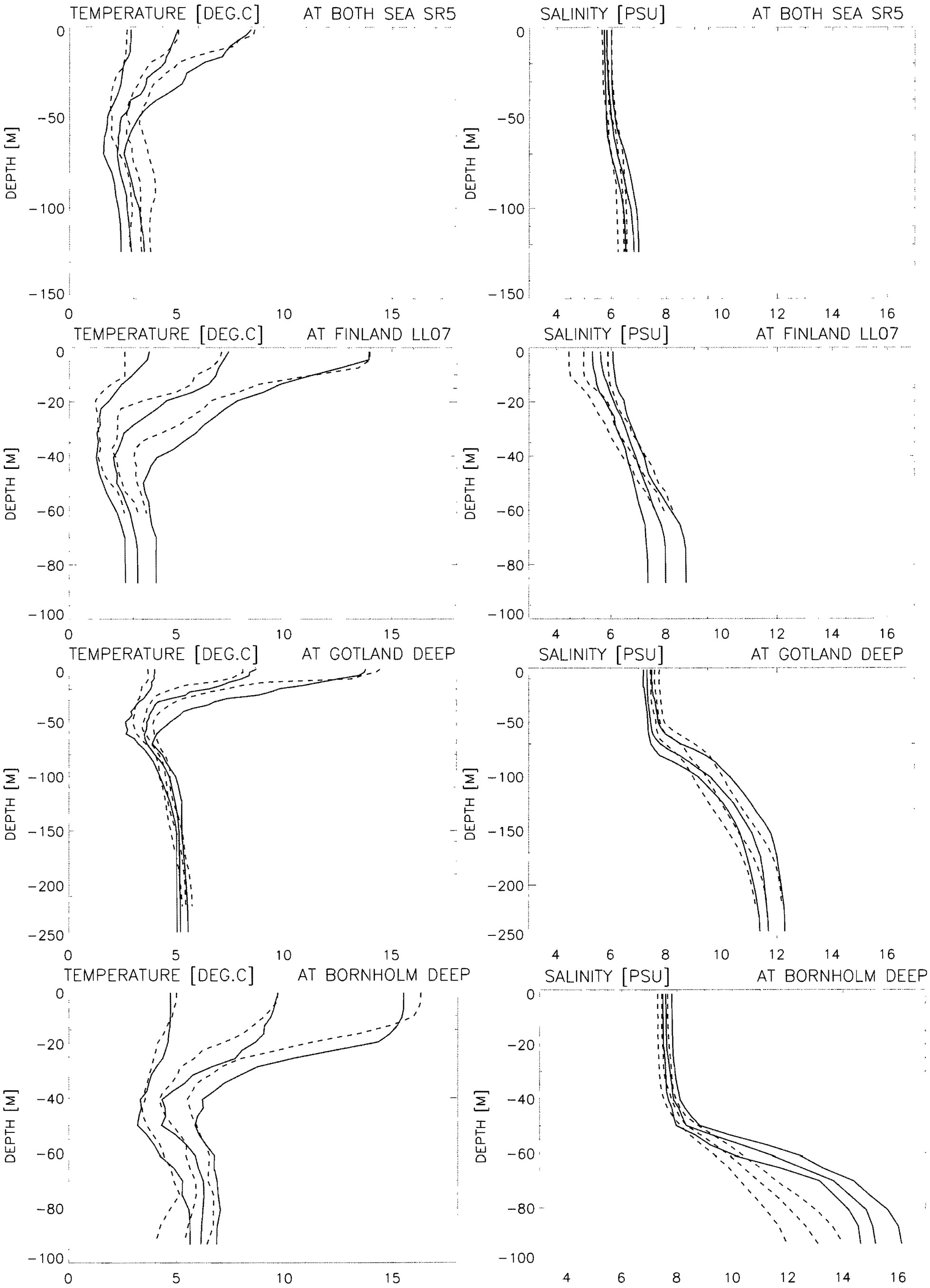

Figure 12. *Observed (solid) and simulated (dotted) median, first and third quartile profiles for temperature (ºC) and salinity (psu) from the Bothnian Sea (first row), Gulf of Finland (second row), Gotland Basin (third row) and Bornholm Basin (fourth row).*

A more detailed model description of RCO is presented by Meier et al. (1999). First results of multi-year simulations are reported by Meier (1999) and some validation analysis is included in Meier et al. (2000). The agreement between model results and observations is quite good. In the following, selected results of multi-year simulations for the period May 1980 until December 1993 using the 6 nm version of RCO are discussed, forced by the gridded meteorological observations, river runoff and sea level elevation at the boundaries as mentioned earlier.

In Figure 12 median profiles of temperature and salinity are depicted at 4 stations for this period. The model reproduces salinity gradients from North to South as well as from the surface to the bottom. The halocline is not eroded during the almost 5000 days long integration. However, the problem of coarse resolution level models with overflow is visible in results from Bornholm Basin. As the bottom boundary layer is not resolved, smaller inflows over the sills of the Danish Straits and through the Bornholm Channel are underestimated and the decrease of bottom salinity is too strong. Increased horizontal resolution and improved parameterizations will help to overcome these problems. Median sea surface temperatures reveal a small error (<0.5°C). The seasonal cycle is simulated correctly.

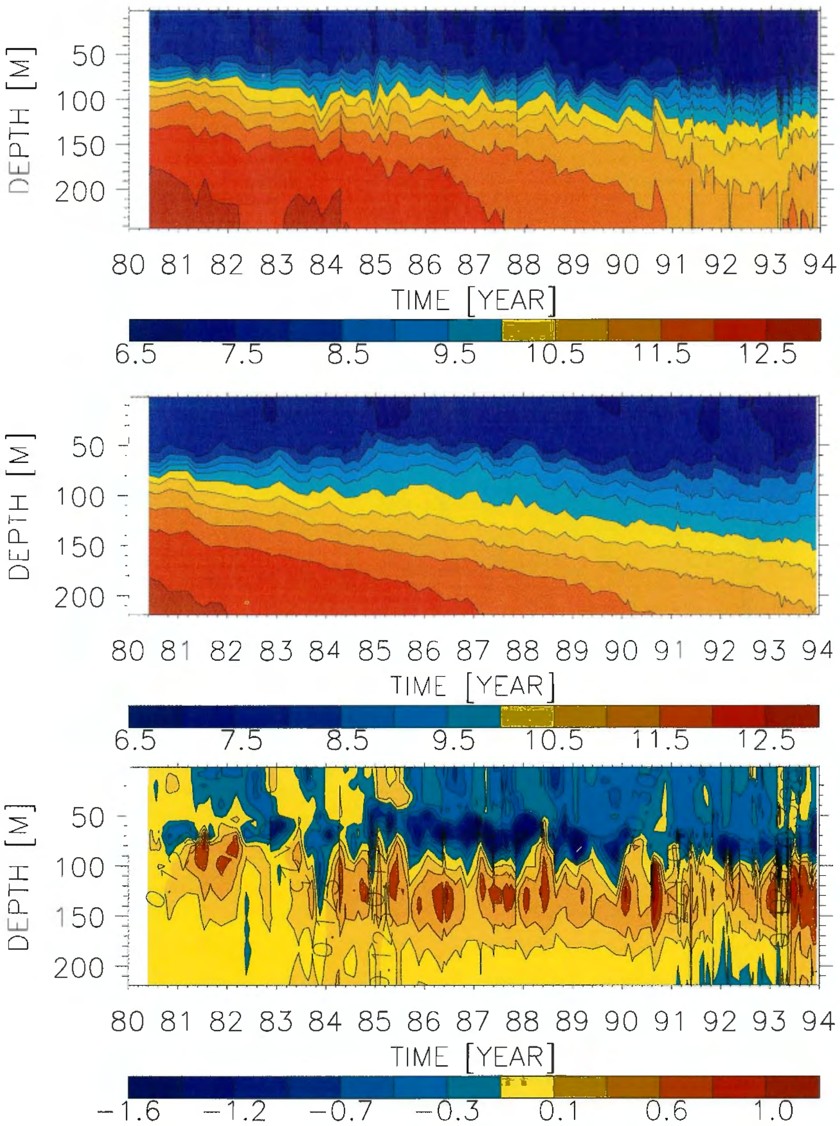

Figure 13. *Top: observed and middle: simulated isohaline depths (psu) from May 1980 until December 1993 at Gotland Deep. Bottom: the difference between observations and model results. The time axis starts at May 26, 1980.*

The 16 year stagnation period in 1976-92 serves as an excellent test for deep water parameterization because the Baltic proper was not affected by horizontal advection of saltier water. Only vertical diffusion across the halocline alters the salinity in the deeper layer. During the stagnation period, the decrease of salinity in the deeper layer of the Baltic Sea is remarkable (Fig. 13). No saltier water from the North Sea is advected horizontally into the Gotland Deep until the major salt water inflow in January 1993. However, the influence of this event was mainly restricted to the Bornholm Basin. The correspondence of observed and simulated isohaline depths is satisfactory and indicates a proper choice of deepwater mixing parameterization.

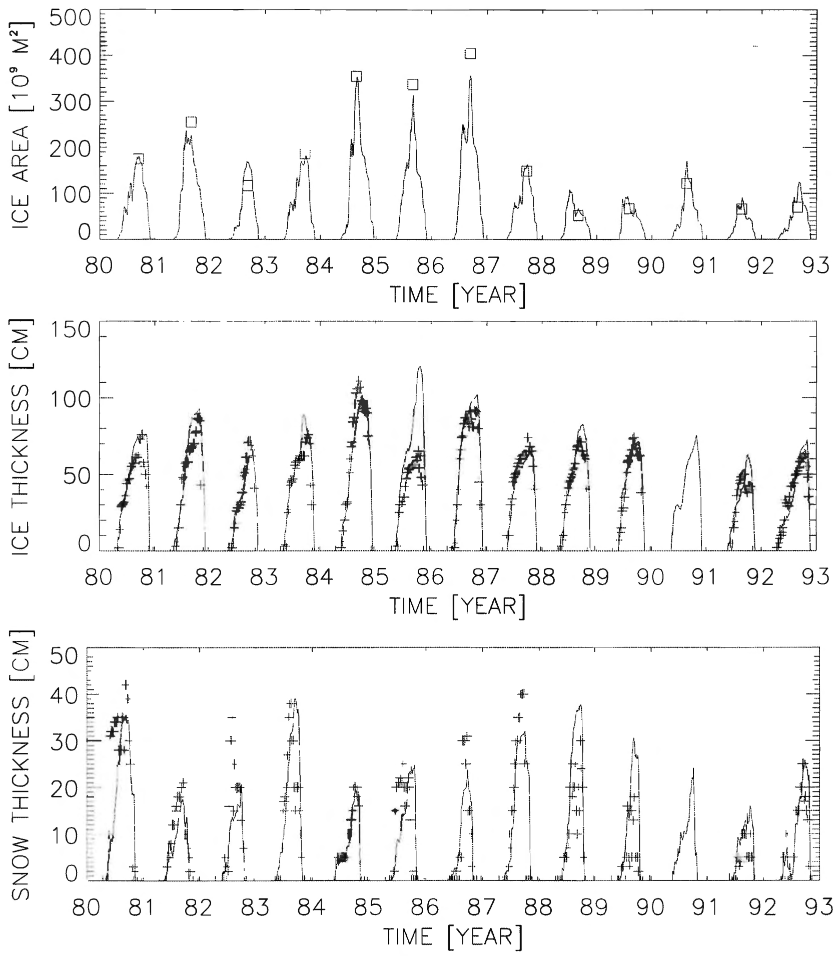

Figure 14. *Top: Simulated ice covered area (10^9 m^2) for May 1980 - July 1993. Squares denote observed maximum ice extent (cf. Omstedt and Nyberg 1996). Middle: simulated ice thickness (cm) and bottom: simulated snow thickness (cm) for May 1980 - July 1993 at the monitoring station Kemi in the Bothnian Bay. Plus signs denote observations from Finnish Marine Research (1982), Kalliosaari and Seinä (1987), Seinä and Kalliosaari (1991), Seinä and Peltola (1991) and Seinä et al. (1996). The winter 1990/91 data are not available.*

Figure 14 (top) shows simulated total ice extent compared with the observed maximum ice extent. Ice extent is highly correlated with air temperature but represents also a sensitive measure of model performance. Hence, the correspondence between model results and observations is encouraging. In some mild winters, maximum ice extent is somewhat overestimated. Nevertheless, the overall agreement is good. That is also true for the date of the maximum ice extent, with the only exception of the winter 1988/89 when the ice model gave a higher ice extent earlier than the observations. The agreement of simulated ice and snow thickness with measurements at the coastal station Kemi-Ajos (Fig. 14 middle-bottom) is regarded as good too, although the ice thickness during the severe winter 1985/86 is overestimated and the snow thickness is underestimated during some years (e.g., 1982/83). However, one has to keep in mind that the precipitation data from the SMHI database might have a large error and that the used snow ice model in RCO is quite simple. Ice and snow thickness is very sensitive for changes in the snow ice model.

Results from RCA1-88H have been used as atmospheric forcing for RCO to simulate corresponding climate change in the Baltic Sea. Two 9-year time slice simulations representing control (pre-industrial) and scenario (future) climate have been performed with the 6 nm version of RCO. Initial conditions for temperature and salinity have been calculated from observed profiles from May 1980. Sea level in Kattegat has been prescribed from tide gauge data at Ringhals/Sweden for the period 1980-1989. The river runoff is calculated with the large-scale hydrological model, the HBV-Baltic model (Graham 1999a), also forced by RCA1. The annual and seasonal mean SST changes (scenario minus control run) are shown in Figure 15 and 16, respectively. In addition, two changes are compared to each other: the difference between the standard scenario and the control run and the difference between the scenario run with spin-up and the control run. Extreme initial conditions are obtained for this second scenario run by integrating the Baltic Sea model for 100 years assuming no salt water inflow. The second scenario is called "extra scenario" in the following.

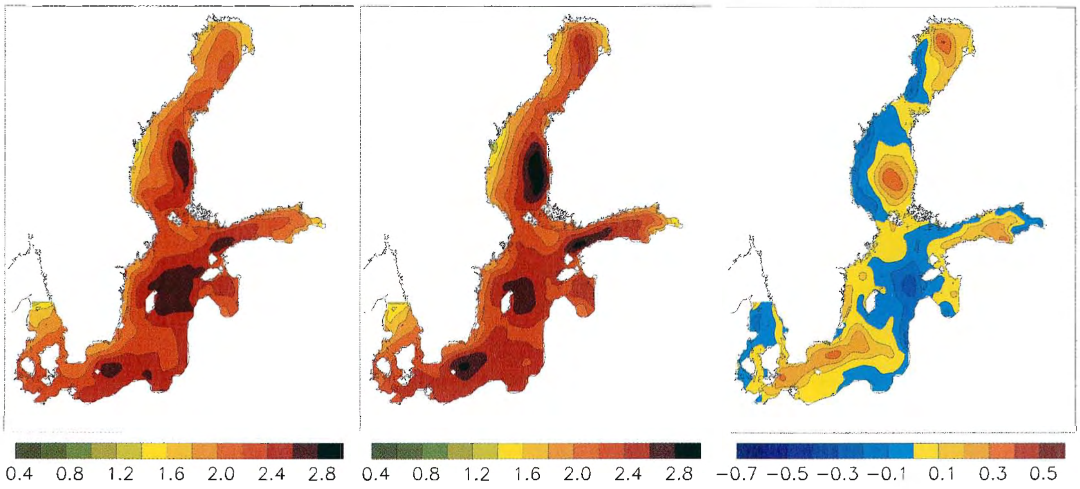

Figure 15. *Simulated (climate) change in annual mean sea surface temperature (°C). Left: scenario minus control run, middle: scenario run after 90 years of spin-up time minus control run, right; difference between the results in the left and the middle columns. Note the different color bar in the difference (rightmost column).*

The annual mean SST change is about 2.3°C averaged over the Baltic Sea in both scenario experiments. Maxima (>2.6°C) are found in the eastern Bothnian Sea, southern Gulf of Finland, central Gotland Basin and Bornholm Basin. Near the Swedish coasts, in the northern Bothnian Bay and at the east of the Gulf of Finland the warming is only about 2°C (locally even smaller). Minimum change occurs in the Kattegat close to the open boundary as in case of inflow, temperature profiles are nudged towards present-day climatology in all simulations. The differences between the two scenario experiments are small in the annual mean and range between -0.4 and 0.5°C locally. The largest warming of more than 3.8°C is simulated in the Bay of Bothnia and Bothnian Sea in summer using the standard scenario experiment.

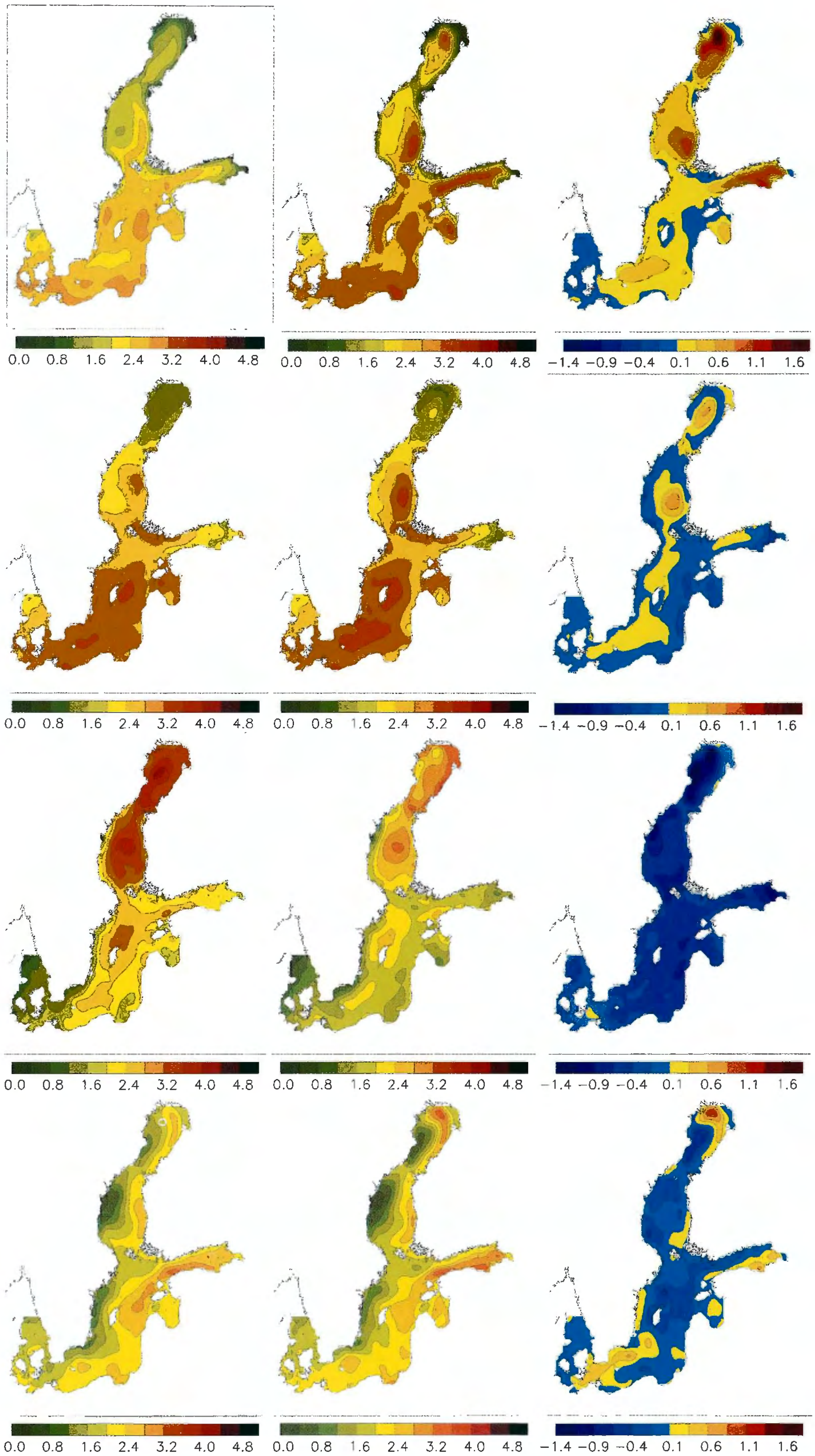

Figure 16. *Simulated (climate) changes in seasonal mean sea surface temperatures (^oC). Left column: scenario minus control run, middle column: scenario run after 90 years of spin-up time minus control run, right column: difference between second and first column. From top to bottom: winter (DJF), spring (MAM), summer (JJA) and autumn (SON) seasons. Note the different color bar in case of the difference.*

Contrary, warming of SST is smallest in the northern parts of the Baltic in winter and spring where these areas are still ice-covered in the scenario runs. Only those regions warm up where the ice has vanished in the mean, i.e. in the Bothnian Sea in spring. In autumn a pronounced east-west asymmetry in the whole model domain is found. Upwelling areas get warmer by less than 1.2°C whereas downwelling areas get warmer by >2.4°C. This signal is so intense that also the annual mean is affected. Seasonal area mean changes in the extra scenario run do not differ by more than 0.5°C. Also similar horizontal anomaly patterns are found in this scenario but there are local differences as well. The right column in Figure 16 shows the differences, which can be taken as a measure of the uncertainty due to the unknown initial (salinity) conditions. In general, these differences range between -1.4 and 1.8°C, i.e. they are smaller than the simulated climate change. The largest positive and negative differences are found in winter and summer, respectively, both in the Bothnian Bay. Consequently, the simulated climate change in the northernmost basin with the weakest haline stratification is the most uncertain. Although present-day stratification is small, it limits mixed layer depths effectively. With the even smaller stratification in the extra scenario experiment, summer mixed layer depths increase and SSTs decrease consequently.

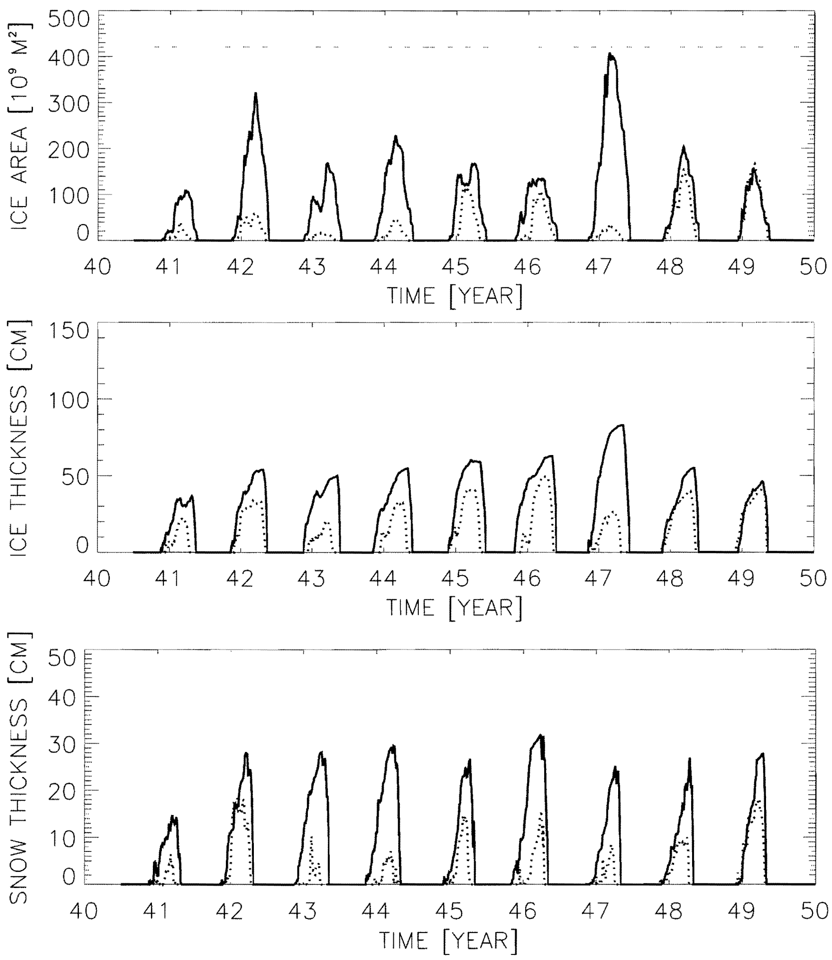

Figure 17. *Top: simulated ice covered area (10^9 m^2) and middle: ice and bottom: snow thickness (cm) at Kemi for 9-year control run (solid) and scenario run (dotted).*

The comparison with area mean 2 m air temperature is also interesting. These in the annual, winter, spring, summer and autumn means are 2.9°C, 3.5°C, 2.9°C, 2.4°C and 2.6°C, respectively. Obviously, the higher temperature change in the atmosphere in winter does not warm the water body to the same amount due to the isolating effect of the sea ice that remains in the scenarios.

