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Climate change projections for Finland during the 21st century

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On the basis of fifteen global model simulations of future climate, using the SRES emissions scenarios for greenhouse gases and aerosols, we have constructed national-scale seasonal and annual climate change scenarios for Finland during the 21st century. In approximate terms, the annual mean temperature is projected to rise by 1–3 °C and the annual mean precipitation by 0%–15% by the 2020s, relative to the baseline period 1961–1990. The corresponding increases by the 2050s are 2–5 °C (temperature) and 0%–30% (precipitation), while by the 2080s they are 2–7 °C and 5%–40%, respectively. The projected temperature trends are markedly stronger than that observed during the 20th century. The ranges in the climate change projections reflect the uncertainties arising from differences in model formulation and in emissions scenarios but are, to some extent, affected by the internal variability of climate as well. Seasonally, the projected precipitation changes and their statistical significance are largest in winter and smallest in summer. On the other hand, the projected rather small summertime warming is at least as statistically significant as the larger warming in the other seasons. Based on a literature review, it seems very likely that changes in mean climate are associated with changes in climate extremes as well.

Introduction

According to a questionnaire survey in Finland (Bärlund and Carter 2002, Carter *et al.* 2004), scenarios for future changes in climate (as well as in other environmental and socio-economic factors) are of wide interest in the fields of research, policy-making, planning, education and public information. The preferred attributes for scenarios, i.e., plausible representations of the future, was for those with supra-national or national-scale spatial resolution and annual or seasonal temporal resolution. The time horizon of interest ranged from a decade to beyond a century.

As part