In Figure17, the ice extent, and the ice and snow thickness at station Kemi-Ajos in the northern Bothnian Bay results of the control and scenario run are depicted. That there is interannual variation in the severity of winters is clearly shown. Compared with the hindcast simulation (Fig. 14), the control run somewhat overestimates the number of normal and severe winters but remains within the natural variability. In the control simulation there are two winters when the maximum ice extent reaches (or almost reaches) 420×10^3 km^2 which means that the Baltic Sea is totally frozen. In the scenario run, most of the winters are mild, indicating a remarkable decrease in ice winter severity. Ice and snow thickness at station Kemi in the control run is realistic. Snow thickness is slightly smaller than during the hindcast period 1980-93. In the scenario run both quantities are much smaller than in the control run.

2.3 The hydrological model: The HBV

The HBV model (Bergström and Forsman 1973, Bergström 1995) started as a very simple lumped hydrological model. It has gradually become more and more distributed. In the latest version HBV-96 (Lindström et al. 1997), full distribution into sub-basins and statistical distribution of some properties within these are introduced. The snow routine is basically a degree-day approach with a liquid water holding capacity that delays runoff at the onset of melt. Sub-basin variability is provided for by elevation zones, vegetation zones and a statistical distribution of snow to account for patchiness and snowdrifts above the treeline (Fig. 18).

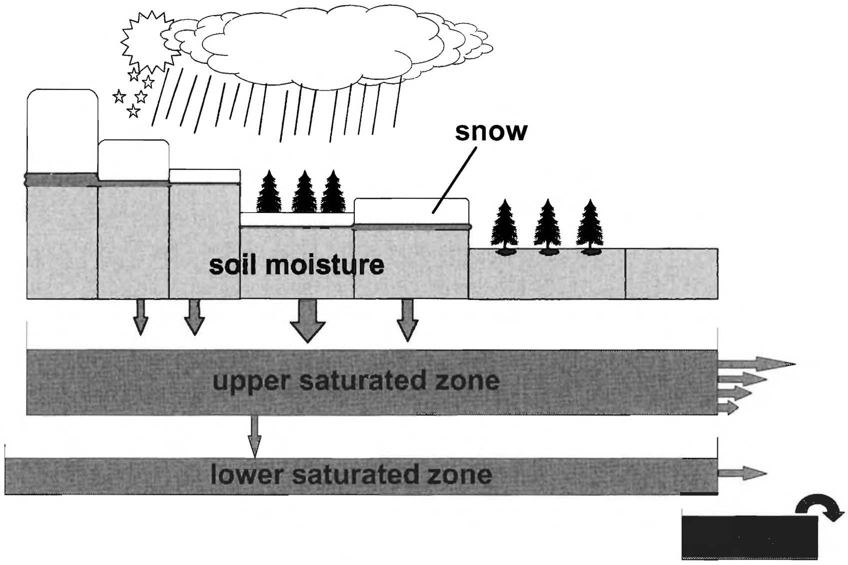

Figure 18. *Schematic picture of the HBV model as it is used in one sub-basin. Note the subdivision into elevation zones, forests and open areas and the statistical distribution of snow above the timberline. Major lakes are modeled explicitly while smaller ones are integrated into the lowest zone of the model.*

The HBV model was one of the first hydrological models to adopt a variability parameter in the soil moisture procedure. The technique has proven to be very useful and it is relatively insensitive to scales (Bergström and Graham 1998). The soil moisture routine is based on simple equations that describe how the ground responds to snowmelt and rain and how evapotranspiration is reduced as the soil dries out (Fig. 19).

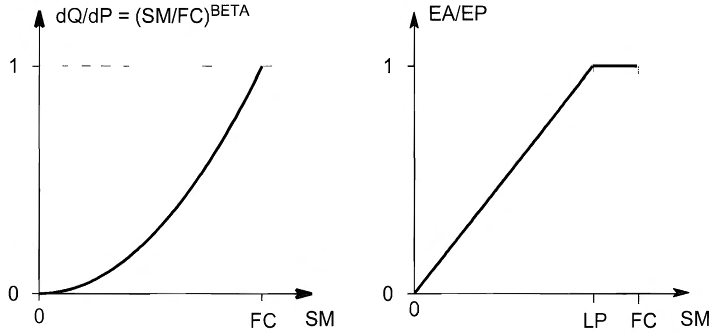

Figure 19. *Principle for the soil moisture accounting routine in the HBV model. Left: Runoff response (dQ/dP) as a function of soil moisture (SM). Right: Estimation of actual evapotranspiration (EA) from potential evapotranspiration (EP) and soil moisture. FC is the maximum available soil moisture storage capacity.*

Actual evapotranspiration is in the model calculated from estimates of potential evapotranspiration, usually using monthly mean values calculated with the Penman formula or using a temperature index method. In the SWECLIM simulations, one method used is a simplified version of the Thornthwaite method (Thornthwaite 1948) which relates potential evapotranspiration to air temperatures by a seasonally dependent coefficient (Sælthun et al. 1998).

Within SWECLIM it is attempted to narrow the gap between the climate models and hydrological models. Therefore it was decided to strive away from off-line evapotranspiration scenario simulations towards a more integrated approach, thereby making as much use of the evapotranspiration simulations in the regional climate model (RCA) as possible. In analogy with the use of temperature and precipitation scenarios, it was decided to transfer relative changes in evapotranspiration from the climate scenarios into the hydrological model. The temperature index technique is used as a reference, which leads to the following two versions of the HBV model:

- HBV-a, the standard model with temperature-index evapotranspiration formulation. Temperature anomalies affect evapotranspiration in the climate change mode on a degree-day basis.
- HBV-b, a model based on climatological values of potential evapotranspiration, which are forced to give the same relative changes in actual evapotranspiration as the formulation in the regional climate model, when run in a climate change mode.

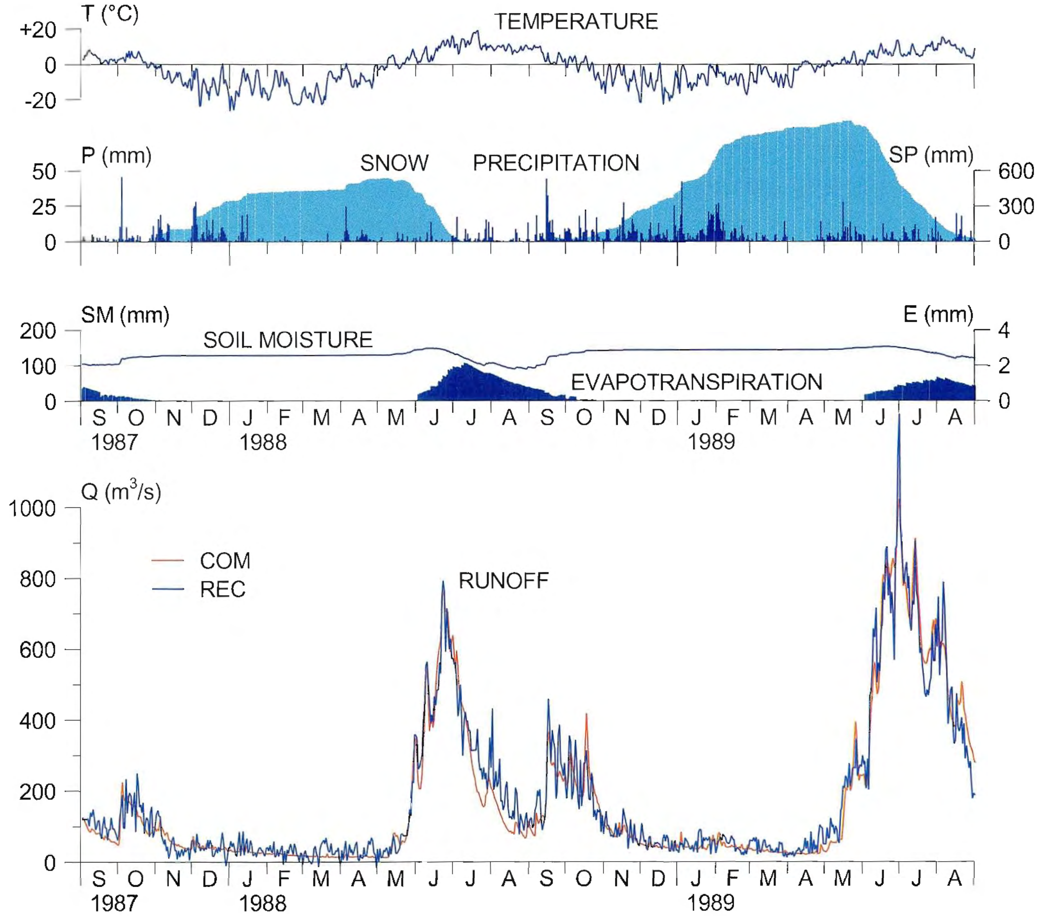

Figure 20. *Two years of simulated inflow to the Suorva reservoir by the HBV model based on observed station data of air temperature and precipitation.*

There are several routing options for water in the HBV model. For Scandinavian conditions it is usually sufficient to use the two reservoirs of the saturated zone, with gradually increasing recession coefficient in the upper one, and to model major lakes explicitly by a storage-discharge relationship. Further smoothing of the runoff curve is obtained when the sub-basin option is used. This means that several sub-models, which respond non-synchronously to input, model a catchment. An example of output from a simulation with the HBV model is shown in Figure 20.

2.4 The SWECLIM regional climate simulations

An important milestone in SWECLIM was the completion of the first regional climate scenario in 1998. This was done with the first version of the regional climate model (RCA0) that included the atmospheric model together with a very simple representation of ice on the Baltic Sea and the inland lakes. The Hadley Centre HadCM2 GCM data were used to force the regional model. The control simulation showed that the regional model could reproduce the main characteristics of the observed, present climate with respect to temperature, precipitation etc. Even though errors already present in the global model were inherited, in particular the precipitation distribution was much improved, as expected from the higher resolution possible in the regional simulation. The regional climate change scenario also displayed characteristics similar to the global model climate change scenario, but finer details were given over the Nordic region. An important conclusion from the first simulation was the need of a more realistic Baltic Sea and inland lake modeling for the Nordic simulations. A sensitivity study showed convincingly that in particular the wintertime climate was seriously degraded if the regional sea and lake surface temperatures were taken directly from the global model.

The second set of regional climate scenario calculations was done with an improved version of the regional climate model (RCA1) in 1999-2000. The surface energy balance and hydrological calculations were improved and more physical Baltic Sea and inland lake models were included. In addition, scenarios were made with data from two different global models, those from the Hadley Centre (HadCM2) and from the Max-Planck-Institute for meteorology in Hamburg (ECHAM4/OPYC3). It was found out, however, that the snow melt had been falsely sensitive to the length of the time step. This affected especially the 22 km resolution run, where short time steps were necessary due to the small grid size. Unfortunately, the sporadic instability of the old HIRLAM convection scheme was worsened with the increased resolution and a severe shortening of the time step (to ~2 min) was necessary to keep the model from "exploding" too often. This made the simulation very time and resources consuming. In any case, the snow melt formulation was dealt with and at the same time some improvements in the radiation scheme (Räisänen et al. 2000b) were worked in. An additional set of simulations was thereafter performed at 44 km resolution. These became the final Phase 1 scenario results. These did not produce dramatic bulk differences from the first simulation with RCA0. Some clear improvements in the control simulations and more physical responses in the scenarios can be identified though. In particular, seasonal variation in precipitation came into a better agreement with the present climate, the simulation of the radiation budget, land-based evapotranspiration and snow on land were clearly improved. Furthermore, more confidence could be placed on the simulation of the inland lakes and the Baltic Sea that are parts of the regional climate system.

The SWECLIM scenario calculations (based on two global models and the different regional model versions) all indicate qualitatively similar mean regional climate change: an overall regional land area warming of 3-4°C in the annual mean and precipitation increases that are most marked and up to 20-30% over the northern parts of Sweden, for the period of 50-100 years to the future. However, as the regional climate model tools have been successively improved, the most recent scenarios are to be preferred over the first ones. Additionally, the analysis of possible changes in variability, extremes and some more special parameters needs to be developed further.

So far, six downscaling simulations of greenhouse gas induced climate change in northern Europe have been prepared in SWECLIM. The first, with the regional model version RCA0 (Rummukainen et a. 1998, Räisänen et al. 1999), was made in 1998, at 44 km resolution, and boundary data from the HadCM2 GCM. The same HadCM2 data have also been used in the other simulations with the revised version of the regional climate model, the RCA1: in 1999 the RCA1-88H was run, with 88 km resolution, which was then used to force the "double-nested" RCA1-22H with 22 km resolution. At the same time, a simulation (RCA1-88E) was done using boundary data from another GCM, the ECHAM4/OPYC3. Even though the two sets of forcing GCM data differ in terms of the greenhouse gas forcing (the increase in equivalent CO_2 is 150% HadCM2 and 100% in ECHAM4), a compensating difference in their climate sensitivity results in the virtually same global mean warming (about 2.6°C) in both cases. In this sense, the downscaling of these two GCM experiments gives quantitatively comparable regional scenarios. The 88 km RCA1 simulations have been discussed in Rummukainen et al. (1999c), Rummukainen et al. (2000), Räisänen et al. (2000a, 2000c) and Bergström et al. (2000a, 2000b). The RCA1-22H results have not been publicized much (though see Räisänen 1999). Finally, in early 2000, after updates in the RCA1 radiation scheme and snow treatment, simulations forced first with the HadCM2 data and then the ECHAM4 data were rerun with 44 km resolution (RCA1-44H, RCA1-44E, Räisänen et al. 2000c).

Here, a comparative basic view on the six SWECLIM regional climate change scenarios is given. However, as the regional model has been considerably improved between the scenarios, the different simulations should not be assigned similar weights in one's mind. The two final simulations (RCA1-44H and RCA1-44E) are considered the most relevant.

Climate changes in the Nordic area are discussed to indicate how the projections from RCA0 have been modified in the later experiments. Some statistical analysis is also made with emphasis on the latest simulations: RCA1-44E and RCA1-44H.

Temperature, precipitation and wind speed in the Nordic area. Changes in the annual means of surface air temperature, precipitation and wind speed in the Nordic area in the six RCA experiments are shown in Figure 21. Area mean changes for Sweden are given in Table 1 (annual means; the driving GCMs are also included) and in Figure 22 (seasonal cycles).

The Sweden annual mean warming is largest, 3.9°C, in RCA0, but it is almost as large even in the two latest (RCA1-44H and RCA1-44E) simulations. The three earlier RCA1 simulations exhibit a slightly (at most about 1°C in RCA1-22H) smaller warming. The HadCM2-driven experiments all indicate qualitatively the same seasonal cycle in Sweden, with a maximum in warming in December-January and a minimum in July-August, but with differences in particular in the magnitude of the wintertime maximum. In the ECHAM4-driven experiments, the warming is largest in late autumn rather than in midwinter and the summertime warming is somewhat larger than in the HadCM2-driven experiments.

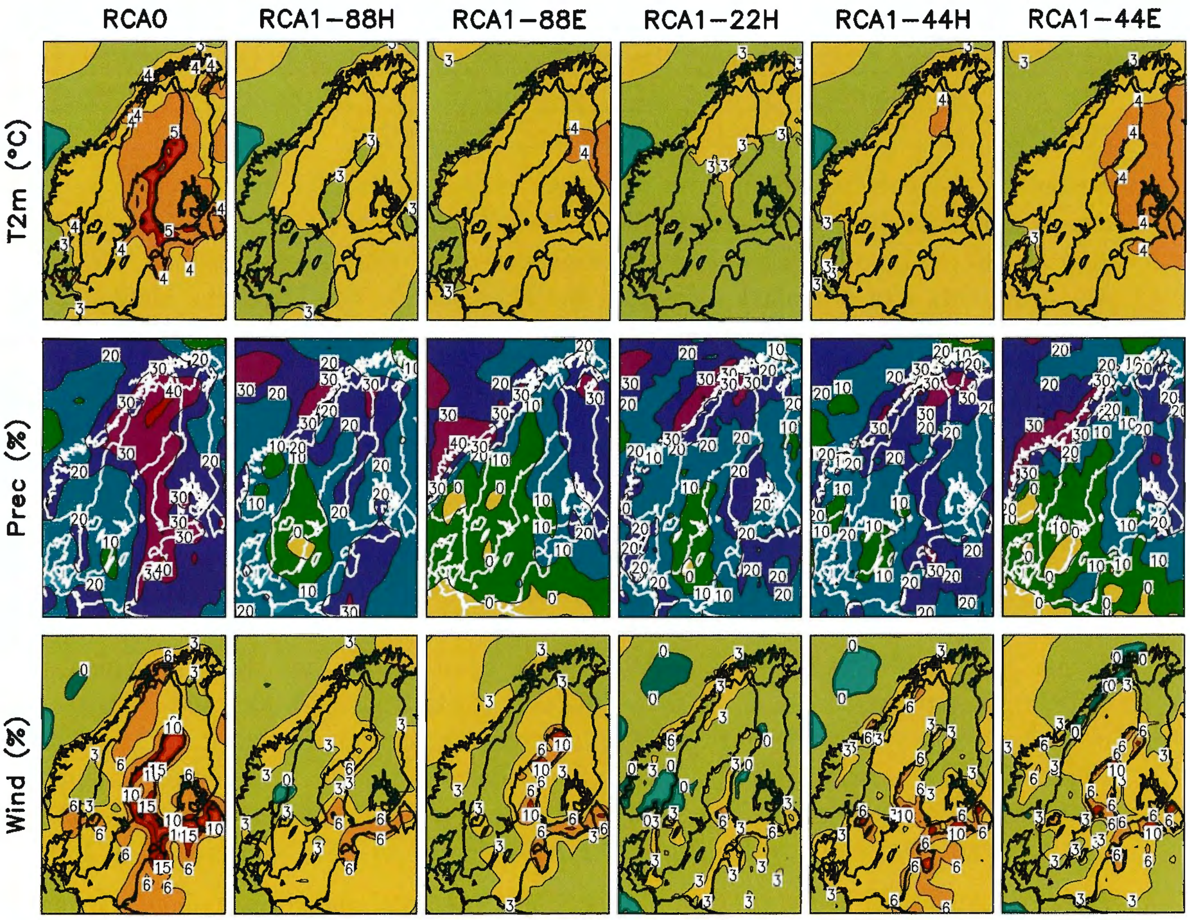

Figure 21. Changes in annual mean temperature (°C), precipitation (%) and wind speed (%) in RCA0, RCA1-88H, RCA1-22H, RCA1-88E, RCA1-44H and RCA1-44E.

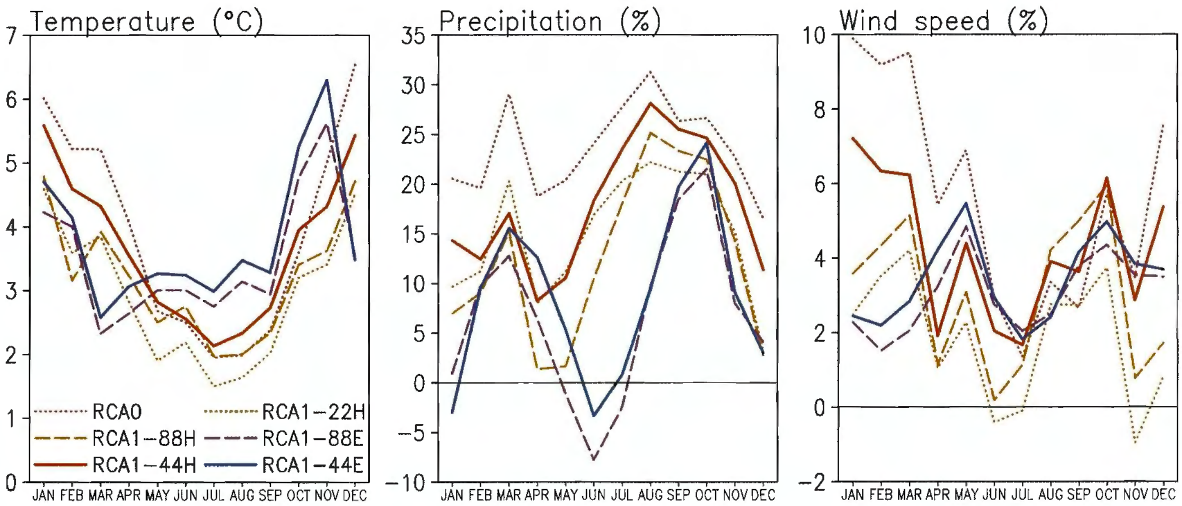

Figure 22. Seasonal cycles of Sweden mean temperature (°C), precipitation (%) and wind speed (%) change in the four experiments. A three-month running average is applied to precipitation and wind speed to reduce noise.

The downward-upward swing in the magnitude of the simulated warming in course of the SWECLIM1 history mainly seems to reflect the compensating effects of two model improvements. As compared with RCA0, the RCA1-88H and RCA1-22H experiments driven by the same boundary data show a somewhat smaller warming especially in winter because the inclusion of the PROBE-models make the treatment of the water bodies more physically consistent (see below). All the first four experiments neglect, however, the direct radiative effect of the increase in CO_2 (thus, the increased CO_2 is only felt through the horizontal and bottom boundary conditions), which acts to reduce the simulated warming. The correction of this in RCA1-44H and RCA1-44E amplifies the warming by a few tenths of a degree.

Table 1. *Changes in Sweden annual area mean temperature (°C), precipitation (%) and wind speed (%) in the six RCA experiments (RCA0, RCA1-88H, RCA1-22H, RCA1-88E, RCA1-44H and RCA1-44E) and in the driving models, HadCM2 and ECHAM4 (wind speed is not available for ECHAM4).*

	RCA0	RCA1 -88H	RCA1 -22H	RCA1 -88E	RCA1 -44H	RCA1 -44E	HadCM2	ECHAM4
Temp. (°C)	3.9	3.2	2.9	3.5	3.7	3.8	3.8	3.6
Precip. (%)	24	13	15	7	18	8	17	12
Wind (%)	5.6	3.0	1.8	3.0	4.3	3.4	1.4	N/A

In the geographical distribution of the annual mean warming, RCA0 stands out with a distinct maximum over the northern Baltic Sea (Figure 21). This annual mean maximum reflects a much more pronounced maximum in winter (Figure 23a). In the RCA1 simulations, no maximum in annual warming appears in this area and the wintertime warming is several degrees smaller than in RCA0 (as shown for the latest two RCA1 simulations in Figure 23b-c).

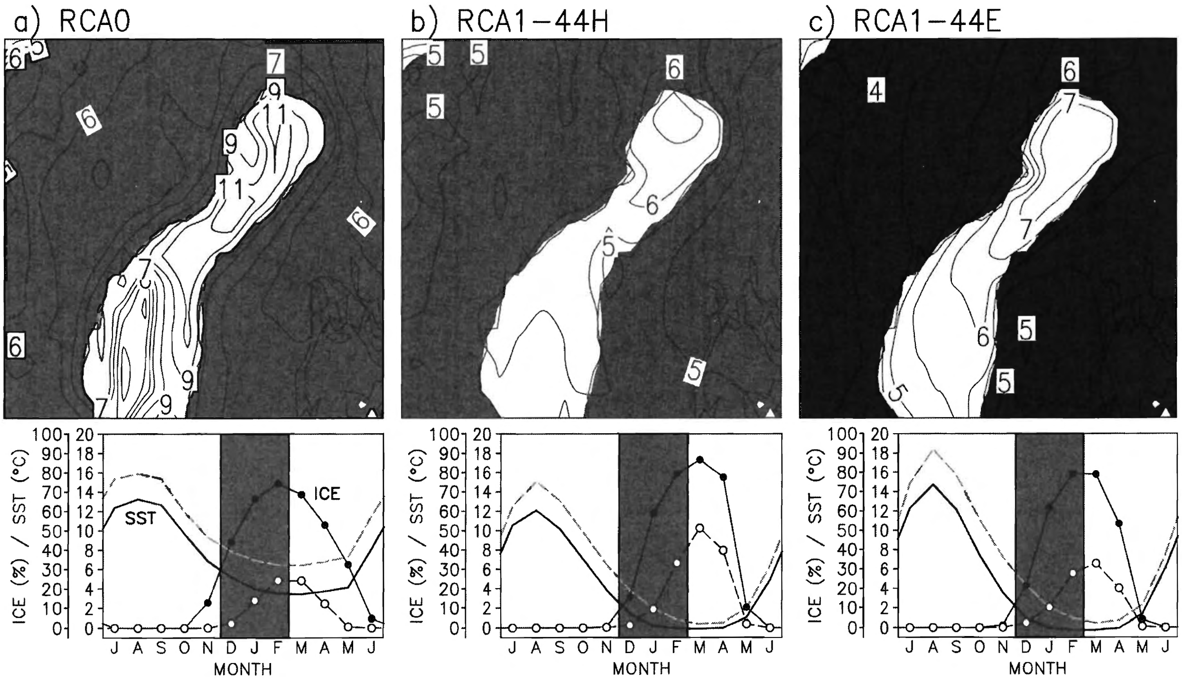

Figure 23. *Change in December-February mean surface air temperature around the northern parts of the Baltic Sea (above) and seasonal cycles of sea surface temperature (lines without markers) and ice cover (lines with markers) averaged over the northern Baltic Sea (below). Results are shown for a) RCA0, b) RCA1-44H, and c) RCA1-44E. Contours in the maps at every 0.5°C until 7°C and every 1°C thereafter. In the lower panels, the solid lines represent the control runs and the dashed lines the scenario runs; the December-February period is indicated with shading.*

The water surface temperatures in RCA0 were taken from HadCM2, which was problematic since the HadCM2 simulated winter SST in the northern Baltic Sea had a serious warm bias in the control run (a similar problem was associated with the extrapolation of the SSTs to inland lakes). To prevent this from deteriorating the wintertime control climate, ice cover was made independent of water temperature and ice proxies inferred from soil temperatures were set up (Rummukainen et al. 1998). This gave a reasonable decrease in ice from the control run to the scenario run. Unfortunately, it also made the surface climate overly sensitive to the decrease in ice, since, where ice disappeared, the air came to contact with the spuriously warm surface water data from the HadCM2 (the HadCM2 scenario run mean SST over the northern Baltic Sea were over 6°C). This affected the simulated climate change even over land areas of northern Europe, due to large increases in sensible and latent heat flux from the Baltic Sea and the inland lakes.

The RCA1-simulations with the SSTs and ice in the Baltic Sea and inland lakes modeled explicitly with the PROBE-models (see Rummukainen et al. 2000) also indicate a substantial reduction of ice. However, the impact of this on air temperature is much smaller than in RCA0, because the average SST is even in the scenario run stay relatively close to the freezing point.

All RCA simulations indicate a general increase in annual precipitation in the Nordic area. As with temperature, however, the Sweden area mean increase was larger in RCA0 than in all RCA1s. The RCA1 simulations in general show patches of marginally decreasing precipitation somewhere in southeastern Sweden. The contrast between larger increases in northern than in southern Sweden is qualitatively the same in the scenarios.

Compared with the RCA0 results, the increase in Sweden mean precipitation in RCA1-88H, RCA1-22H and RCA1-44H is smaller throughout the year. The difference is largest in winter and spring and is in these seasons probably explained by the more realistic treatment of water bodies in RCA1 than in RCA0. The two ECHAM4-driven RCA1 experiments, RCA1-88E and RCA1-44E are relatively close to the HadCM2-driven RCA1 simulations from late autumn to early spring, but they show a much smaller increase in precipitation during the rest of the year. A slight decrease in summer precipitation actually occurs especially in RCA88-E. With both HadCM2 and ECHAM4 boundary data, the latest 44 km RCA1 simulations show generally somewhat larger increases (or smaller decreases) in precipitation than the preceding 88 km simulations. Note that the seasonal cycles of precipitation and wind speed were smoothed by 3-month running averaging to reduce noise in Figure 22 – the actual month-to-month variations in the simulated change are larger than those shown.

An increase in the average wind speeds in most of the year and in most of the Nordic area has also been a qualitatively robust feature in the RCA simulations. As with temperature and precipitation, the change was largest in RCA0, which indicated considerably strengthened mean winds in the Nordic area with the largest change in winter, in particular over the Baltic Sea where ice was reduced. A slight general annual mean increase occurs even in the RCA1 experiments, with a more or less pronounced maximum over the Baltic Sea. However, the magnitude of the increase is smaller in the RCA1s than in RCA0, even though the last two (RCA1-44H and RCA1-44E) of these show somewhat larger increases than the first three.

The large increase in wintertime surface winds in RCA0 was not evident in the average geostrophic wind speed and was therefore suspected to be a stability-related effect, although the governing mechanisms were less clear over land than over the Baltic Sea (Räisänen et al. 1999). In RCA1, the more physically consistent treatment of the water bodies makes this destabilizing effect smaller. This appears as the most probably cause of the more modest changes in mean wind speed in the RCA1 simulations than in RCA0 (although in the choice of the GCM-forcing also contributes in between the HadCM2-driven and ECHAM4-driven RCA1-runs).

Differences and similarity. The simulated changes clearly depend on the RCA model version, model resolution and on the driving GCM. The last dependence implies that the quality of the driving GCM data set poses a constraint to the regional scenarios that cannot be improved just by improving RCA. Moreover, the differences between RCA1-44H and RCA1-44E (or RCA1-88H and RCA1-88E) are generally similar with the differences between the two driving GCMs. An illustrative example of this, the changes in JJA (June-August) precipitation, are shown in Fig. 24. Note, e.g. the large increase in precipitation over the Baltic Sea in RCA1-44H and HadCM2. On the other hand, RCA1-44E and ECHAM4 indicate a marked decrease in precipitation in central Europe.

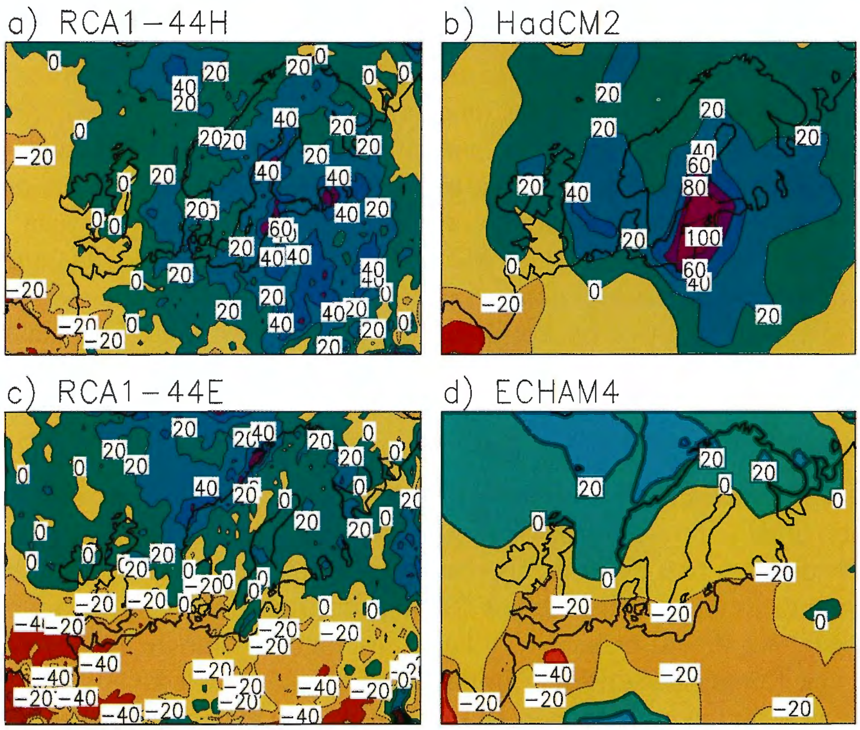

Figure 24. *Changes in summer (June-July-Aug) precipitation in RCA1-44H, HadCM2, RCA1-44E and ECHAM4. Contours at every 20%.*

To approach the issue more quantitatively, a more statistical comparison of the simulated climate changes in different experiments has been performed. To characterize the differences in climate change between the different experiments, the root-mean-square (rms) values of these differences were calculated over all land grid boxes within the RCA1 boundary zones. The results reveal interesting features:

1. There is no tendency of the two 44 km RCA1 experiments to be closer each other in terms of the seasonal and annual mean climate change than the original HadCM2 and ECHAM4 simulations. In the case of precipitation change, RCA1-44H and RCA1-44E are generally further from each other than the two GCMs. This is, however, basically because RCA resolves smaller-scale geographic details than the driving models. The systematic difference in difference vanishes

when the RCA results are smoothed to a scale comparable with the GCM resolution.

2. RCA1 and the driving model (RCA1-44H vs. HadCM2 and RCA1-44E vs. ECHAM4) are closer each other in terms of the simulated temperature and precipitation change than the two GCMs or the two RCA1 simulations themselves. As scaled by the rms difference between the two GCMs, the seasonal and annual rms differences in temperature change between RCA1 and the driving model vary between 20 and 47%. The same range for precipitation is 44-89%.

The differences between RCA1 and the driving GCM results reflect partly small-scale ("meso-scale") detail in RCA1 that cannot be resolved by the GCMs. However, there are also differences on the larger horizontal scales at least formally resolved by the GCMs. In the case of temperature change, the dominating contribution to the total rms differences in fact clearly comes from the latter. In the case of precipitation change, the meso-scale and the large-scale differences are of more comparable magnitude.

A potential risk in emphasizing the differences between different experiments is that of concealing the actually existing similarities. The relative similarity between two experiments can also be quantified, comparing their common features with the magnitude of their differences (Räisänen 1999). Considering the whole RCA1 land area, such statistics indicate quite a high degree of similarity between the temperature changes in RCA1-44H and RCA1-44, but at best a moderate similarity between the precipitation changes. The differences in temperature and precipitation change between RCA1 and the driving GCM (RCA1-44H - HadCM2 and RCA1-44E - ECHAM4) appear essentially unrelated between the two pairs of experiments. This differs somewhat from the 88 km RCA1 results reported by Räisänen (1999). For this pair of simulations, a systematic tendency of RCA1 to moderate the GCM simulated warming by a few tenths of a degree was found. This appears to have been related to the old radiation scheme that could not treat the increase in CO_2.

Role of internal variability. Like the real nature, model simulations show substantial unforced, so-called natural variability. Some part of the simulated changes and differences in between any two experiments results from this variability, rather than being a genuine response to the greenhouse gas forcing. In order to exactly separate the signal from the noise, one should make a very large ensemble of climate change experiments, using the same forcing but different initial conditions. In such an ensemble mean climate change description, only the forced signal would be expected to be present.

Without such ensembles, the exact contributions of the signal and the noise remain unknown. However, the probable magnitude of the noise can be estimated from the simulated interannual variability. Some results from this type of calculations are shown in Figure 25 as maps of standard errors (square root of the variance) for the differences in climate change between RCA1-44H and RCA1-44E (note that the standard errors for the individual experiments are smaller).

The estimated standard error for the difference in annual mean temperature change is relatively modest, generally well below 1°C, but larger values are obtained for the seasonal changes. The standard error in winter locally exceeds 2°C, which actually indicates a 5% possibility of getting a 4°C difference in temperature change between the two experiments just by chance. Similarly, the standard errors for the difference in precipitation change are substantially larger in the individual seasons (especially summer) than in the annual mean.

The estimates of the contribution of internal variability obtained in this way are, of course, statistical. In any individual grid box, the contribution might be either much larger or much smaller. When the variances are averaged over a larger area, the estimate becomes gradually more meaningful. A measure of the relative importance of internal variability is obtained by dividing the area mean variance associated with internal variability by the area mean square of the simulated climate change or by the area mean squared difference in climate change between different experiments. Such an analysis indicates that the simulated warming in RCA1-44H and RCA1-44E (and the other experiments) is much larger than the noise expected from internal variability, but that the changes in precipitation are much more severely disturbed by this. For the differences in temperature and precipitation change between the various experiments, the signal-to-noise ratio is even lower. As a rule of thumb, about a half of the differences between the two 44 km RCA1 simulations appear to arise from internal variability. The same applies to the differences between these simulations and the driving GCMs.

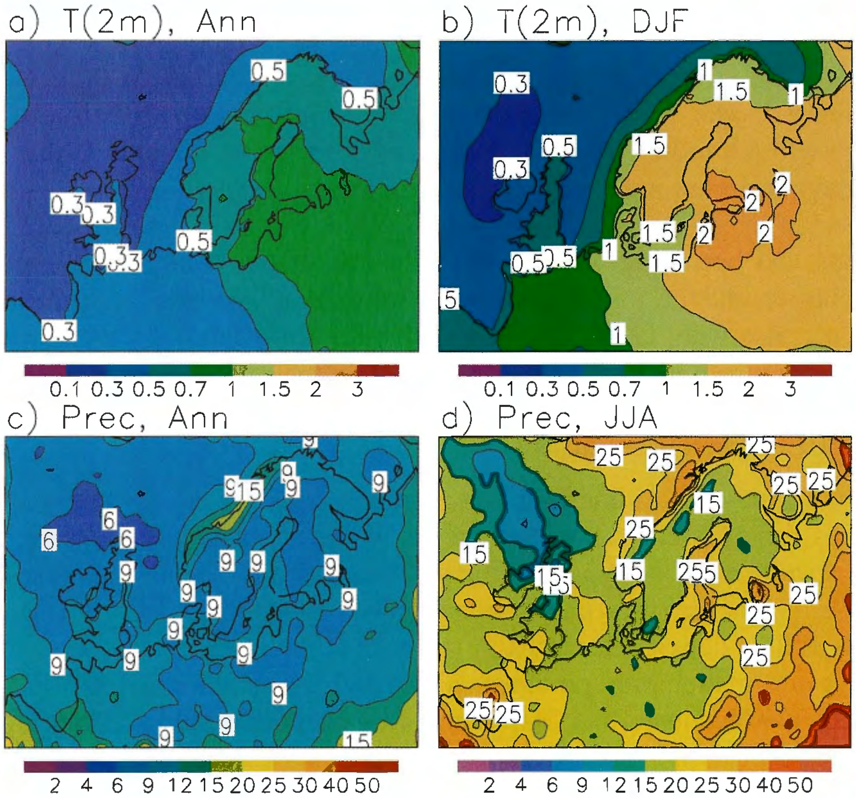

Figure 25. *Standard errors associated with interannual variability (see text) for the difference in climate change between RCA1-44E and RCA1-44H. The standard errors are shown for temperature (°C) in the annual mean (a) and in winter (b) and for precipitation (%) in the annual mean (c) and in summer (d).*

Summary of SWECLIM Phase 1 RCA-scenarios

1. During the history of the RCA model development from RCA0 to the earlier (RCA1-88H, RCA1-88E and RCA1-22H) and latest (RCA1-44H and RCA1-44E) versions of RCA1, the results of the climate change simulations have gradually evolved. The latest RCA1 simulations show generally slightly smaller increases in all of temperature, precipitation and mean wind speed than RCA0, but slightly larger increases than the first RCA1 simulations. Nevertheless, most results have remained qualitatively similar. The relative similarity between the latest RCA1

simulations and RCA0 is partly due to the fact that two of the major model improvements between these, the more realistic treatment of the Baltic Sea and lakes and the updating of the radiation scheme, have had somewhat opposing effects.

2. The driving GCM data have a major impact on the simulated regional climate. The changes in mean temperature and precipitation are, considering the model area as a whole, more similar between RCA1 and its driving GCM than between the RCA1 simulations run with same resolution but different GCM-forcings, or between the two GCMs. Downscaling does not seem to systematically increase or decrease the differences in temperature and precipitation that already exist between GCM simulations.
3. Internal variability is of importance in interpreting the results of the rather short, 10-year simulations, especially in the case of precipitation. When differences between simulations are considered, internal variability becomes a major issue with temperature as well.

These points emphasize the importance of further developing the regional modeling. For example, it will be of great interest to see how the coupling to the 3-D Baltic Sea model of the RCO affects the results. However, it is also indicated that even though a regional climate model is made more sophisticated, accurate <u>predictions</u> of future climate change will not ensue. The scenarios can be made more useful, though, for users. To reduce the interfering impact of internal variability, longer downscaling experiments or ensembles of experiments are desirable. Indeed, the results suggest that, if longer GCM-periods had been used to drive RCA, some of the resulting differences in the simulated climate change might have been substantially smaller. On the other hand, differences are also truly GCM related and distinct from internal variability. This part would be retained even in longer experiments. Regional runs forced by different GCMs and GCMs with different greenhouse gas/sulfur scenarios will also add on the usefulness of SWECLIM regional scenarios.

Despite this, a fundamental question is how much does the downscaling actually matter? As far as the differences between the RCA and its driving GCM are, even at the local scale, smaller than the typical differences between different GCM experiments, it probably does not matter very much. In particular, some of the RCA-GCM differences may actually reflect deficiencies in RCA rather than the higher resolution. Thus, impact studies using information only on changes in mean temperature and precipitation could probably be performed using the GCM simulated changes directly, except in the immediate vicinity of coastlines and steep orography such as the Alps or the Norwegian mountains. However, many impact studies need data that extend far beyond such basic parameters. An example of an important area that still needs a lot of research is how regional models modify GCM-estimates on changes in the daily variability of climate. In this respect, high resolution may be more important than is the case with the time mean climate. Aspects of the daily variability, such as heavy precipitation events, are frequently associated with small-scale weather phenomena typically poorly captured in GCMs. More generally, there is great value in regional climate modeling producing a more realistic and physically consistent description of local-scale daily weather than is possible with coarse-resolution GCMs. Adding geographic detail to GCM produced estimates of the time mean climate change is not the sole use of regional modeling.

Just looking at the simulated climate changes gives a somewhat subdued view on the effect of model improvements. A better measure of this is attainable from a comparison and analysis of the control simulations. Even better, simulations forced by meteorological analyses, such as the ECMWF ones, can be used for evaluating model performance in terms of quantifiable realism. Such studies will be conducted also in the continuation of the SWECLIM-program.

2.5 Statistical downscaling and basic process studies

The basic process studies in SWECLIM touch upon areas where weaknesses are found in climate modeling systems. Much attention is focused on the hydrological and energy balance at the surface. In addition to improving the surface physiographic databases, the simulation of soil moisture and snow have been reformulated with hydrological modeling concepts. It has also been an important undertaking to include effects of vegetation in evapotranspiration, rainfall interception and surface resistances, using in part the French Interactions between Soil, Biosphere and Atmosphere (ISBA, see Noilhan and Planton 1989) concept. Different formulations of the surface energy- and water-balance have been tested, leading into important improvements in the SWECLIM regional model system. The future aim is to integrate full hydrological calculations in the RCA model thus making it possible to obtain impacts on river flow etc. directly.

Closely associated with the energy balance and water balance calculations is the parameterization of clouds and convection. Here work has been performed on the representation of cloud formations, convection and cloud cover, as well as on the feedback between clouds and radiation. Improvement on the radiation scheme have already been implemented in RCA (Räisänen et al. 2000b, 2000c). Studies on cirrus and on the impact of regional sulfur emissions on cloud albedo have also been made or initiated (Zurovac-Jevtic 1999a, 1999b). Even those parameterization studies that have not yet led to changes in the regional model will hopefully benefit future decisions about parameterization changes.

Fronts in regional climate models. In regional climate simulations, it is of course the large-scale that governs regional weather patterns. On regional scales, however, features embedded *within* the large-scale flow may significantly influence the statistics characterizing the simulated climate scenario. Frontal zones are important examples of such features. When determining the temporal and spatial variability and typical extreme values of for instance temperature and winds, the characteristics of the frontal zones are highly influential. They also play an important role in estimations of precipitation and cloudiness.

Of importance for the simulation of frontal zones is the parameterization of vertical diffusion. It influences the sharpness of the zones. Earlier studies indicate that the HIRLAM model tends to overestimate the turbulent fluxes in frontal zones in the mid- and upper troposphere resulting in too weak frontal gradients. Here, a study is performed to investigate the effects on frontal zones caused by the vertical diffusion scheme, forcing the RCA-model with global weather analyses from ECMWF. One way to estimate the sharpness of frontal zones is to consider the Richardson number (Ri). It is a stability parameter, defined by the ratio between the Brunt-Väisälä frequency and the wind shear. Below the jet often associated with frontal zones, the shear is strong and consequently Ri is small. This implies a possibility for shear-induced instability. Ri is also a central parameter in the vertical diffusion scheme for determining the amount of turbulent exchange. Ri is used to compare results from simulations with different parameter values in the turbulence parameterization scheme.

So far, results show a sensitivity to the parameterization of vertical diffusion in the free troposphere, where the value of a parameterized length-scale, within which the turbulent exchange may "reach", the so called mixing length, is an influential parameter. Case studies show that despite a higher resolution in the regional model, somewhat lower values of wind velocity and temperature gradient are simulated, compared to the forcing boundary fields interpolated from the global weather prediction model at ECMWF. These results suggest that vertical diffusion in the mid- and upper troposphere may be too strong in the RCA model.

The SWECLIM regional ocean studies include the development of the RCO ocean-sea ice model for the Skagerrak-Kattegat-Baltic Sea region (see section 2.3), its coupling with the regional climate model RCA (see section 2.1-2.2 and 3.1) and improving the understanding of the ocean processes playing a role in the regional climate. The latter is considered in the following, in terms of analytical and process-based regional ocean studies for the Skagerrak, the Kattegat and the Baltic Sea. Some points of interest are:

- The ice conditions (of importance to shipping), especially in the northern parts.
- The living resources in the brackish Baltic Sea are sensitive to small changes in the salinity (e.g. in the deep water in the southern part of the Baltic Sea; cod).
- Large parts of the Baltic Sea and the Kattegat occasionally have an oxygen concentration too low, indeed toxic, for higher organisms. Apart from eutrophication, the oxygen condition depends strongly on salinity stratification and water exchange between basins, and is thus sensitive to regional climate changes.
- The Skagerrak is the most productive part of the North Sea. Changes in the outflow from the Baltic Sea might alter the conditions in this region and thus, for example, have impact on the fishing industry.
- Flooding is a potential severe problem along the coast. Rise in the mean sea level and changes in storm surges can have large economical consequences. (The potential damages to society are even larger along the southern North Sea coast.)

Historical ocean data have been analyzed to define statistics for use in model validation, scenario interpretation and for investigation of the sensitivity of processes and properties to changes in climate. Analyses have shown that the memory of the Baltic Sea is of the order 100 years. This emphasizes that in order to achieve realistic scenarios from a 10-year regional ocean model simulation, proper initial conditions have to be calculated. Due to the large variability in e.g. inflow events, the representativity of future scenarios needs careful assessment as well.

Baltic Sea ocean climate. Winsor et al. (2000) discuss 100 years of hydrographic data and related forcing. The hydrographic state of the Baltic Sea is dominated by freshwater supply that in combination with a narrow connection to the open ocean is responsible for the regional special conditions; low mean salinity and poorly ventilated deep water.

For the freshwater supply, monthly mean river runoff in 1920-1990 has been studied. The overall mean river runoff is 14,000 $m^3 s^{-1}$ for the Baltic Sea and 15,200 $m^3 s^{-1}$ for the Baltic Sea including the Kattegat and the Danish straits (during this period, the whole range was from 18,200 $m^3 s^{-1}$ and 10,400 $m^3 s^{-1}$). The natural variability of the freshwater supply by rivers is large. The other component in the Baltic Sea freshwater supply is the net precipitation, studied e.g. within BALTEX. It is plausible that the annual mean net precipitation might vary between 500 $m^3 s^{-1}$ and 4000 $m^3 s^{-1}$. The natural variability of the system's annual freshwater supply ranges then from 10,000 m^3 s^{-1} up to about 20,000 m^3 s^{-1}, with large positive and negative deviations on decadal scales.

Annual means of salinity at hydrographic stations are studied for an idea of the conditions in the Baltic Sea. The magnitude of the variations in the surface salinity is ~1 psu (='practical salinity units' ~‰) and up to 3 psu in the deep water. The difference in scales of salinity variations between the surface layer and the deep water is in part a reflection of the difference in volumes associated with these water masses.

The intermittent inflow of deep water is reflected in the salinity data. For example, the stagnant period 1976-1992 resulted in a monotonous decreasing salinity. The major inflow in 1993 gave, on the other hand, a clear change in the deep-water salinity. During the 20th Century, the Baltic Sea mean salinity has varied within ~1 psu.

The freshwater storage in a given volume is defined as the amount of freshwater needed to dilute the volume from specified background salinity to the present state. It is a robust quantity integrating over the freshwater forcing and also illustrates the special Baltic Sea character, compared to the world ocean. The background salinity is taken as 33 psu (~ the deep water in the Kattegat). The estimated mean freshwater storage in the Baltic Sea is about 16,700 km^3. This can be compared to a total volume of the Baltic Sea of 21,000 km^3. The residence time of the fresh water in the Baltic Sea is about 30 years. Annual deviations from the mean freshwater storage in the Baltic Sea are shown in Figure 26, together with the accumulated river runoff. The freshwater storage follows the integrated river runoff so the volume-averaged salinity also follows this quantity and the Baltic Sea has a memory of at least several decades. Thus, to describe the future one needs to know the history of the runoff.

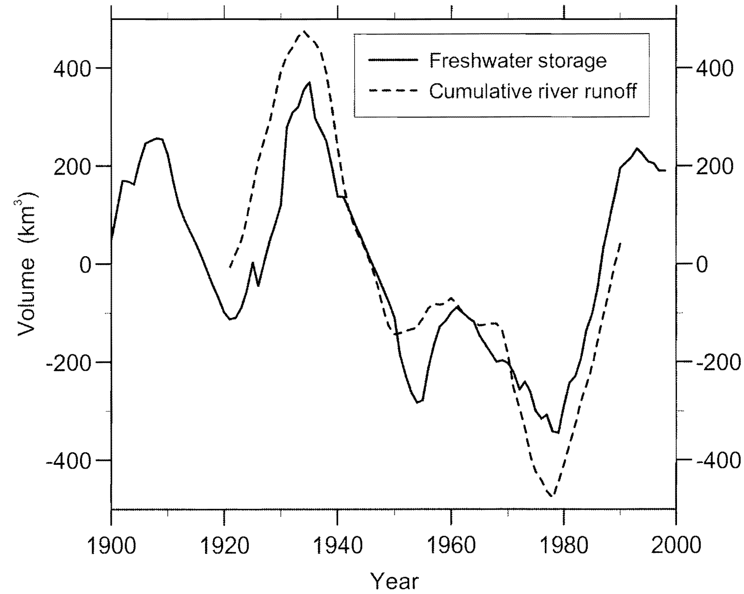

Figure 26. *Annual perturbations of the freshwater storage of the Baltic Sea (solid line) together with the accumulated perturbations of the annual river runoff (dashed).*

The seasonal cycle of the freshwater storage, on the other hand, can not be explained by the seasonality in river runoff. The dominating factor is the seasonal variation of the water exchange through the Danish straits.

Ocean climate scenario with process-based modeling. The RCA0 regional climate scenario (see section 2.4) has been used not only to force the 3-D RCO model (see section 2.2) but also the process-based regional ocean models in SWECLIM (Omstedt et al.

2000). The latter are based on Stigebrandt (1983), extended by Omstedt (1987, 1990), Omstedt and Nyberg (1996), Omstedt and Axell (1998) and Gustafsson (2000a,b).

The process-based modeling aims lay in between simple conceptual and fully-resolved 3-D simulations. The models are simpler to understand and require less computational resources than 3-D ocean simulations. Consequently, a larger number of simulations can be performed, for example to span model/process sensitivities. The trade-off is that details of the processes that might be relevant cannot be resolved. Process-based models and models with explicitly high 3-D resolution offer complementary handles on the problems studied. In SWECLIM, process-based Baltic Sea modeling is used to analyze the results from the regional RCA model with respect to the heat and water cycles and sea ice-sea surface temperature. Special scenarios of the Baltic Sea climate (and change) are also targeted. For these purposes, PROBE-Baltic model is run one-way coupled, i.e. applied without feed back on the atmosphere. The two-way coupled use of the PROBE-Baltic is described in section 2.1. Another model tool used is the steady-state model of Gustafsson (1997), to calculate the steady-state response of Baltic Sea surface salinity to prescribed atmospheric/river. In this analytical model the upper layer of the Kattegat and Belt Sea is treated as a single water mass (box), while the lower layer is treated as dynamically passive source of water and salt. The coupling to surrounding sub-basins includes a geostrophic outflow to the Skagerrak, entrainment flow from the lower layer, fluctuating flow across the sills and fresh water input to the Baltic Sea. The model provides the surface salinity in the outflow-water from the Baltic Sea.

The process-based Baltic Sea simulations. Three runs are discussed, one for the observed climate and then two for the RCA0 control and scenario time slice simulations.

The standard run was done with observed/analyzed meteorological forcing fields (for 1980-95 with model initialization for Nov 1980), observed monthly-mean river runoff to the Baltic Sea and daily-mean sea level in the Kattegat. The results are used to assess the realism of the model, i.e. how closely it follows observations. Thereafter, the climate-application runs, forced with the two 10-year RCA0 runs were performed. Note that compared to the observed climate, the RCA0 control run exhibits some important seasonal biases, such as cold spring and damped seasonal precipitation cycle. These affect the off-line ocean runs. The same initial conditions were applied in the PROBE-Baltic as in the standard run. The river runoff was based on the HBV-Baltic model also forced by the RCA0. The same lateral boundary conditions were applied in all runs.

Sea surface temperatures of the Eastern Gotland Basin simulated by the PROBE-Baltic model are shown in Figure 27. The standard-run is shown together with standard hydrographic station data averaged over a 15 to 20 year period during present climate conditions. The modeled conditions are close to the observations, though with a winter-spring cold bias.

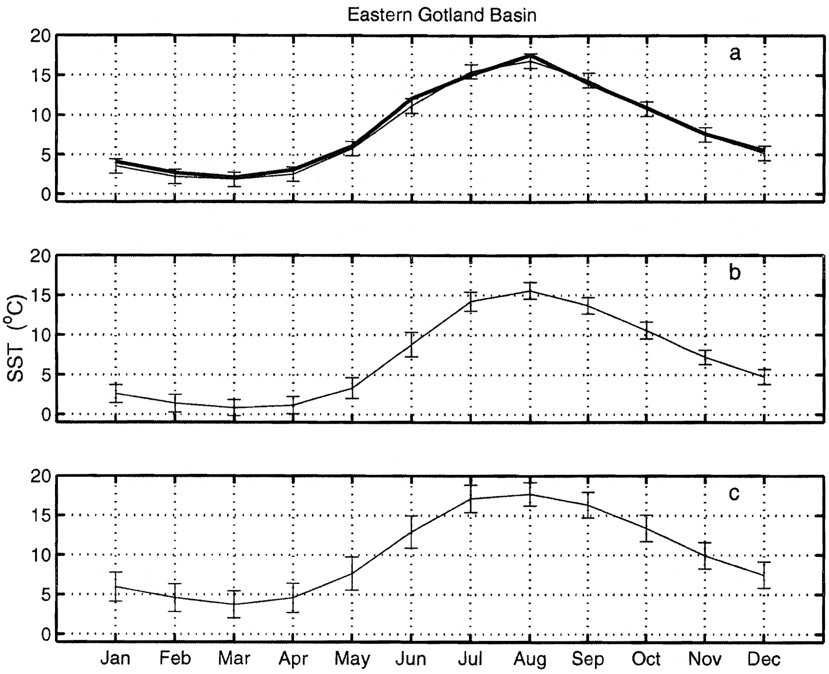

Figure 27. PROBE-Baltic -modeled sea surface temperatures in the Eastern Gotland Basin from the: a) the standard run (thin line), together with observations (thick line) b) run forced by the RCA0 control run, and c) the scenario run forced by the RCA0 scenario. The error bars show the standard deviation in the calculations extending to 10 years.

Even the PROBE-Baltic forced by the RCA0 control run shows realistic seasonality and realistic winter temperatures at freezing (note that the ice proxy description that had been used in RCA0 was tuned to give ~observed mean ice extent). The PROBE-Baltic run is in this case colder than in the standard run, particularly in spring. The PROBE-Baltic forced by the RCA scenario run still shows similar seasonality but now with higher sea surface temperatures, in summer and particularly during the winter, in line with the atmospheric changes.

The PROBE-Baltic modeled extent of sea ice when forced by the RCA0 runs is illustrated in Figure 28.

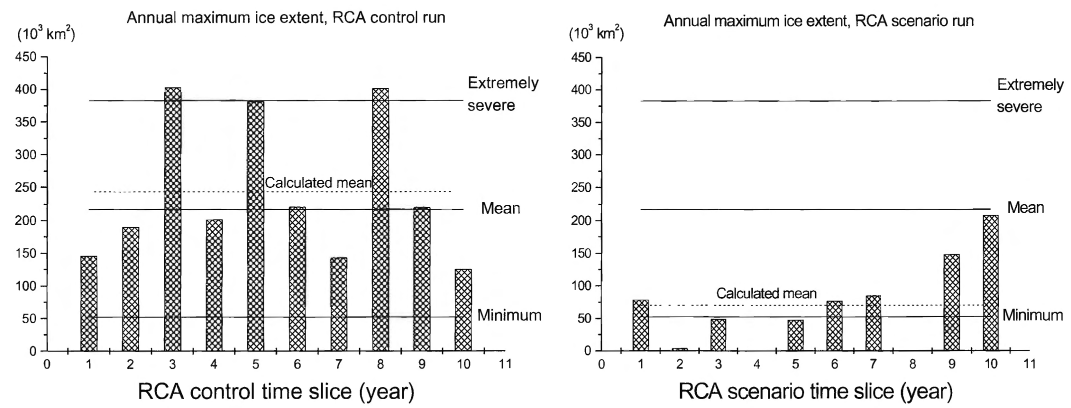

Figure 28. *Modeled annual maximum extent of ice. The ice classification follows Seinä and Palosuo (1993). The horizontal lines are for the minimum, mean, and extreme ice extent during 1720-1997. Left: forcing from RCA0 control run. Right: forcing from RCA0 scenario run.*

The control run shows slightly more ice (i.e. colder conditions) than what has been observed. In the scenario, the annual maximum ice extent is much reduced. The maximum extent of ice in the scenario is above the minimum value encountered during the observed climate only during 5 out of the simulated 10 years, and that there is no ice during 2 out of the 10 years (these results would likely be less severe if the PROBE-Baltic simulations were redone with the RCA1-results). The heat cycle (as measured by sea surface temperature and extent of ice) was realistically reproduced even with RCA0-data forcing PROBE-Baltic for the present climate conditions.

Different estimates of the Baltic Sea water and heat balances exist. Omstedt and Rutgersson (2000) have calculated evaporation rates using the PROBE-Baltic model forced by observed data for 1980-1995. ECHAM4 GCM simulations for the Baltic Sea have been reported by Jacob et al. (1997). Earlier estimates of the water balance of the Baltic Sea are given by HELCOM (1986). These can be compared with the water-balance components from the set of RCA0 (precipitation and forcing of river runoff), the HBV-Baltic (river runoff), the PROBE-Baltic (evaporation) and the steady-state ocean model (salinity).

Of the long-term mean water balance of the Baltic Sea (excl. the Kattegat and the Belt Sea), covering the river runoff, the net precipitation and the surface salinity, rather high net precipitation rates over sea and rather large river runoff to the sea are simulated. In the control, the total freshwater input to the Baltic Sea was ~22,200 $m^3 s^{-1}$, which is ~5000 $m^3 s^{-1}$ more than how the estimates range for the present. The total freshwater input in the scenario was even higher, ~25,400 $m^3 s^{-1}$. The freshwater input in the control run, and probably also in the scenario run are too high. One way to try to reduce these biases in deriving estimates of the climate change impacts is to take the difference between the scenario and the control run to represent the climate change. This would lead to a lowering of the salinity of about 1 psu from the present values. In any case, the RCA0-driven water cycle (net precipitation over the open sea and river runoff) shows too large freshwater input to the Baltic Sea.

To look into the vertical structure of salinity, the Baltic Sea time-dependent response to the observed forcing field (standard run) and to the RCA0-forcing (control and scenario run) was studied for the Eastern Gotland Basin that represents the typical conditions. The standard run follows closely the observations. In the control run salinity is slightly reduced in the water column, especially above the deepest layers. In the scenario run the salinity is reduced even more. The calculation is much influenced by the initial conditions and does not come to a balance with the water cycle within the short integration length, due to the long stratification spin-up time for the Baltic proper. Hence, the use of short time periods for predictions of the Baltic Sea climate change is questionable. To illustrate the long-term adjustment of the salinity stratification, a 100-year time integration was also performed, with the same initial conditions, reusing the 10-year forcing fields 10 times. As the Kattegat sea level data were taken from the period 1985 to 1995, one major inflow event (cf. 1992-93) occurred in each 10-year period. The salinity structure in the Eastern Gotland Basin, for the simulation years 1-10, 40-50 and 90-100, is illustrated in Figure 29.

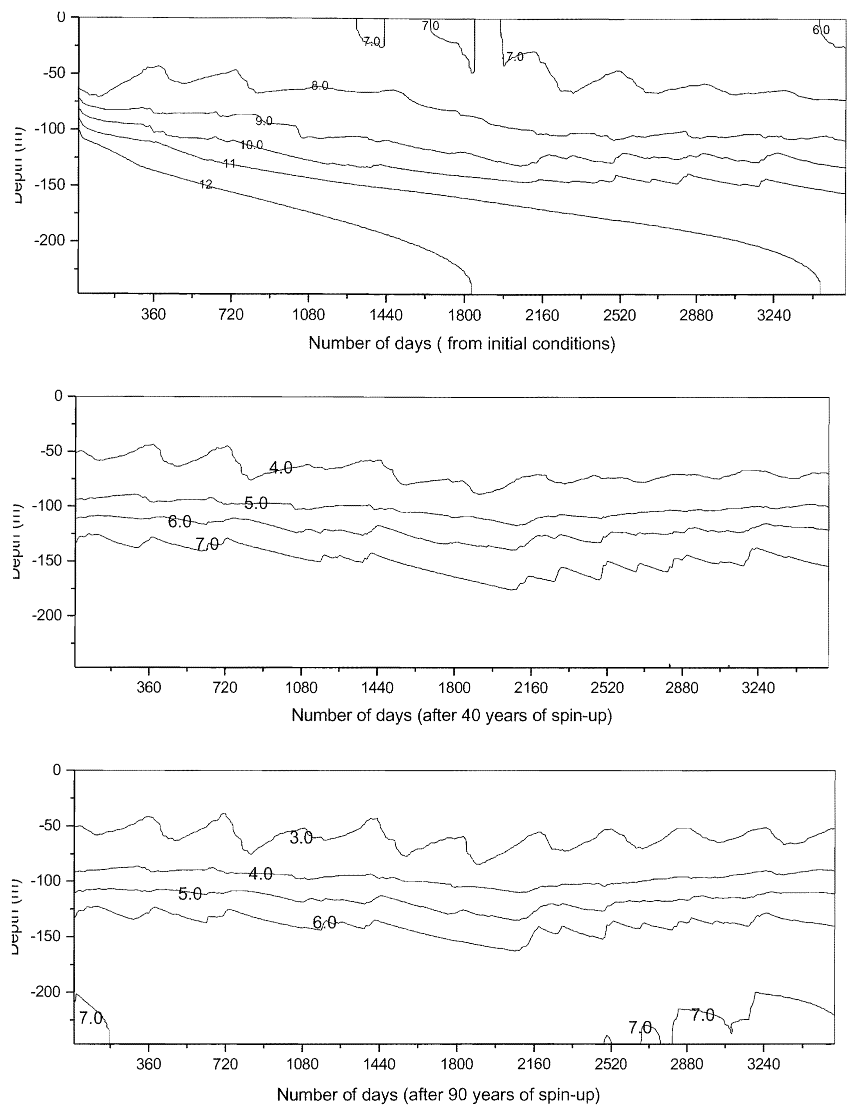

Figure 29. *Modeled vertical structure of salinity based on the RCA0-scenario run forcing. Top: right after the start from initial conditions, middle: after 40 years and bottom: after 90 years.*

The calculated sea surface temperatures and ice extent did not drift/differ significantly between the beginning and the end of the 100-year run. This is likely explained by the fact that the same 10-year sequence of wind, as well as Baltic Sea in- and outflows, was repeated. The mixed layer depth did not change significantly either, even though the amount of salt did, as the shape of the stratification remained largely the same. In the actual future, changes in the atmospheric and sea level forcing are more than likely, so these results are still rather illustrative.

As the results indicate that correct initial conditions are necessary in the regional ocean climate simulations. The evolution of the Baltic Sea on a time-scale of up to 100 years might have to be accounted for. One way to apply this would be to use the PROBE-Baltic to calculate initial conditions for more specific time slice simulations with RCA, RCO and RCA+RCO.

In the climate change sense, the investigated scenario indicates strong potential impact on both the heat and water cycles, with increased sea surface temperatures, much reduced extent of sea ice and reduced salinity. Coupling of the ocean, atmosphere and land-surface models and consideration of possible changes in the inflows and outflows to the Baltic Sea are also important to consider.

Variability of ice extent. Omstedt and Chen (2000) have analyzed the connection of atmospheric circulation, the North Atlantic Oscillation (NAO), and large-scale circulation indexes over Scandinavia on inter-annual variation of maximum ice extent in the Baltic Sea with statistical downscaling methods. This is part of the increasing understanding on the recent and long-term variations in the climate conditions throughout the Baltic Sea and Skagerrak region that is desired for a proper characterization of climate scenarios. Sea ice is a key element in both the water and heat cycles in the region with large variations from year to year.

The data on the long-term variations of the annual maximum ice extent (Seinä and Palosuo 1993) since 1720 were studied. The data represent the overall winter conditions and imply some decreasing trend in the Baltic Sea ice cover. As analyzed with ocean-sea ice models, the regional sea ice is highly sensitive to changes in air temperature and wind.

Statistically significant relations have been found between the ice extent and both the winter NAO index and the zonal winter geostrophic wind over the Skagerrak and Kattegat region. However, great variation in the strength of the relations exists. A model based on a set of regional circulation indexes has been developed and it has confirmed the importance of the zonal flow and wind vorticity. The statistical model has a reasonably good skill and should be useful in constructing further scenarios even from various GCM results. As only a part of the variability is captured (as is typical to statistical models), the extreme ice extents, mild as well as severe conditions, are likely underestimated, however.

Deep- and intermediate water flows through topographic constrictions represent rather more specialized regional ocean process studies. From a climate point of view, correct modeling of such processes is essential, since the deep-water fluxes in the Baltic may be critical for the long-term properties of the basin, with implications for maintaining the environmental conditions for marine life and fish stocks.

The dynamics of two specific areas have been examined; the Bornholm Channel and the Irbe Strait, the connection to the Gulf of Riga (Laanearu et al. 2000; Laanearu 2000). In these passages, no well-defined control sections exist (the location of the most pronounced horizontal constriction does not coincide with that of the maximum sill height). The work performed has shown that this problem can be resolved. The transport calculations for critical flow show good correspondence with field data.

Sea level variations and exchange through the Danish straits are very important for the Baltic Sea climate. In the regional ocean modeling for the Baltic Sea, observations of sea level variations in the Kattegat have so far been used to calculate the water exchange. As this is not possible in climate scenarios, other avenues need to be explored. As a part of SWECLIM, an analysis of historical sea level observations has been underway to relate the regional sea level variations to large-scale atmospheric circulation patterns, in a statistical way and in a mechanistic way (Ivarsson and Rodhe 1998).

Some findings from the ocean process studies are:

- There is a significant long-term decreasing trend in the maximum ice extent over the Baltic Sea in 1720-1997. Before (after) 1877 a relatively cold (warm) regime seemed to govern. However, the year to year variability is high.

- In 1720-1880 (colder climate), there is an increasing trend in the variability and a decreasing trend in 1880-1997 (warmer climate). Almost no net variability trend is found over the entire period.
- Periodicity at ~2 and ~8 years dominates the ice extent variation. This points to the importance of short-term processes in the system.
- Both the empirical and numerical modeling show that there is an asymmetry in the sensitivity of the ice system to perturbations. Around the present conditions, a warm climate anomaly produces a stronger response than a cold climate anomaly. Obviously, conditions are altered more drastically if the ice melt threshold is passed.
- The ice extent is rather well correlated to large scale atmospheric circulation in winter (cf. Koslowski and Loewe 1994) but the relationship might not be stationary in time. Such a relation could be utilized in a regional interpretation of GCM simulations, in combination with the more detailed regional model studies.
- The good agreement in Baltic Sea ice extent estimations from the numerical ice-ocean model and observations provides more confidence in the ice-ocean model. The verification studies are especially useful to assist in model development and scenario interpretation studies in SWECLIM.

The studies on ocean processes is important in improving our insight into the Baltic Sea as a component of the regional climate system. It also links to the development of regional modeling and the interpretation of the regional climate scenarios. The same is true for the statistical downscaling studies and the impact studies pursued in SWECLIM and with data from SWECLIM by external groups. These will be discussed next.

Statistical downscaling. In the plans for SWECLIM, statistical downscaling was suggested as a complementary alternative to regional simulations (Rummukainen 1997, Xu 1998, 1999). The department of Earth Sciences of the University of Göteborg was taken on as consultants to the Rossby Centre and given the task to pursue the issue.

The main objective of statistical downscaling within SWECLIM is to add on the dynamical (regional model) downscaling as concerns regional scenarios. In Phase 1, the focus of the analysis was on monthly temperature and precipitation and in developing the suitable statistical analysis tools. In the future, these tools will be applied on a larger range of GCM-results, as an effort to address the certainty/uncertainty of GCM-derived scenarios, and on some additional climate parameters, such as sea level.

So far, standard climate normal (the 30 year mean of 1961-90) of Swedish temperature and precipitation data have been analyzed by geostatistical techniques (Hellström and Chen 1999). A 10-km temperature database has been completed and made available for evaluation of model development performance in Sweden. In addition, parameters that represent the large-scale synoptic situation over Scandinavia have been studied as a step in creating the statistical downscaling tools. Sea level pressure (SLP) and large-scale surface air temperature have since then been chosen (Chen 1999) as predictors for statistical models. For the observed past climate, the link between monthly Swedish precipitation variability and SLP variability over the Atlantic-European region is strong for all months, especially for winter. The North Atlantic Oscillation (NAO) pattern appears to be the most important one (Busuioc et al. 2000a,b). Impact of NAO on the Swedish temperature is described in Chen and Hellström (1998, 1999). Omstedt and Chen (2000) and Chen and Omstedt (1999) also identified the role played by NAO on sea ice and sea level variability in the Baltic Sea. The observed SLP over the last 123 years have been analyzed with a set of circulation indices (Chen 2000) and EOF analysis (Busuioc et al. 2000b), also with the GCM-comparisons in mind (Chen et al. 1999). Some difference between the observations and GCM results for the present climate were noted, which has implications for the scenarios created by the statistical downscaling model.

To complete the statistical downscaling model, the large-scale predictors and the local climatic variables were used to develop and test a multiple regression downscaling model for temperature (Chen and Chen 1999a), precipitation, sea ice over the Baltic (Omstedt and Chen 2000), and sea level in Stockholm (Chen and Omstedt 1999). Canonical correlation analysis (CCA) was used to create another model for precipitation (Busuioc et al. 2000b) and temperature (Chen and Chen 1999b). A comparison between the two showed negligible difference in terms of the explaining power and independent verification performance for the observed climate. Generally the models could account for a large part of the total variance and better results were obtained if long-term climate was compared. As an example, the verification of the regression model for temperature at two stations is displayed in Figure 30 using results from the statistical model version utilizing both the large-scale SLP field and surface temperature field (Chen 1999).

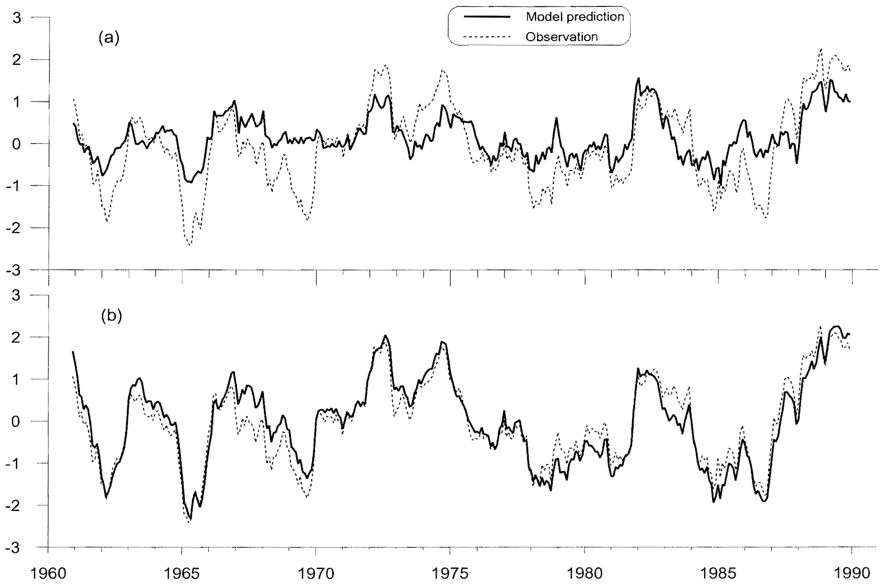

Figure 30. *Temperature anomalies calculated by the statistical downscaling models in comparison with observations for Uppsala. The so-called independent verification period is shown, i.e. when the statistical model is not constrained by the actual observations. (a) using only SLP as the large-scale predictor and (b) using the SLP and the large-scale surface temperature as predictors. Note the increase in statistical model performance in the second version. The monthly data have been smoothed by 12 month moving average.*

The established models have even been used to create statistical downscaling scenarios based on the same GCM data as interpreted with RCA. In comparison to RCA, the mean temperature and precipitation changes given by the first versions of the statistical model, between the two 10 year GCM runs were found to be relatively small.

Where differences between the dynamical and statistical downscaling results emerge, different explanations should be examined: 1) the statistical model is not perfect (there is some unexplained variance), 2) the dynamical model (RCA) is not perfect; 3) the large scale field in the GCM-simulations deviate from observed climate in the control/present-day time slice period case and may likewise not be fully realistic for the future climate in the scenario time slice period case, 4) a 10-year period is likely too short compared to the amount of natural variability.

As a second step, the large-scale temperature and humidity/precipitation were added to the statistical downscaling models for temperature and precipitation respectively, which gave promising results in terms of the climate change signal. As an example, the statistical downscaling result for the annual mean temperature change in the HadCM2 GCM-results case is shown in Figure 31. The latest RCA1 (RCA1-44H) downscaling result for the same GCM data is also shown for comparison. An important conclusion from this exercise is that the role played by the atmospheric circulation expressed by SLP is limited in representing the climate change signal. Consequently, other predictors are needed to improve the skill of the statistical downscaling model.

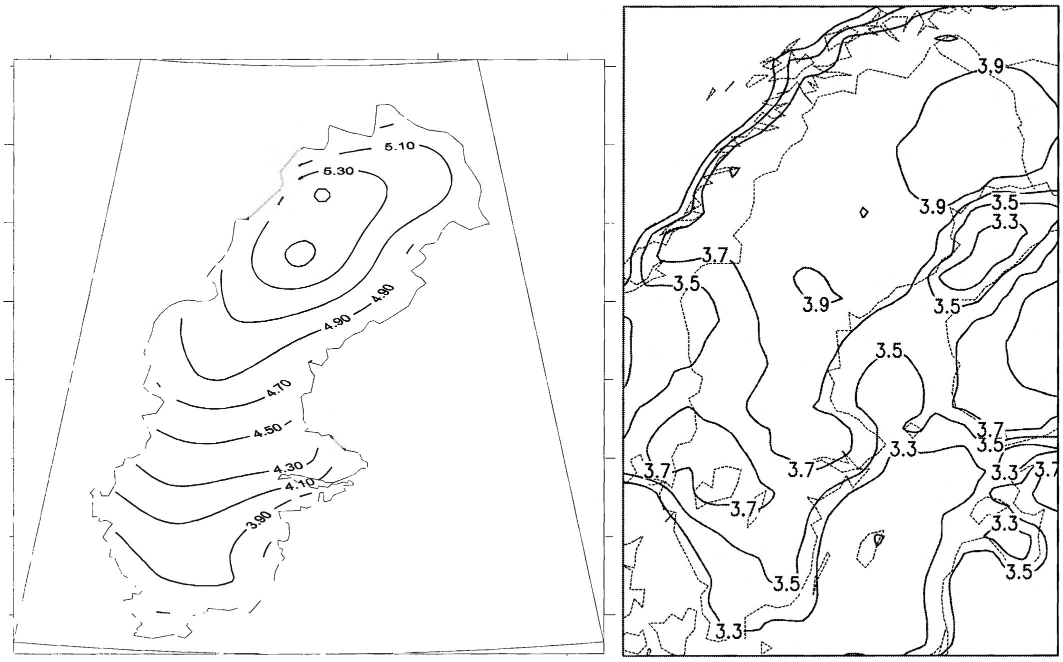

Figure 31. *Left: Change in annual mean temperature for Sweden, as interpreted with the statistical model using the circulation indices and the large-scale temperature as predictors from the two 10-year HadCM2 time slices used by SWECLIM in program Phase 1. Right: the corresponding result from the RCA-simulation (RCA1-44H).*

SWECLIM-studies on GCM-simulations. An important motivation of regional climate modeling is to add desired detail on global climate scenarios prepared with General Circulation Model (GCM) simulations. The use of GCMs in the creation of climate change simulations is a necessary step on the road to regional assessments. The nature of the transport and interactions in the atmosphere and in the ocean requires that the whole global domain needs to the accounted for. This spatial requirement is coupled to the required length of original climate simulations (typically >100 years to properly capture 1) the forcing on the climate system from the transient increase in greenhouse gases and 2) the interplay between the atmosphere and the ocean). Consequently, even with today's computing resources it is in practice still impossible to run GCMs on a much higher horizontal resolution than 200-300 km. This is rather coarse for local-to-regional climate scenarios or practical impact analyses. This is where and why regional climate models come into use.

Regional modeling is always strongly affected by the driving GCM results. This is especially evident in the large scales, such as atmospheric circulation and movements of air masses and location of storm tracks at mid-latitudes. Even area means of surface parameters are largely constrained in many cases. Where there are important surface elements that exert forcing on climate, such as effects of orography or coastlines on precipitation, use of regional models may significantly modify and improve the regional climate simulation over the results attainable from GCMs. The higher resolution in regional models, compared to GCMs, improves also the simulation of fronts and maybe even extremes. Nevertheless, as regional modeling provides for more detailed interpretation of GCM-results, the driving GCMs constitute a major and inevitable constraint in regional climate scenarios. As the future state of the climate system cannot be observed and as the manmade forcing can only be projected from present-day trends and expectations of our behavior in the future, all climate scenarios for the future come with uncertainty that at best can be quantified in some sense. This means that GCM-scenarios on climate change include uncertainty and of course, so do the regional climate scenarios created from the GCM-results.

Basically, different sources of uncertainty contribute in climate scenario simulations:

1) How large will the future emissions of greenhouse gases and sources of atmospheric particulate be?
2) How large a fraction of the emissions accumulate in the atmosphere. This is related also to interactions between the atmosphere, the oceans, atmospheric chemistry and the action of the biosphere. In the case of particles with short atmospheric residence times even the geographical distribution is likely important.
3) Given changes in the atmospheric content of greenhouse gases and particles, how large changes will occur in the radiative forcing?
4) Given changes in the radiative forcing, how sensitive will the climate system prove to be to such? How does this relate to natural variability in the climate system?
5) Even if the global climate system responses can be quantified in the large-scale sense, how certain can the regional and local assessments be made?

To deal with (1), work is conducted to extrapolate future emission scenarios from present trends and assumptions on future population growth, technological prospects, sociological considerations etc. The recent emission scenarios (IPCC 2000) span a wide range of these constraints and could be expected to cover the development that will actually take place.

To deal with (2), the ongoing improvements in the climate system description will enrich the understanding of the future net atmospheric concentrations. Simulations with different atmospheric loadings are also made to span some of the alternatives.

The (3) and the (4) relate largely to parameterizations in the climate models. It has long been understood that especially the treatment of radiation and clouds, as well as interfaces between the components of the climate system such as the atmosphere and the ocean are not well enough known. The use of a number of climate models with varying solutions to the parameterization problems is helpful in exploring the likely limits to the issues.

To address (5), regional modeling is helpful, but high quality global modeling is of course imperative to begin with.

To make any sense out of scenario simulations and to understand differences between different scenario experiments using different GCM forcing, it is imperative to understand how the driving GCMs perform. Ultimately, the variability in the scenario results using different GCMs will provide information on the uncertainty in a scenario. It is also found that RCA works more easily with some GCM than with another and this may provide clues for improving the models. Also, the match, or mismatch, between GCM and regional model is sensitive to how the lateral boundaries are treated, and different nesting strategies have been developed. Understanding regional aspects of global climate change is also very important, in order to understand what time slices to select for a scenario and how that choice affects the results.

In SWECLIM, studies on a larger set of GCM-simulations have been done to investigate some of the uncertainties listed above. Räisänen (2000) studies the results of several GCMs run with the same atmospheric future increases of greenhouse gases (cf. (1-2) in the above) in the second phase of the Coupled Model Intercomparison Project (CMIP2). The results therefore illustrate the uncertainty in climate simulations due to (3) and (4) of the above. The 12 atmosphere-ocean GCMs (that were available at the time) were forced by a gradual (1% per year compound) increase of atmospheric CO_2, up to a doubling during the simulations. The global mean and Nordic land area (Finland, Sweden, Norway and Denmark) mean changes in temperature and precipitation of these experiments are shown in Figure 32.

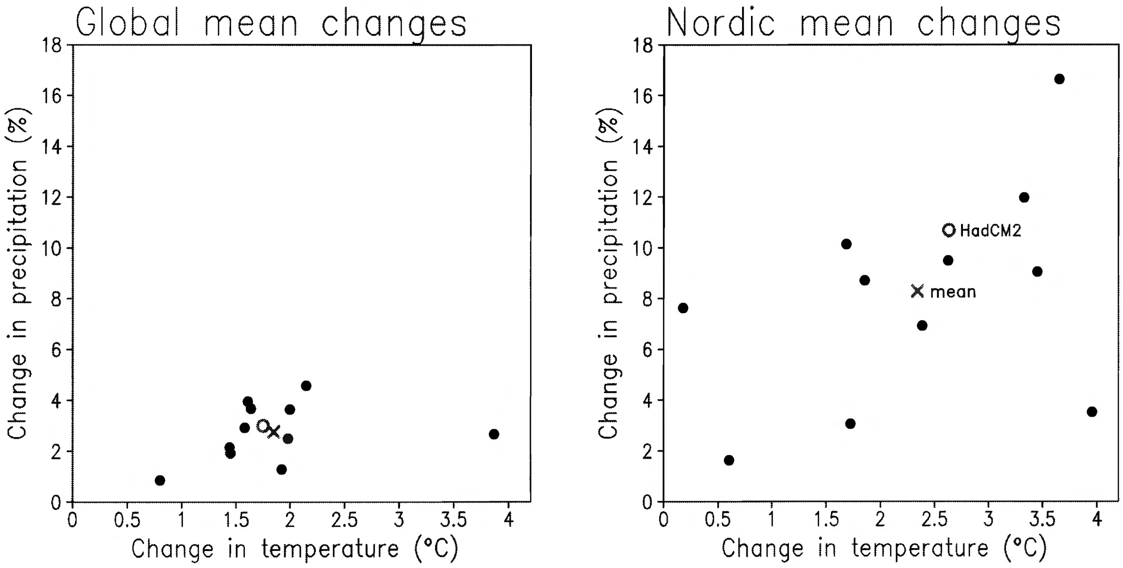

Figure 32. *Changes in annual mean temperature and precipitation in 12 global climate model simulations run with a gradual doubling of atmospheric* CO_2*. The left panel shows global mean changes and the right panel changes in the Nordic land area. A cross indicates the mean of the 12 models. One of these GCMs has also been used in the SWECLIM regional modeling (the HadCM2). Its CMIP2-results are labeled in the figure. The mean of the 12 models is also calculated and labeled.*

The scatter between these GCM experiments is substantial in the global mean and becomes even larger when the climate changes in the Nordic area are considered. Nevertheless, the trend of the global mean changes is the consistent warming and increasing precipitation in all experiments. This is the case even in the Nordic area, except for one experiment in which a cooling of the surface water in the northern North Atlantic virtually balances the warming caused by the doubled CO_2. Also seen is that the models generally indicate climate changes in the Nordic area to be stronger than the global mean changes.

The qualitative agreement between the 12 CMIP2 models indicates that regional model dynamical downscaling of CO_2-induced climate change in the Nordic region can be a meaningful exercise, even as only few GCMs can in practice be targeted in the regional modeling. However, the large quantitative inter-model differences stress the importance of trying to account for different GCM simulations in the regional assessments as a means of informing the users of climate scenarios of the scenario uncertainties.

Another aspect that can be illustrated with the CMIP2-results is the transient time evolution vs. the amount of simulated natural variability in the regional climate system in Northern Europe. This is illustrated with the time series of annual mean temperature change for the Nordic land area (Fig. 33).

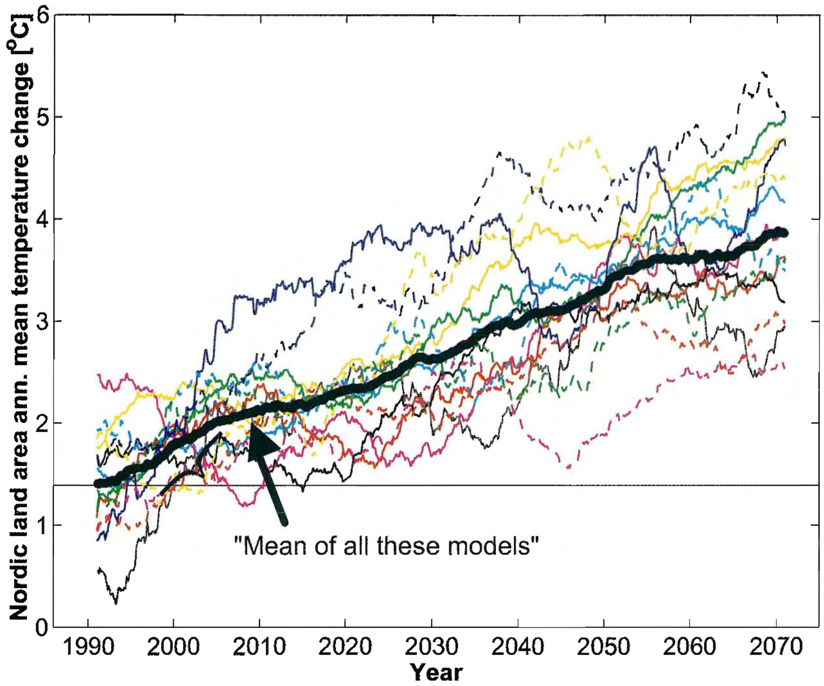

Figure 33. *The transient annual mean temperature change for the Nordic land area in a number of the GCMs participating in CMIP2. The different line colors and styles are for the individual model simulations. Note the varying but generally large amplitude of the 1-10 year variations. The heavy black line is for the inter-model mean transient change that averages over the different courses of the simulated natural variability in the models and bring out the forced climate change trend, i.e. climate warming due to the gradual doubling of atmospheric* CO_2.

As is obvious from Figure 32, the performance of the HadCM2 GCM is relatively close to the mean of the 12 other GCMs in terms of both the global mean and the Nordic mean temperature and precipitation changes. The other GCM of its results have so far been used in the SWECLIM regional modeling, the ECHAM4/OPYC3, was not available in the CMIP2 intercomparison for Räisänen (2000). These two GCMs (Johns et al. 1997, Mitchell and Johns 1997, Oberhuber 1993, Roeckner et al. 1999; note that SWECLIM has used the greenhouse gas -forced simulations rather than simulations including also sulfate aerosol effects) have been studied in additional detail. Note that SWECLIM uses another HadCM2-simulation than the one entered to CMIP2.

The HadCM2 and the ECHAM4 have a number of biases in their simulated control climates. For example, HadCM2 has a cold bias of 1-4°C in spring and summer in the Nordic area (see Räisänen and Döscher 1998). The simulated temperatures in ECHAM4 are slightly above those observed. ECHAM4 misrepresents the seasonal cycle of precipitation in the Nordic area (less precipitation in summer than in winter). The spectral orography in ECHAM4 makes the precipitation maximum associated with the Scandinavian mountains overly diffuse. Both of these models underestimate the north-south gradient in wintertime sea level pressure across Scandinavia and give a too weak westerly flow. Problems are likewise evident in the simulated conditions in the Baltic Sea and in the northern North Atlantic, the complete lack of ice in the Baltic Sea in HadCM2 being a striking example. ECHAM4 provides for more ice on the Baltic Sea but also rather large SST biases in some parts in the region. Nevertheless, although some of the biases are substantial, the HadCM2 and ECHAM4 control climates are both of a reasonably high quality. Relating these to the 12 GCM simulations in the CMIP2 suggests that all present GCMs suffer from similar or worse biases in aspects of their control climates (Räisänen 2000).

The HadCM2 and ECHAM4 global mean warming, defined as the 10-year mean difference between the scenario and control time slices obtained for SWECLIM, is 2.60ºC in HadCM2 and 2.65ºC in ECHAM4, even though the forcing used in the two experiments is different. In HadCM2, the scenario time slice has about a 150% higher CO_2 concentration than the control run time slice. In ECHAM4 the difference in the radiative forcing between the two time slices is roughly equivalent to a 100% increase in CO_2. The weaker forcing in ECHAM4 than in HadCM2 thus appears to be balanced by larger climate sensitivity in ECHAM4. These GCMs also indicate a similar annual mean warming (typically 3-4ºC) and increase in precipitation in (10-20%) in the Nordic area. Some differences are seen in geographical and seasonal details.

Due to the brevity of the 10-year time slices available for SWECLIM from HadCM2 and ECHAM4, climate changes inferred from the differences between these are to some part associated with model-simulated internal variability rather than with climate change (cf. Fig. 33). For HadCM2, the availability of the original century-long transient simulations allowed a quantitative study (Räisänen et al. 1999). The climate changes obtained as the difference of the two 10-year time slices were compared with the changes obtained by subtracting a 240-year control-run mean from a 110-year scenario run mean (50 years on both sides of the 10-year time slice). The two methods of calculation yielded (within two decimals) the same global mean warming, but in the Nordic area the increases in annual mean temperature and precipitation were smaller (by 0.6ºC and 4%) in the long runs than in the time slice. This was largely associated with the scenario run time slice being somewhat warmer and wetter than expected from the evolution in the long transient run. Nevertheless, the differences in the annual Nordic mean changes can be considered relatively small. As expected, however, the differences in the seasonal and geographical details of change were more pronounced, especially concerning precipitation.

Regime transitions and climate change. As already touched upon in the above, the regional climate of northern Europe is conditioned by the large-scale climate variations and changes. An important aspect is the existence of different persistent states in the large-scale flow in the Northern Hemisphere, as is observed. These recurring quasi-stationary states appear to have rapid onsets and breakdowns. The Pacific North American pattern (PNA), the North Atlantic Oscillation (NAO) and blocking episodes are some major examples. The frequency of atmospheric blocking over the eastern North Atlantic and western Europe plays an important role for the regional climate in Sweden. Studies with intermediate models have been used to look into the physical mechanisms responsible for these states of the large-scale flow. Multiple stationary flow equilibria have been created in models with orographic forcing. The synoptic-scale baroclinic waves and the shape of the sub-tropical jet have also been shown to be of importance.

The interest in such investigations in the climate change context is well explained by Palmer (1999). He hypothesizes that the primary response of the climate system to a small forcing (such as the increase in greenhouse gases) might be a change in the residence frequencies of sectorial persistent states of the atmosphere, such as regional weather regimes, without necessarily affecting the geographical structure of these states. If true, this would guide both the analysis of observations and modeling for identifying signs of forced climate change and the improvement priorities of GCMs.

To build on the ideas in Palmer (1999), a study of blocking frequency and the frequency of transitions between persistent states is included in SWECLIM. So far, analysis has been performed on the two 10-year time slices imported from HadCM2 GCM (Thor 1999). No significant differences in the blocking frequency was found between the control and scenario time slices. However, significant differences in the frequency of transitions between persistent states were found between the two periods, see Figure 34. This agrees with the hypothesis that an increased greenhouse forcing would change the residence frequencies of the persistent states of the large-scale circulation (exhibiting a rather non-linear character).

However, the physical mechanisms responsible for the differences in residence frequencies apparently induced by the increase of CO_2 have not been deduced. Changes in one or more of the physical mechanisms may be responsible. The changes in transition frequency found in the present study may be resulting from a change in the spatial organization of the baroclinic eddies, as an increase in the westerly flow in the subtropics has been noted in response to the increased greenhouse gas forcing in the HadCM2. These ideas will be further pursued in SWECLIM by analysis of other GCM data and by quasi-geostrophic 2-3 layer atmospheric modeling tool.

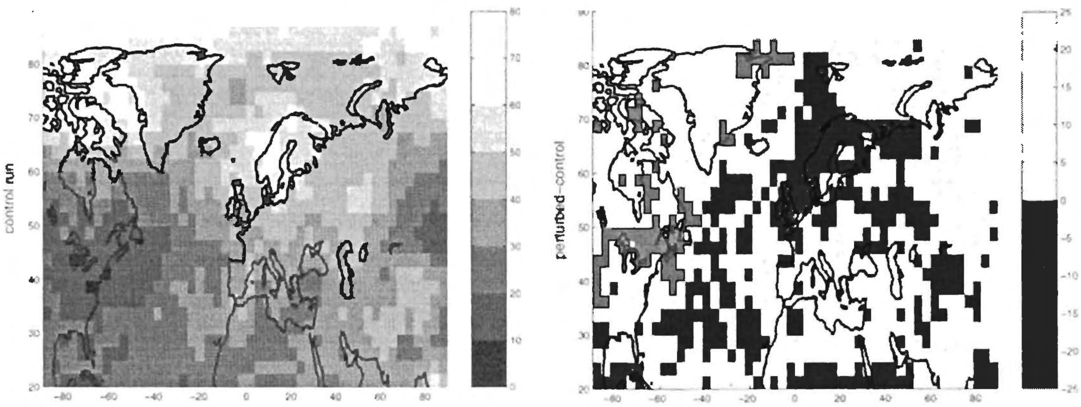

Figure 34. *The number of transitions between persistent states within the 10-year set of HadCM2 data used in SWECLIM. The number of transitions during five years of the control run time slice is shown in the left panel, showing the region of high blocking frequency accompanied by a large number of transitions over Scandinavia and north-western Siberia. The difference between the control run and the scenario periods is shown in the right panel. Significant differences are shown in two shades of gray. White indicates insignificant differences.*

2.6 Impact analysis and cooperation with external groups

To demonstrate the possible impacts of climate change in Sweden, concretization of the effects with impact studies is needed. Explicitly within SWECLIM, water resources impact studies are made. In cooperation with external user groups, impact studies on forest growth potential and risks, traffic on land and on sea, soil frost conditions (e.g. of relevance to construction of buildings and roads) and glaciers (of relevance to tourism, ecology) and storms (e.g. of relevance to insurance companies).

Water resources scenarios

The water resources scenarios are one example of impact studies based on the regional climate scenarios. This issue has great societal and economic dimensions. The water resources aspect of climate change impacts is not new (e.g. Nemec and Schaake 1982, Gleick 1987, Bultot et al. 1988, Lettenmaier and Gan 1990, Nash and Gleick 1991, Cohen 1991, Vehviläinen and Lohvansuu 1991). However, the parameterization of evapotranspiration and feedback mechanisms to water losses from increasing CO_2-concentrations has not been really been addressed (cf. Martin et al. 1989, Lockwood, 1999) and the interface between climate data/scenarios and the hydrological models is typically not sufficiently refined (Bergström et al. 2000b). These issues are addressed in SWECLIM.

The Nordic perspective on climate change impacts on water resources has much in common with the rest of Europe, although focus is more on hydropower production and less on water supply. Flooding, physical planning and dam safety are common issues, as are the water related problems of the environmental sector and the Baltic Sea. In the Nordic countries the Finnish SILMU project (Roos 1996) is probably the most comprehensive study on climate change impacts. Related to the water resources the joint Nordic study on Climate Change and Energy Production (Sælthun et al. 1998) is a very complete one.

The task to derive water resources scenarios from regional climate scenarios is not trivial. A logical step would be to feed the hydrological model with direct model output from the regional climate scenario. However, as GCM-simulations and subsequently regional scenarios forced by them exhibit biases in e.g. the regional seasonal cycle of precipitation and in some cases the annual precipitation total, the use of direct output from the climate model would lead to an unrealistic hydrological control run. For the time being, a strategy has been adopted where climate change impacts on water resources are simulated by a hydrological model imposing differences between the control run and the scenario run on observed time series of driving variables, instead of absolute values from the respective runs. (Fig. 35).

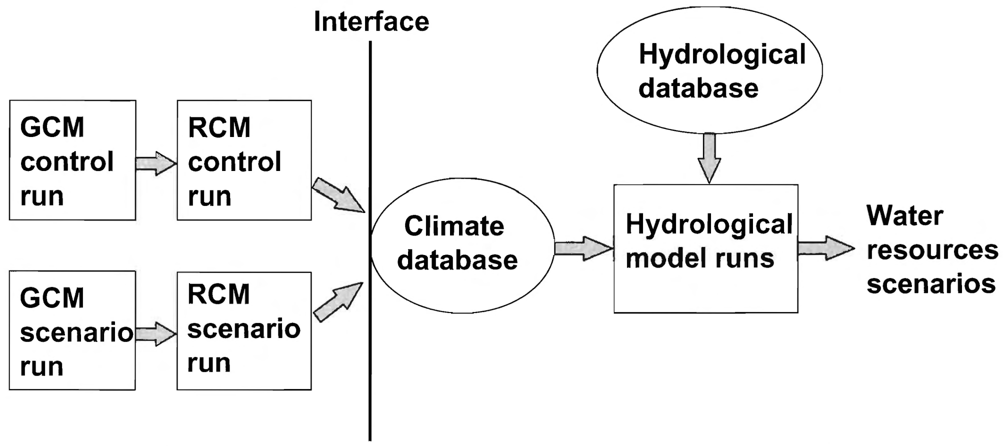

Figure 35. *Schematic presentation of a strategy for simulation of water resources scenarios from General Circulation Model (i.e. global climate model) (GCM) simulations starting and regionalization with regional climate models (RCM).*

To rely on the simulated relative changes can be used to bypass biases (compared to observed statistics) in the climate simulations. This leads, however, to a potentially dangerous simplification if the same relative changes are assumed for extreme values as for the average conditions or when it is assumed that the number of days with precipitation stays the same under a changing climate. Extremes and variability, however, might react differently, compared to the mean climate. An example of the possible complexity of responses in near-surface temperature and daily precipitation is shown in Figure 36, based on RCA1-results.

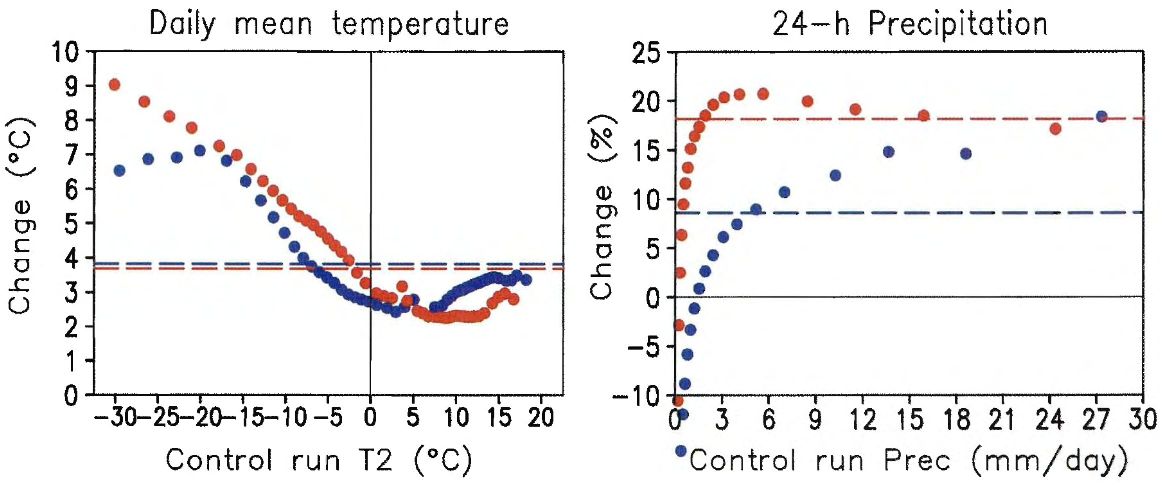

Figure 36. *Analysis of the regional climate change in* *<u>left</u>: near-surface air temperature and* *<u>right</u>: 24-hr precipitation in the two latest SWECLIM scenarios (RCA1-44H: red, RCA1-44E: blue). The calculated changes (markers) are given for a wide range control run values spanning the winter and summer periods throughout Sweden. The annual mean changes are indicated with the dashed horizontal lines. In case of temperature, the winter range of control run values spans from below -30°C to +5°C. The lowest temperatures rise much more than the higher ones and to use even the seasonal mean change would underestimate the former and overestimate the latter.*

The results from the hydrological modeling include, first and foremost, the impacts to river runoff including extremes. In the case of regional warming, these can be pronounced in areas where snow accumulation and melt dominate the present regime. The impacts on soil moisture content and groundwater recharge and storage are other important aspect where a contribution can be made.

The "evapotranspiration problem". Compared to how evapotranspiration is modeled in hydrological applications for the present climate, there is uncertainty in how it should be modeled in climate scenarios. This is a topic SWECLIM works on (Bringfelt 1998, Gardelin and Lindström 1997). The following questions should be addressed (Gardelin 1999a):

- How to create a climate sensitive parameterization for hydrological models? How to validate such a parameterization?
- What use can be made of present-day observations of evapotranspiration in various climates? What use can be made of the evapotranspiration changes in climate models?
- Shall, or can, vegetation and other land use changes in the future be accounted for? How to treat feedback to evapotranspiration from increasing CO_2?
- How to estimate the uncertainty in the estimates of evapotranspiration in climate scenarios?

For example, rather than using the routines in the HBV model that depend on temperature alone, the relative changes in evapotranspiration can be taken from the climate scenarios. In addition, more physically based routines in the hydrological model rather than empirical ones should be aimed at. A strategy for the calculation of evapotranspiration in the SWECLIM water resources scenarios is given in Table 2 (see also Gardelin 1999b). So far the methods A and B have been used. Feedback from increasing CO_2 to plant use of water and thus evapotranspiration has not yet been considered.

Table 2. *Estimation of evapotranspiration in water resources scenario simulations with the HBV. PET=potential evapotranspiration, AET=actual evapotranspiration.*

	Today's climate	**Future climate**
A. Temperature index method	PET calculated with temperature index method (simplified Thornthwaite type). AET calculated with LP function in HBV model.	Difference in temperature between today's and future climate in RCA model used for calculation of future PET with temperature index method. AET calculated with LP function in HBV model.
B. Penman method	PET calculated with Penman method (monthly mean values). AET calculated with LP function in HBV model.	Difference in AET between today's and future climate in RCA model applied as a difference in PET in HBV model. AET calculated with LP function in HBV model.
C. RCA model PET	PET from RCA model (monthly mean values). AET calculated with LP function in HBV model.	PET from RCA model (monthly mean values). AET calculated with LP function in HBV model.
D. RCA model AET	AET from RCA model used as input data to HBV model together with temperature and precipitation.	AET from RCA model used as input data to HBV model together with temperature and precipitation.

Results from the hydrological scenario simulations are presented as future changes in the seasonal variation of runoff, snow storage, soil moisture and ground water storage. Long time series of annual runoff and snow storage for future climate are compiled as well as changes in extreme values and frequency analysis of annual and seasonal floods.

Test catchments and data sets. Experience from previous projects has shown that it is important to have an efficient modeling production system when a number of scenarios are planned for. Therefore it was decided to develop a standard set of drainage basins, where every new climate simulation easily can be transformed into a water resources scenario. Altogether 16 basins were identified, of which 6 are considered of prime interest and the remaining 10 can be used for more detailed studies if needed (Eklund 1999). The six primary basins are from north to south (Fig. 37): Suorva in Stora Luleälv, Kultsjön in Åseleälven, a tributary to Ångermanälven, Torpshammar in Gimån, a tributary to Ljungan, Höljes in Klarälven, Blankaström in Emån and Torsebro in Helge å.

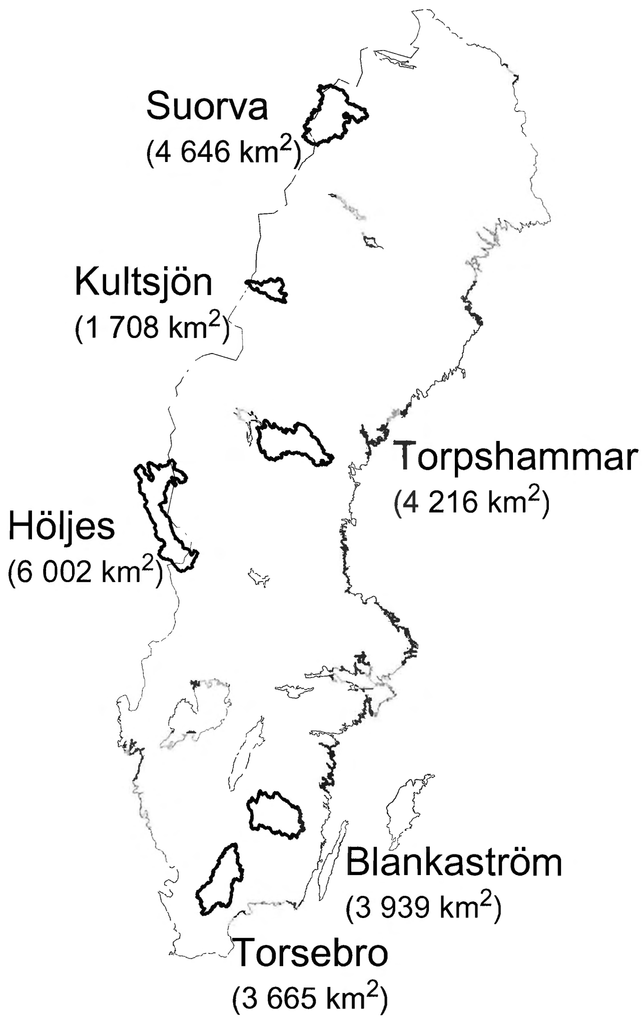

Figure 37. *Six primary test basins .*

The first four basins are of special interest for the hydropower industry although there are power plants in all six rivers. The Suorva reservoir is the most important one in the Swedish hydropower system, with a storage capacity of 6 km^3.

The entire drainage basin to the Baltic Sea has also been studied in SWECLIM. The total land area of the Baltic Drainage Basin covers approximately 1.7 million km^2 and includes territories from altogether 14 nations with more than 80 million inhabitants. Of environmental significance are also some major cities in the basin such as St. Petersburg, Helsinki, Tallinn, Riga, Vilnius, Warsaw, Copenhagen and Stockholm, among others. River runoff to the Baltic Sea has been identified as one of the key factors influencing its ecosystem so water resources scenarios are of high environmental relevance. The Baltic basin is also identified by the World Climate Research Programme as a continental-scale study area for the understanding of the energy and water cycle. This work is carried out under the framework of the BALTEX program. Within NEWBALTIC the HBV model has been set up for the entire Baltic basin (see Figure 38) as a foundation for validation of climate models (Graham 1999a).

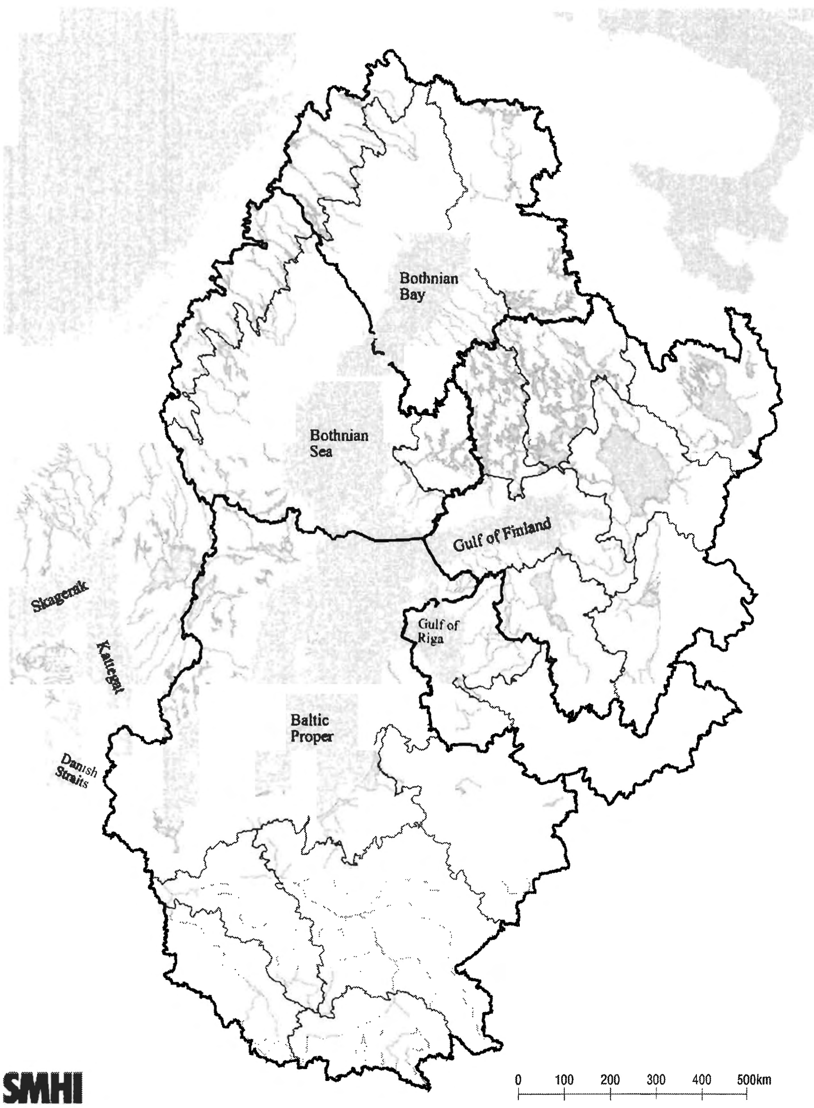

Figure 38. *Subbasins in the application of the HBV model to the Baltic basin (cf. Graham 1999a).*

Water resources scenarios. When the first regional scenarios (RCA0) became ready, it was obvious that some processing was needed before the water resources applications. Otherwise the monthly climate change anomalies would have varied excessively. For the six smaller basins, monthly values from the regional scenarios were smoothed to 3-monthly average running mean values. Average monthly temperature and anomalies precipitation averages were used for the entire Baltic basin. All the monthly anomalies were averaged over the 10-year period, thus creating a standard set of 12 monthly values.

The first four of the scenarios for Suorva, Kultsjön, Höljes and Torsebro were based on the first regional climate scenario from the Rossby Centre (RCA0) and published in the annual report of SWECLIM (1999). They are shown in Figure 39, together with curves from the Nordic project on Climate Change and Energy Production.

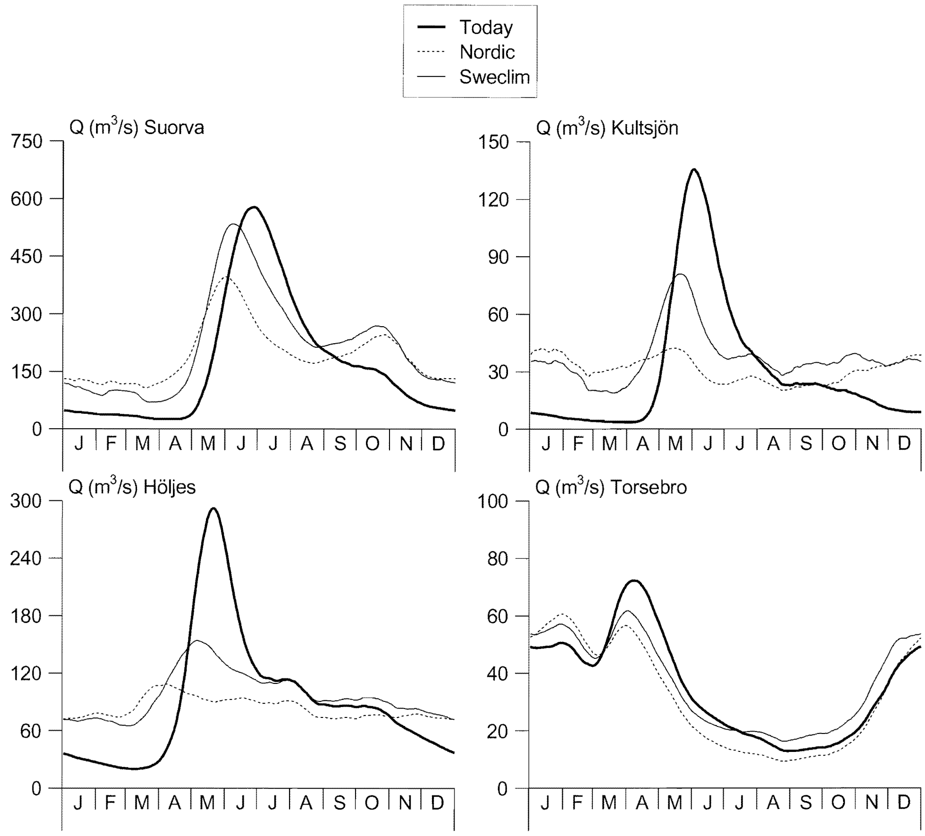

Figure 39. *The annual cycle of river runoff in four test basins today and after some 100 years according to the first regional climate scenario from the RCA0-scenario and the Nordic project on Climate Change and Energy Production. Evapotranspiration is calculated according to method A in Table 2. The curves are smoothed.*

Figure 40 shows a more complete presentation of six simulations based on the second and third climate simulation (RCA88-H and RCA88-E) with a coarser resolution of 88 km and the two ways of parameterizations in the hydrological model. The results are also summarized in Table 3.

Table 3. *Relative average changes in runoff in the six test basins according to the two RCA1-88 regional climate scenarios and the two versions of the HBV model (%).*

	HBV-a	HBV-b
Suorva RCA88-H	+25	+30
Suorva RCA88-E	+23	+28
Kultsjön RCA88-H	+13	+23
Kultsjön RCA88-E	+11	+22
Torpshammar RCA88-H	+10	+38
Torpshammar RCA88-E	-19	+2
Höljes RCA88-H	+0.8	+14
Höljes RCA88-E	-1	+12
Blankaström RCA88-H	-41	-10
Blankaström RCA88-E	-38	-21
Torsebro RCA88-H	-21	+3
Torsebro RCA88-E	-26	-11
Mean	-5	+11

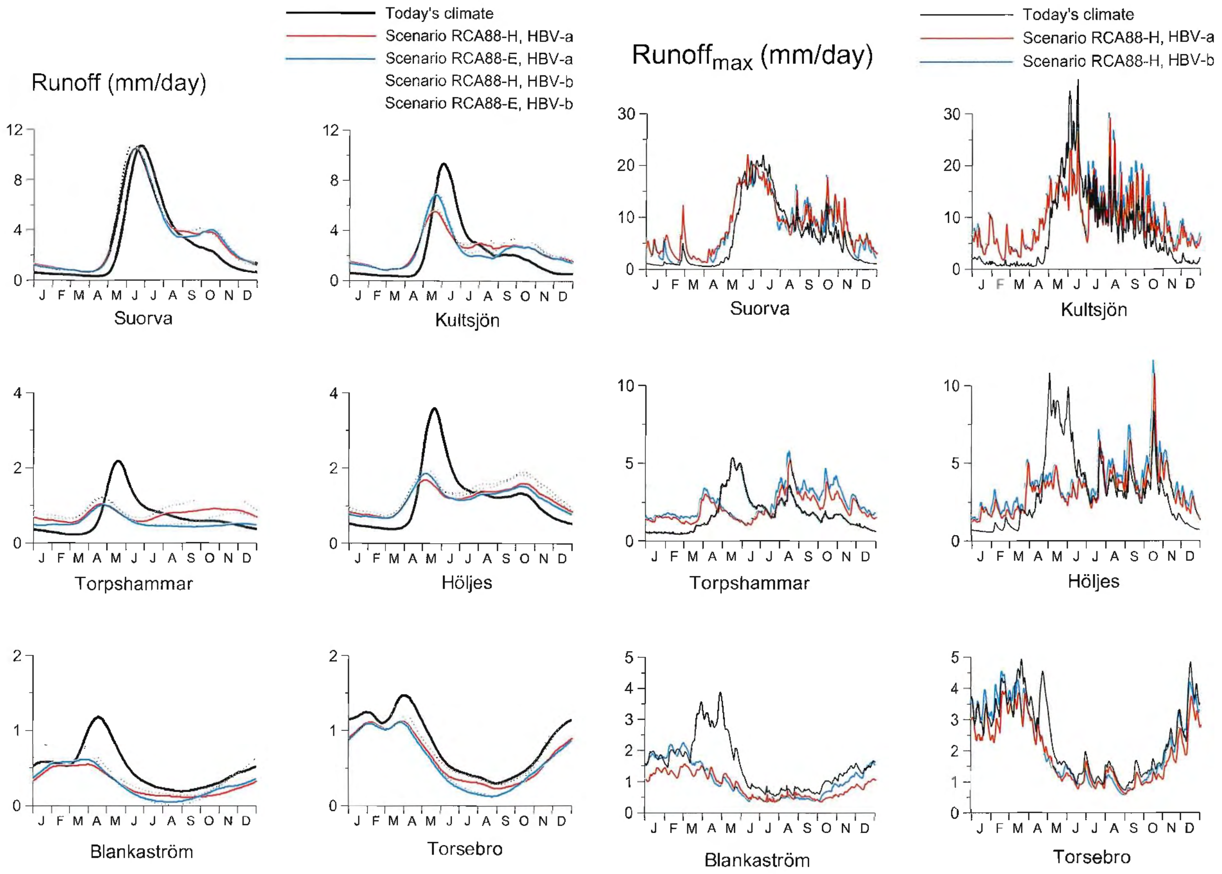

Figure 40. *Left: the annual cycle of river runoff in six test basins today and according to the RCA1-88H and RCA1-88E scenarios and two versions of the HBV model (HBV-a and HBV-b). The curves have been smoothed. Right: the annual cycle of extreme daily runoff in six test basins today and according to the RCA88-H scenario and two versions of the HBV model (HBV-a and HBV-b).*

The simulations carried out so far confirm the dramatic effects on the stability of winters we can expect from a global warming (cf. Saelthun et al. 1998). The spring floods tend to be less dominant and during winter melt periods generate water that adds on the presently low flows in winter. Worth noting is also the strong decline in low flows according to the HBV-a scenario in the southern basins, which is a combined effect of low precipitation and increased evapotranspiration. The timing of extreme values shows a tendency to shift from spring to winter in the north. This is a significant feature as winter floods are often critical; they may occur when reservoirs are full and without capacity for flow dampening. Although maximum snow storage generally declines in all basins there may be an increase for individual years. The reason is that solid precipitation anomalies sometimes can dominate over increased melt due to warming.

Statistical analysis of water resources scenarios. Extreme values can be calculated with so-called frequency analysis and expressed as e.g. 100-year floods. This means flooding that on the average would take place once in a century. Statistical analyses of daily peak flows have been made separately for spring flows (Jan-July) and for summer-autumn flows (Aug-Dec). Results based on conventional frequency analysis according to the Gumbel probability distribution function are shown in Figure 41.

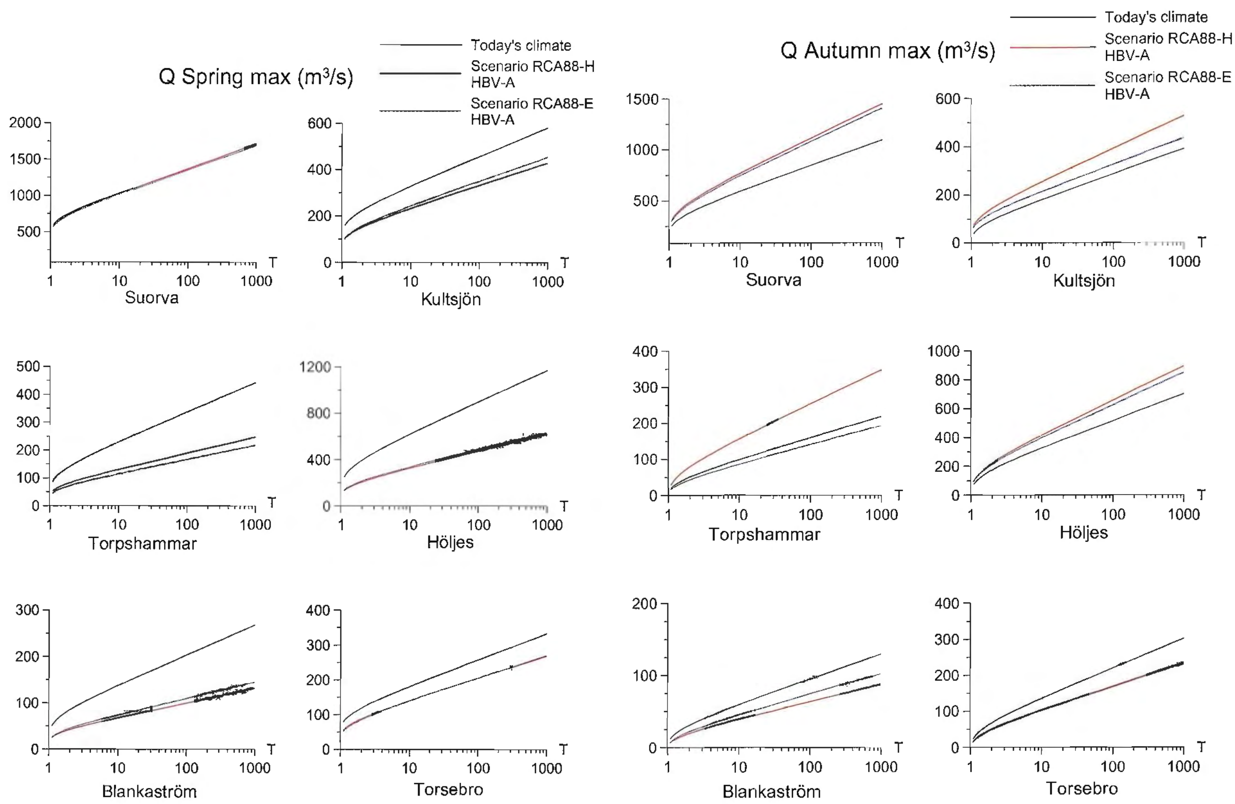

Figure 41. *Frequency analysis of (left) spring and (right) autumn floods for six test basins, using RCA1-88 and HBV-a. T denotes return period.*

Tables 4 and 5 list the relative changes of the magnitudes of the 100-year spring floods and summer-autumn floods respectively in the future climate. Also shown are the return periods of the present-climate 100-year flood in the future climate according to the scenarios. The analyses indicate decreasing annual flood risks (not shown), mostly related to decreasing spring floods. The impact on simulated summer and autumn floods is an increase in the north and decrease in the south. If this becomes reality it will have significant impact on the frequency of spillways to be activated. It is, however, important to bear in mind that the analysis is still based on very short records of simulated climate change (10 years) interpreted via a 30 years hydrological simulation.

Table 4. *Estimated change in the 100-year spring flood (Jan-July) based on the RCA1-88s and HBV-a/b.*

	Change in 100-year spring flood (%)		*Return period of today's 100-year spring flood under the scenario conditions*	
	HBV-a	HBV-b	HBV-a	HBV-b
Suorva RCA88-H	+0.5	+0.4	100	100
Suorva RCA88-E	-0.5	-1	110	110
Kultsjön RCA88-H	-28	-25	>1000	>1000
Kultsjön RCA88-E	-24	-22	>1000	870
Torpshammar RCA88-H	-44	-37	>1000	>1000
Torpshammar RCA88-E	-51	-46	>1000	>1000
Höljes RCA88-H	-48	-44	>1000	>1000
Höljes RCA88-E	-46	-43	>1000	>1000
Blankaström RCA88-H	-51	-35	>1000	>1000
Blankaström RCA88-E	-46	-32	>1000	>1000
Torsebro RCA88-H	-21	-7	700	170
Torsebro RCA88-E	-20	-8	640	190

***Table 5.** Estimated change in the 100-year summer-autumn flood (Aug-Dec) based on the RCA1-88s and HBV-a/b.*

	Change in 100-year summer or autumn flood (%)		*Return period of today's 100-year summer or autumn floods under the scenario conditions*	
	HBV-a	HBV-b	HBV-a	HBV-b
Suorva RCA88-H	+31	+36	20	10
Suorva RCA88-E	+27	+32	20	20
Kultsjön RCA88-H	+36	+48	20	10
Kultsjön RCA88-E	+13	+28	50	20
Torpshammar RCA88-H	+58	+82	10	5
Torpshammar RCA88-E	-12	+7	240	70
Höljes RCA88-H	+27	+40	30	20
Höljes RCA88-E	+21	+35	30	20
Blankaström RCA88-H	-33	-5	>1000	140
Blankaström RCA88-E	-22	-2	550	110
Torsebro RCA88-H	-23	-8	600	170
Torsebro RCA88-E	-24	-12	670	230

Development of the interface. The presently used technique in the interface between the regional climate model and the offline hydrological simulations is a great simplification, which risks to smooth variability. A way to overcome such interface problems would be to fully integrate the hydrological model into the climate model to perform the calculations online. This, however, requires some further development of both climate and hydrological models. Meanwhile, improvements in the interface technique can be made to ensure that variability and extremes are better represented. For example, a more developed transfer of the driving data from the regional climate scenarios to the hydrological modeling has now been used. The result that the warming in the regional climate scenarios is stronger for low temperatures than in the mean temperature (see Figure 36 has in been explicitly taken into account in the latest hydrological scenarios by the introduction of a temperature-dependent increase of the base temperature used in HBV-runs. Another important difference between the hydrological simulations based on RCA1-88 and on RCA1-44 is the spatial extraction of meteorological variables from the RCA model. From the RCA1-44 simulations, the changes in the meteorological variables that are then superimposed on the hydrological database in HBV have been integrated over larger regions to reduce such fine-scale structures than can best be ascribed to noise. In Figure 42 the effect of these changes in the interface on river runoff is illustrated. These results indicate a smaller effect on snowmelt and consequently the decreases of the spring floods in the northern basins compared to the results based on the RCA1-88 simulations and the earlier interface.

The use of various climate scenarios (different GCM-simulations, different versions of the RCA regional climate model and different formulations of the HBV hydrological model) has given information on the uncertainties in the water resources scenarios. The general shift in the runoff regime is consistent in all the scenarios, but uncertainties generally grow with an increasing role of local precipitation and evapotranspiration. Consequently the greatest relative uncertainties in the regional analysis are found in the south, where the evapotranspiration is high and the runoff coefficient is low.

There are still open questions in the evapotranspiration treatment. Significant differences are seen between the two simulations with different methods of estimating evapotranspiration. Addressing this will be important on the coming off-line water resources scenarios, in particular for southern Sweden.

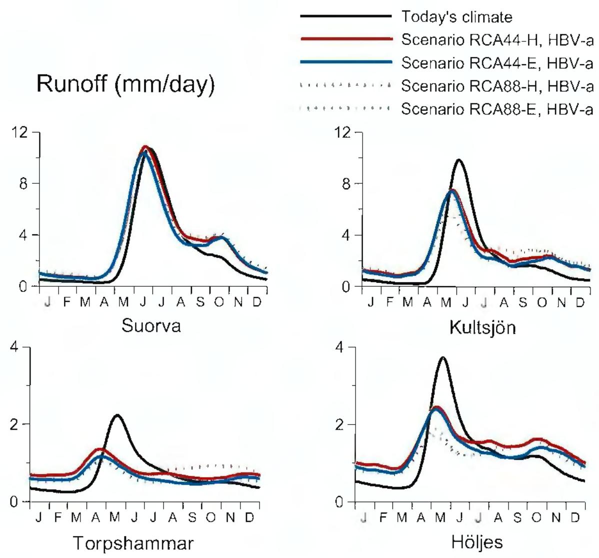

Figure 42. The annual cycle of river runoff in four test basins according to the RCA1-88 and RCA1-44 scenarios.

Water resources simulations in the Baltic basin. The first water resources scenarios for the entire Baltic drainage basin were based on RCA0 (SWECLIM 1998, Graham 1999b, Graham 1999c). Scenarios based on RCA1-88 followed (Graham et al. 2000). The final water resources scenarios of phase 1 were with RCA1-44, applied with a temperature dependent increase of temperature (Graham and Pettersson 2000). Figure 43 illustrates results for the annual river discharge for observations, modeled present conditions (HBV-Baltic) and modeled scenarios for RCA0, RCA88-H, RCA88-E, RCA44-H and RCA44-E.

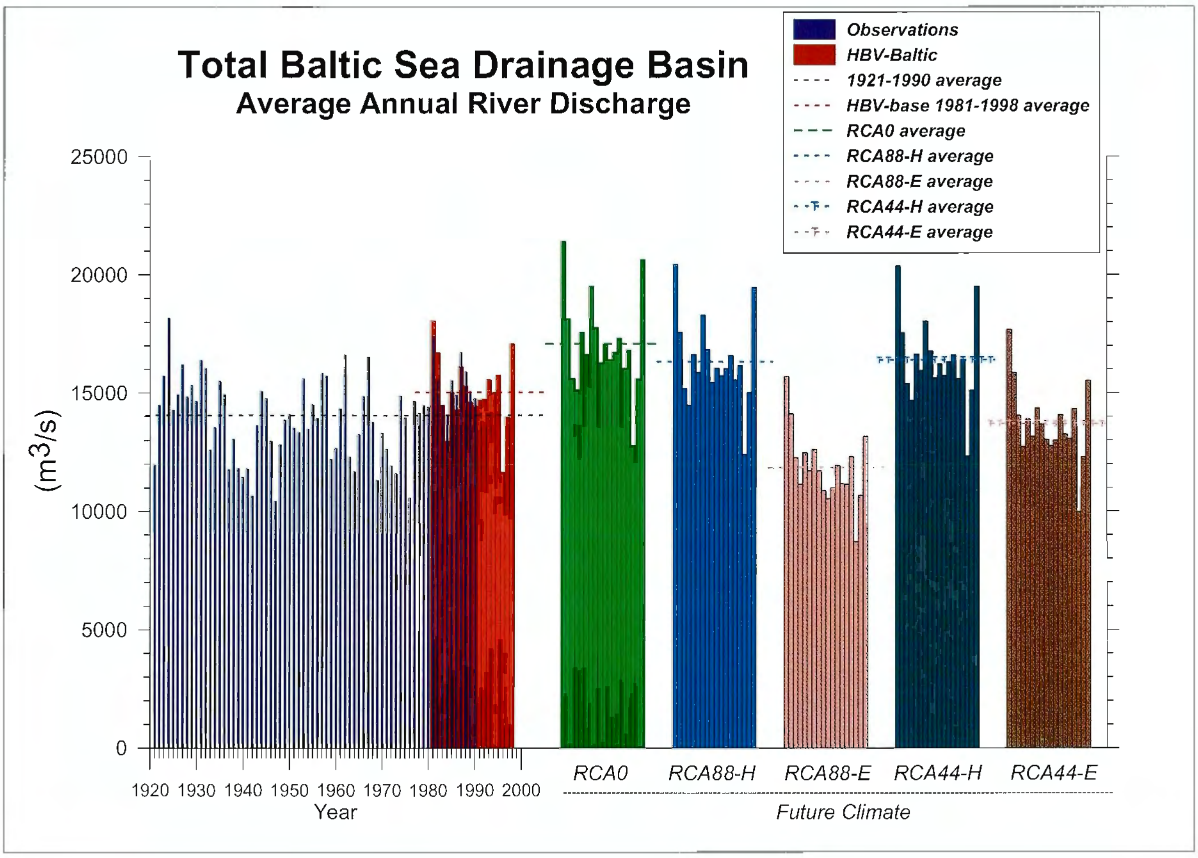

Figure 43. Observed and modeled average annual river runoff to the Baltic Sea and modeled future climate conditions according to RCA0, RCA1 at 88 km resolution and RCA1 at 44 km resolution with temperature dependent changes; all using HBV-A.

The modeled increase in river discharge is considerable for the Hadley Centre forcing runs (RCA0, RCA88-H and RCA44-H). The ECHAM4 forcing results in a decrease in total river discharge. However, this decrease is not as severe for RCA44-E where the scenario temperature change was applied as a function of temperature. The seasonal results from the RCA1-44 scenarios are presented in Figure 44 for the five main drainage basins of the Baltic Basin. This figure demonstrates how a warmer climate will change the snow regime (particularly in the north) such that runoff occurs more regularly over the year. It also shows the largest differences between the two (global model forcing) cases to occur in the southern region of the Baltic Basin.

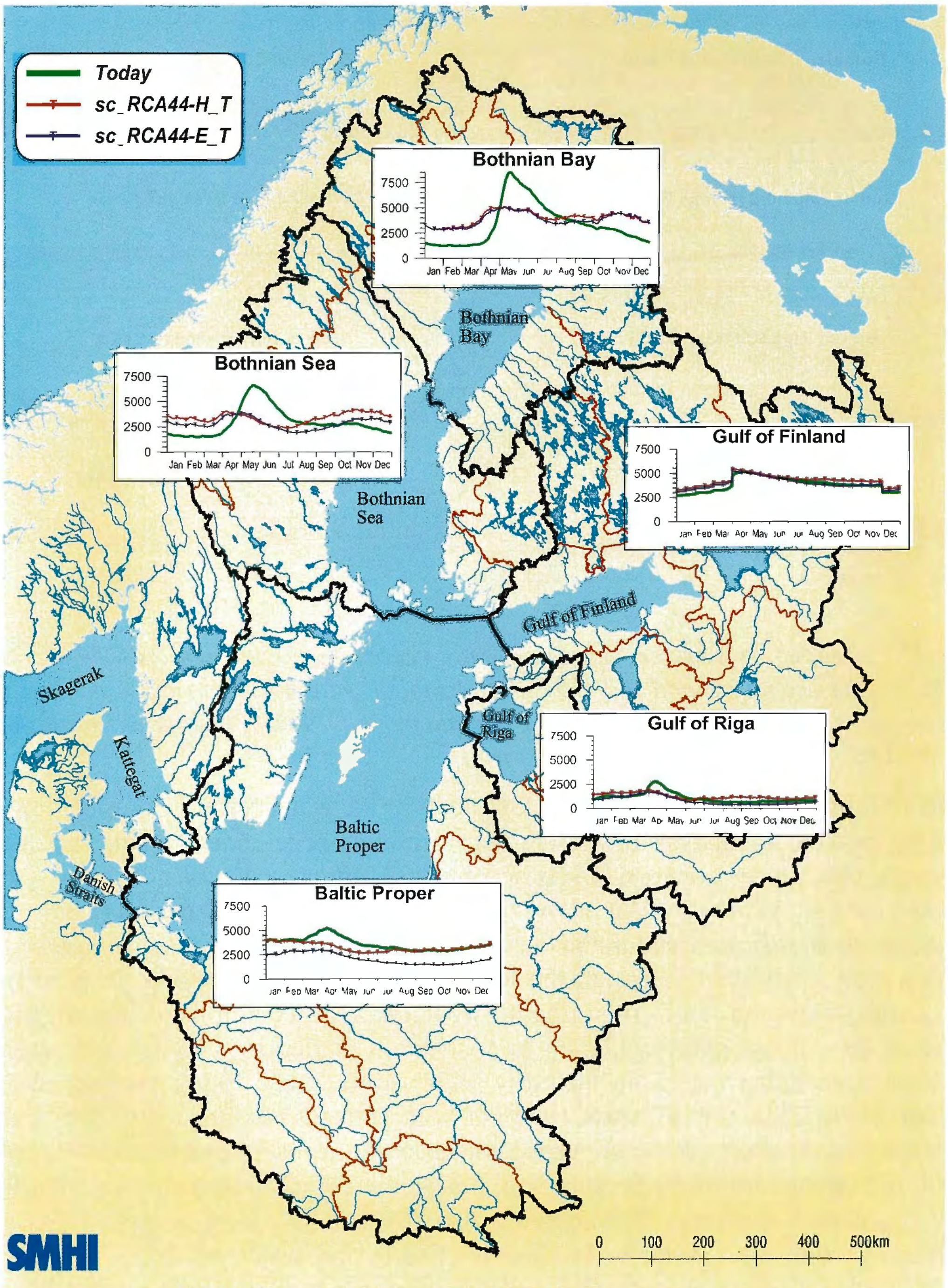

__Figure 44.__ Modeled average seasonal river runoff to the Baltic Sea for present and future conditions according to RCA1-44 runs with temperature dependency and HBV-A.

Figure 45 presents an analysis of changes in extreme runoff to the entire Baltic Sea per main drainage basin, based on the RCA1-44 runs and the temperature dependency on the temperature change. The right panel shows results with Hadley-based scenario forcing and the left panel with ECHAM4-based case. The results indicate that both changes in the maximum floods and a shift towards more severe autumn and winter floods can result if these climate scenarios are realized.

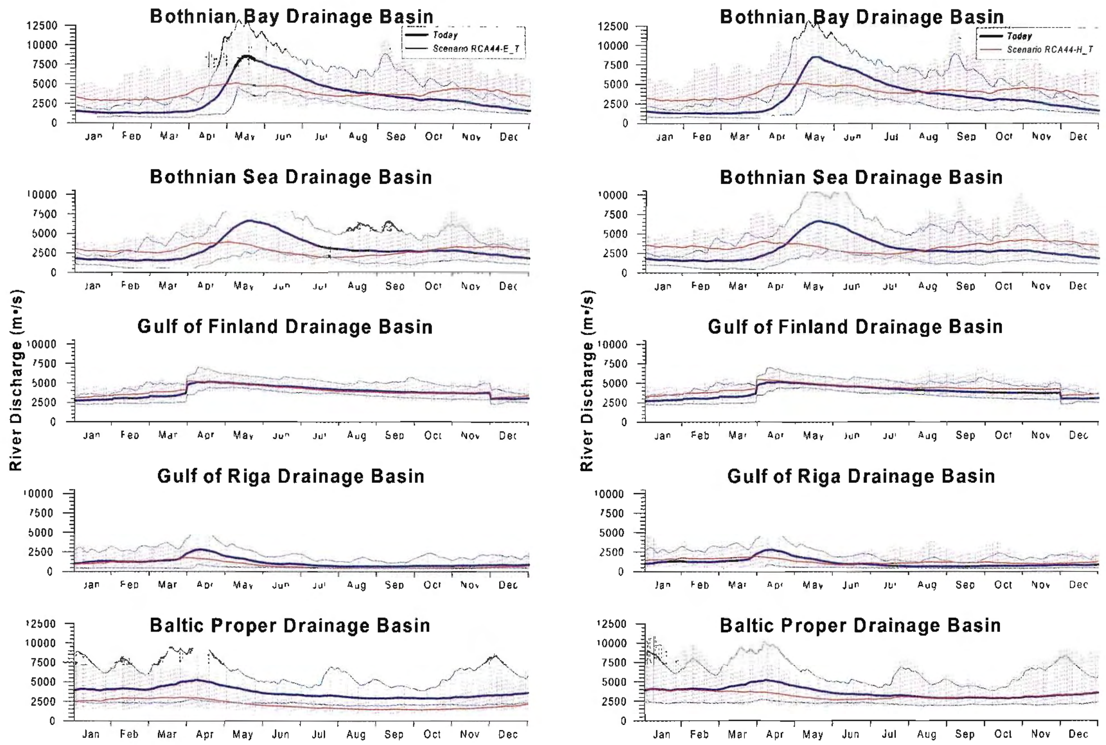

Figure 45. *Changes in extreme runoff regimes according to the* <u>*Left*</u>*: RCA44-E and* <u>*right*</u>*: RCA-44H scenarios and the HBV-Baltic model. In addition to daily means, the highest and lowest daily values are shown for the period 1981-98 ("today": blue), and for the RCA44 scenario simulated changes (red).*

Analysis of long runoff records. The task to analyze the water resources simulations is put into perspective by analysis of present-day variability. The climate change message can be made much more concrete if it is accompanied by presentations of the past and present-day climate variability. An analysis of extreme hydrological events (Lindström 1999) shows no significant trend in the occurrences of hydrological extremes in Sweden over the period 1910-1995, although the long-term fluctuation is strong. In particular the variability in autumn floods in northern Sweden has caused confusion and triggered a debate on the role of river regulation in connection to floods. Summer and autumn floods have been rather rare from the early 1960s to the early 1980s (Bergström and Lindström 1999). Thus the spillways have not been activated so frequently during this period. Some recent summer flood events, for example in the summers of 1993, 1998 and 2000 did cause a lot of media attention, but they were more of a confirmation that the situation is back to normal than anything else. It seems like the physical planning is in disharmony with the natural variability of climate and water resources. The input from SWECLIM as concerns natural variability of extremes was also important for the synthesis of problems related to floods in regulated rivers (Bergström 1999). This information was very helpful during the intense media communication after the summer floods of 2000.

Forestry

Another impact area that has been looked into is forestry, by external groups using the SWECLIM scenario results to study impacts on forest growth and risk of windthrow. Temperature, surface water balance, frost occurrence during spring, length of the growing season, sum of solar radiation during the growing season and wind conditions are taken into account. Rather marked changes can potentially occur. In particular, Bergh et al. (1999) modeled relative in forest production of spruce and pine in Sweden, using the first SWECLIM scenario from 1998 (RCA0). They saw increases of the order of 20% in a large part of central Sweden. Even larger (smaller) increases were seen along most of the coastal regions and in strips along the fjells to the west (inland in southern and northern Sweden). In the northern parts, production increases were found to be due to lengthening of the growth season and increasing total of solar radiation received by the trees during this period. In the very south, increased surface humidity contributed a lot. Effects such as changes in nutrient availability (due to increased soil temperatures, and more CO_2 in the atmosphere) or changed patterns/risk of windthrows, forest fires or harmful insect populations were not included.

In Sykes and Prentice (1999), effects of climate change on forests in Sweden were studied, using results from some global models simulating future warming. Deciduous tree species were noted generally to possibly push their northern growing limit further to the north. Ina addition, they possibly might compete more with pine where the latter otherwise would not be harmfully affected by the changes in climate. Increasing difficulties for spruce in southern Sweden was found, as it would be subjected to temperatures above freezing in winter and thus loose the winter rest period it requires.

It is hoped that the forest industry will become more interested in this type of climate change study as they become increasingly aware of the results.

Traffic

The Finnish Meteorological Institute has used the SWECLIM scenarios to look into possible impacts on shipping on the Baltic Sea (ice climate) as well as road maintenance (snow and soil frost) issues (Tuomenvirta et al. 2000, Venäläinen et al. 2000a, 2000b, 2000c). The analyses on soil frost and snow bear importance also for forestry and construction.

Glaciers, storminess and information/education

Scenario data from SWECLIM have also been delivered for glacier-studies (Oerlemans et al. 1999) and studies aimed at winds and storm frequencies (Lars Barring, Lund University, personal communication). In addition, scenario results have been discussed and provided for students, public servants, media and politicians.

2.7 Education within the program activities

In a research program like SWECLIM the education aspect takes a special role. At the onset of Phase 1, it was recognized that the Swedish competence on the topics addressed by the program was not well secured. A striking illustration of this was the difficulty of recruiting scientists early in Phase 1. Even though several tens of applications were received for the Rossby Centre positions, very few of the Swedish applicants could compete with applicants from other countries. The final outcome was that many of the positions at the Rossby Centre were filled with foreign applicants. In particular the positions requiring a post-doctoral level research scientist could only be filled with foreign scientists. The program research education goal formulated already in Phase 1 reads:

> *"To secure and improve long-term Swedish competence on the climate modeling and climate change issues".*

This includes education and lifting of competence of scientists on all levels, but in particular of the involved PhD students and young postdoctoral scientists. In the early Phase 1 planning there was a special subprogram devoted to education, but following the recommendations of an external review group the activities became incorporated into the other subprograms. One very important aspect of the education in SWECLIM is that it should build bridges between the three main subjects involved in the research: hydrology, meteorology and oceanography. This has certainly been the case!

Three main activities form the essence of the SWECLIM research education:

- Involvement of PhD students and young postdoctoral scientists
- Annual PhD-student-level summer courses
- Researcher-level workshops and seminars.

Within Phase 1, there were SWECLIM-resources for two PhD studentships at the universities. Theses were worked on also at the Rossby Centre. In addition, a number of university-financed PhD students were involved in the research, leading into three dissertations so far. SWECLIM will continue to finance PhD students in the same manner.

In Phase 1, SWECLIM arranged yearly PhD summer courses at Bornö with students from university departments for hydrology, meteorology, physical geography and oceanography. The courses had special climate-change related themes. A number of highly rated international and Swedish scientists were engaged to give the lectures. So far, courses on "The water cycle and its impact on the climate of the Earth" and "Ocean-atmosphere interaction at planetary scales and climate variability" have been arranged.

These courses will continue during the continuation of SWECLIM. The next course is scheduled to take place in 2001, under the theme of "Detection of climate change".

SWECLIM has regularly arranged workshops and seminars with invited scientists from different countries. These workshops have served to ensure that the modeling stands up to highest international standard. Themes addressed at each time have conjured to the stage of the SWECLIM program, in terms of model development and scenario preparation topics. SWECLIM will continue to arrange workshops and seminars. So far, the topics covered are:

- "Workshop on ocean-atmosphere interaction and coupled models", at Arbetets museum, Norrköping, October 29, 1997 (org: J. Mattsson).
- "Boundary layer formulations and surface parameterizations", at SMHI, Norrköping, May 11, 1998 (Tjernström 1998).
- "Workshop on statistical downscaling" at the Department of Earth Sciences, Göteborg University, October 6, 1998 (org: D. Chen).
- "Modeling sea ice coupled to a 3D Baltic Sea model", at SMHI, Norrköping, November 19-20, 1998 (Meier 1998).
- "Hydrological Interpretations of Climate Change Scenarios", at SMHI, Norrköping, March 12, 1999 (Gardelin 1999a).
- "Coupling of Ocean, Ica, Atmosphere and Hydrosphere", at SMHI, Norrköping, October 21-22, 1999 (Döscher 1999).

2.8 Media-interest and information activities

The interaction between SWECLIM and potential users of results from SWECLIM is of key importance. Thanks to the dialogue with users, this has been much developed during phase 1. In addition to supplying users with regional climate scenarios, it is important that they understand the potential and limitations of science, when it comes to answering the questions on climate change and its impacts on society.

Spreading information about a forthcoming climate change in the Swedish society has met with success. Public appearances by SWECLIM scientists have helped to interest the public, the research community and politicians in the issue of climate change and the work performed in SWECLIM. More intense media interest has so far occurred in three phases. The first phase took place in conjunction of the publication of the first scenario results in 1998. The results from the second set of scenario runs in 1999 generated a renewed media interest. Finally, the major winter storms in late 1999 prompted several queries and interviews of SWECLIM scientists. The interest seemed to lie on whether the storms that had hit Europe and the other recent natural disasters around the world were due to climate change and how would such events change in the future.

In addition to the presentations in meetings and workshops and interviews in media, regular channels for the information to reach out from the program are the program reports (SWECLIM 1998, 1999, 2000), and the program Newsletter, published 3 times a year. Scientific reports and articles are also prepared and made available to the research community, via internet and to interested users or members of the public.

It is early to say how large the benefits from SWECLIM for the Swedish industry and society may be in the future. So far, SWECLIM has helped to set the climate change problem on the agenda in certain areas in Sweden. An important lesson that has been learnt is that there are different ways of getting the message across. In addition to directly approaching the decision-makers, information served to the general public, other research groups and students is equally or even more effective. If decision makers have heard about the climate change problem in the media or through their colleagues they are more likely to take information from the SWECLIM program seriously.

During phase 1 emphasis has been put on user contacts in order to identify their needs and inform about the potential of SWECLIM. Some highlights of relevance for the scientific evaluation follow below.

The power industry. The most far-reaching user contacts have been established with the Swedish hydropower industry. The discussions have been channeled through the Swedish Power Association (*Svenska Kraftverksföreningen,* KVF) and it has been agreed that SWECLIM regularly reports to KVFs groups for hydropower, its dam committee and to its group on hydrological development.

The Swedish nuclear power industry has expressed interest in studies on the potential for changes in groundwater recharge in the bedrock and also in possible changes in the salinity of the Baltic Sea.

Water supply. The potential impact of global warming on the water supply sector in Sweden has been discussed with the Swedish co-ordination committee for water quality and water supply (*Samverkansgruppen för vattenkvalitet och vattenförsörjning,* SAMVA). It turns out that this sector is not only sensitive to water shortages. Wetter conditions may also lead to increased risks for the groundwater resources as these may be influenced by more contaminated recharge if rainfall increases. SAMVA will be the future user contact for SWECLIM on all aspects of climate change and water supply.

Forestry and agriculture. SWECLIM has attended a number of meetings with the forestry and agricultural researchers. The first climate simulation from SWECLIM was used by scientists of the Swedish University of Agricultural Sciences for studies on impacts on forest growth (Bergh et al. 1999). Presentations have also been made to the forest industry and farmers organizations. Climatic aspects of special interest to this sector are soil moisture as limiting factor for growth, extreme winds, raised groundwater levels and frost during budburst among others.

The environmental sector. Contacts with the environmental sector are mainly channeled through the Swedish Environmental Protection Agency (SNV). SWECLIM also participates in Swedish IPCC activities, which are coordinated by SNV.

At present the Baltic Marine Environmental Protection Commission, the Helsinki Commission, is carrying out its fourth periodic assessment of the state of the Baltic Sea. The river flow to the Baltic Sea and other hydrological conditions are of great interest in this process. SWECLIM contributes by use of the Baltic Scale hydrological model as a supplement to observations of river runoff, which are becoming increasingly difficult to obtain in near real-time.

Insurance companies. Contacts with the insurance companies have shown that there is a strong interest in climate issues and particular in storm frequencies, flooding and in the uncertainty estimates of regional climate scenarios. Experience has shown that there has been a tendency to underestimate the risks for extreme events even under present day conditions. An ongoing project on risk-zone mapping of major Swedish rivers has identified several problem areas.

Other authorities. Other authorities, which have been informed and have had the opportunity to influence the work of SWECLIM, are the Swedish Geological Survey, the Swedish Rescue Services Agency and the Swedish National Energy Administration. The dam safety aspect of climate change has been discussed with Swedish dam safety authorities (*Svenska Kraftnät*) and results from SWECLIM will in the future be presented to the newly established Swedish Dam Safety Council (*Dammsäkerhetsrådet*).

The Swedish Committee on Climate Change (*Klimatdelegationen*) completed its work in 1998 by the presentation of the book *Om 50 år* ("50 years from now"). Its chapter on regional climate modeling is based on a background report from SWECLIM. Material has also been provided for the final report of the *Klimatkommittén* (SOU 2000).

It is expected that the improved regional climate change assessments will facilitate the planning of adaptation measures on activities with long planning horizons or activities that affect greenhouse gas emissions. In terms of Swedish competitiveness, it will be easier for the government to negotiate in international meetings on emission restriction measures, as well as for businesses to take into account the environmental issues, so to arrive at more environment-friendly practices. The latter is expected to improve their potential to compete nationally and internationally. At the same time, the SWECLIM-group builds up national expertise and educates young scientists on the field of climate modeling and climate change issues. The build-up of the regional climate models and the close networking of the Rossby Centre and the university departments will greatly advance the national knowledge base.

3 Part 3 – future plans

3.1 Moving on to Earth system modeling – coupled regional climate modeling

Already in Phase 1, a version of a coupled regional climate model was established by running RCA with the PROBE-models for the inland lake systems and the Baltic Sea. This was seen to improve the scenarios a lot and certainly indicated that more realistic sea-surface data than those available from GCMs are required for a proper representation of the Nordic climate. However, several shortcomings were still obvious:

- The PROBE-Baltic can only give a rather bulk-view of the Baltic Sea and in particular, its surface temperature and ice structures that the atmospheric model feeds on. The simulation of the regional climate change might be sensitive to a more resolved simulation of the Baltic Sea, including intra-subbasin ice cover, local upwelling and downwelling regions, the narrow straits, and localized air-sea interaction. In addition to affecting the time-mean regional climate, such features are likely to affect the simulation of severe weather extremes, such as episodic coastal snowfall and storms.
- The coupling between the atmospheric model and the PROBE-models was not attempted by using fluxes.
- There was no river runoff coupling in real time between the atmospheric-land surface simulation and the Baltic Sea simulation. Rather, observed climatic runoff data were used.
- The forcing on the Baltic Sea from the world ocean was likewise taken from observed climatic data rather than from the RCA or the GCMs forcing the RCA.
- The spinup of the PROBE-Baltic model was not really solved which can leave significant question marks on the scenario results. Spinup was based on the present-day observed climatic data.

The major model development thrust in Phase 2 will be to realize a more fully-coupled regional climate model, combining the RCA, the RCO and the HBV, as a fundamental building block of an Earth System Model. The PROBE-lake simulation is also kept in as well as the PROBE-Baltic, as an alternative for the Baltic Sea treatment. As mentioned earlier, atmospheric, land surface, hydrological and ocean parameterizations will be further improved.

In fact, 3-D high resolution, fully-coupled simulations (RCA+RCO) will have to be undertaken to start addressing several questions on the regional climate and the feedback in the course of future change. The hydrological link between the atmosphere/land surface and the ocean via river runoff needs to be covered in the modeling system (+HBV), as does the forcing of water exchange between the Baltic and the North Sea through the Danish Straits (GCM-forcing on RCO). Relevant coupling topics are discussed by Döscher (1999).

Spin-up strategy. Initialization of the rather slowly evolving ocean in present-day climate simulations can still be performed using observed data. In any future scenario simulation using the time-slice concept, the ocean may need to be spun up for several decades covering the transient changes and variability from the present-day/control time slice to the scenario time slice. Techniques to deal with this are developed and tested in

SWECLIM. Even with a careful spin-up, the final coupling of atmosphere and ocean models may lead to a "coupling shock", so ways have to be designed to prevent this and to allow for an equilibration.

Coupled and uncoupled hindcast runs and sensitivity studies. To investigate the modeling of ocean-atmosphere surface fluxes to be used in the coupled system, sensitivity runs with the RCO-model and the PROBE-models are performed. Observed atmospheric forcing data will be utilized. The results of such simulations, done at different model resolutions, are compared to find the best solution for the lowest cost. Coupled runs for past conditions (hindcast style) are also carried out to design and assess the benefits of interactive coupling, by comparison to atmosphere-only runs and ocean-only runs. Similarly, the interaction between the North Sea and Baltic must be explored under the conditions of Atlantic wind-forcing, controlling the northern boundary sea surface elevation of the regional domain. Of course, the question whether and what type of coupling is needed for the atmospheric-land surface simulation on one hand and the Baltic Sea-sea ice simulation on the other will also have to be given answers to.

Treatment of the hydrology. A more detailed interactive treatment of the runoff generated in RCA is necessary for a proper coupling with the ocean. The RCA-simulated precipitation climate affects the river runoff and the Baltic Sea system is sensitive to changes in the river runoff. A scheme for horizontal river routing of the grid-box (local) generated runoff will be developed. This will both benefit the hydrological interpretation of scenario experiments and produce the runoff to the Baltic Sea component in coupled simulations.

Improving the sea-ice model. Implementing a good ice-model is one of the major tasks in developing the RCO. It presently includes a 2-level sea-ice component with only one ice class. More sophisticated approaches, with different ice classes can be implemented.

Some of the problems in coupling atmospheric and ocean models (in this case the RCA and RCO) are illustrated in Figure 46. In general, the RCA and RCO horizontal grids differ with respect to resolution (88-22 km in RCA, 2-6 nautical miles, i.e. 4-11 km, in RCO; both models with subgridscale surface types land-water-ice), to rotation (giving unaligned grids) and staggering of variables (how the calculated variables are placed in the grid squares). This means that there have to be careful matching between the properties linking the atmospheric and ocean computations in the horizontal and in the vertical, to avoid unnecessary systematic biases. Resolution-independent interpolation and extrapolation routines are also needed. In SWECLIM, these questions are addressed adapting the OASIS coupler tool (Terray et al. 1999). OASIS offers different methods for interpolation between grids including Gaussian nearest neighbors interpolation and user-defined mapping. Mismatch of coastlines is treated by extrapolation of ocean values over land. When passing fluxes, flux conservation is ensured. By using OASIS, complex technical problems arising from an all-in-one code can be avoided. Instead, independent atmospheric model and ocean model codes can be maintained. This is advantageous in terms of further development and versatility of the models.

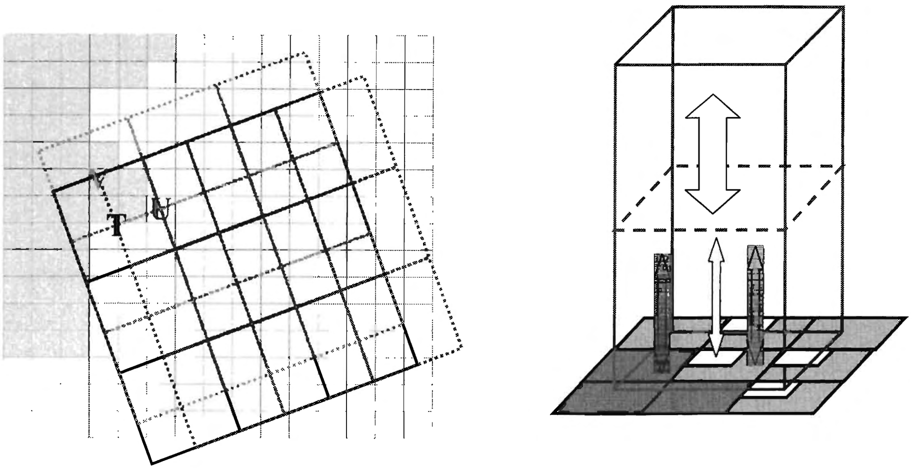

Figure 46. *<u>Left</u>: schematic view of the atmospheric (RCA; larger slanting squares) model grid and the ocean (RCO; smaller squares) model grid. That the calculation of atmospheric temperature and wind components is staggered is also illustrated. <u>Right</u>: the different ocean and atmospheric grids and the subgridscale surface types require a blending/separation of surface fluxes in the vertical when the direction of forcing is upwards/downwards.*

3.2 From phase 1 to phase 2 of the program – plans for July 2000 - - June 2003

Phase of the SWECLIM program was characterized by the building up the network, staffing the Rossby Centre and demonstrating the concept of regional climate modeling for potential users. The first climate scenarios were also created and communicated. A lot was learnt about the modeling tools and also how the message might be got across to the user community. The first step in the transition between the program phases 1-2 that are typical to MISTRA programs was the mid-term evaluation in autumn 1999.

At the time of the mid-term evaluation, activities were well underway in the field of model development, scenario analysis and water resources impact analysis. Preliminary plans for the Phase 1 activities were also drawn and entered into the evaluation process. Based on the material prepared by the project and an interview of some program participants including members of the program board, the international evaluation panel gave very positive view on the progress so far and the plans proposed for the continuation. [Ref: Assessment by the Scientific Review Panel, October 25-27, 1999, by Anders Karlqvist (Swedish Polar Research Secretariat), Wolfgang Cramer (Potsdam Institute for Climate Impact Research), Peter M. Haugan (University of Bergen) and Alan J. Thorpe (The Hadley Centre of the UK Meteorological Office).] The report made by the panel was opened with the statement:

> *"The conclusion of the review group is that this is an excellent programme and that it should be continued with a phase II to fully capitalize on the development work of phase 1"*

Detailed recommendations were also provided. These emphasized focusing instead of diversifying the activities, maintenance of the basic science activities in addition to the creation of climate scenarios, further strengthening of the international contacts, carefully evaluating the Baltic Sea modeling strategy and the construction of the coupled regional modeling tools, further development of the evaporation parameterization and the link between atmospheric and hydrological models, advanced interface tools for the users and securing the long term future of the activities.

The panel also made note of the SWECLIM program so far emphasizing scientific development rather than already having practical impact in the society. [Note, a separate evaluation on the user interaction was carried out simultaneously by MISTRA.] Nevertheless, the panel's view was that

> *"the Swedish government and industrial decision-making during the coming years will benefit directly from the results".*

After the results of the scientific evaluation became available, the process to move the program from Phase 1 to Phase was continued with. At the same time, the program directorship was changing hands due to increasing university duties being placed on the director of SWECLIM in 1997-1999.

The signs from MISTRA were that the scientific evaluation was an important defining document in drawing up the phase 2 plan. Also, the general requirements by MISTRA on the supported programs had been reshaped, emphasizing more detailed deliverable definition, the nature of the planning documents being easily in practice of use for the program boards and the preparation of synthesis analyses in the programs. However, the continuation of the phase 2 planning was not too easy as nothing definite was communicated on the expected length of the continuation. (The options were: termination instead of a second phase, a 3-year phase 2 or a 4-year phase 2. Of these the first option was not too probable given the scientific evaluation results.) Neither was the future budget fixed other than the general notion that the same or somewhat increased level of funding as in the phase 1 could be assumed. This would have meant about 16-18 MSEK per year.

During the previous years, the situation at the whole SMHI had also become more difficult. The public funding had not really kept up with the cost increases, all things considered, and some development projects were still ongoing. The commitment of the SMHI to continue funding in part the SWECLIM took time to prepare, awaiting the government response to submitted budget needs. The commitments and links between MISTRA, Naturvårdsverket and Energimyndigheten, all with their own financial constraints and R&D priorities, preparing joint supporting of a number of MISTRA programs were also long unclear.

Nevertheless, the first step was to draw up preliminary budget scenarios for MISTRA to be used as reference material in preliminary handling of SWECLIM's phase 2. This took place in December and now for the first time, more definite guidelines on phase 2 were set. MISTRA's board decided on another three years of support. This was also set to be the definite final MISTRA-funding to the SWECLIM activities, in line with the MISTRA principles that assume other agencies to take over the programs when long-term activities are to be maintained after the consolidation of activities. The total 3-year phase 2 funding frame from MISTRA to SWECLIM was set to 36 MSEK. The decision was conditional on the drawing up of more detailed plans by the following May and in practice, on acquiring promises of additional financial resources from other sources.

This led to the phase 2 planning within the program in January-April 2000 and the plans submitted April 28 to MISTRA. The plan outlined the development of the regional climate model tools (RCA, RCO, HBV and their coupling), the plan for new climate scenarios and their assessment for users, interaction with the users and the basic process studies to be made.

The final SWECLIM phase 2 decision came after the meeting of the board of MISTRA in June 2000. It reiterated the preliminary decision and confirmed the final length of MISTRA-support (3 years, till June 2003) and their funding contribution. Together with the committed funds from SMHI, involvement in two EU-projects and some additional project funding from the Swedish National Space Board, Räddningsverket and Elforsk, the phase 2 funding was secured finally in November 2000.

4 Discussion

At the onset of the SWECLIM program many aspects of the global climate change issue were still rather debated. No regional scenarios or first-hand expertise of such for Sweden were readily available. Since then much has been learned internationally and in Sweden. The issue of climate change has been integrated in the discussions of almost all areas in the society. International negotiations on the climate problem have become more concrete and progress towards first steps of addressing the anthropogenic growth of greenhouse gases in the atmosphere is being made. However, it is very evident that in order for this process to have success, information about climate research, climate modeling, climate scenarios and practical wording of the possible and/or likely consequences need to be available for the decision-makers and the general public.

In the SWECLIM program we have shown that regional climate simulations are possible with the resources allocated. The results produced illustrate the severe impact of the anticipated global climate change in the near future on the Swedish climate and the Swedish society. The SWECLIM results have so far had a clear impact in the Swedish society through the extensive media coverage that the program has obtained. Cooperation with other Nordic and international projects is very beneficial in many respects as well. Despite the rather short time since the start of SWECLIM, the model system set up has been compared with other regional model systems around the world and we have shown that the performance of the model system is in the same class as other top ranking models. An innovative component in SWECLIM is the coupling of an atmosphere and ocean model and hydrological modeling in a regional climate model system. Furthermore, no other regional climate modeling group in the world has so far considered the issues of the Nordic inland lake systems and the Baltic Sea in decade-length climate simulations and scenarios. Other landwinning achievements are the extended-length 3-dimensional Baltic Sea simulations, the closing-in of the meteorological and hydrological modeling philosophies and the close cooperation of the SWECLIM scientific work and the applications by external research and planning bodies.

The MISTRA-organized scientific evaluation of the program, phase 1, in November 1999 acknowledged that the program is heading in the right direction and provides valuable results. This led to the decision that SWECLIM will continue with a second program period of three years. It is not yet clear what will happen after this period, but it is clear that the scientific problems connected with regional climate change will be high on the agenda for many years to come. In SWECLIM we have demonstrated that we have a model system to investigate such problems and that we are competent to lay out a scientific strategy to understand regional climate system and the anticipated future changes. The existence of the scientific and practical expert group on such issues is very much appreciated and utilized by the media and other organizations. We thus find it very important that the research initiated with SWECLIM obtains also long term support and future in Sweden.

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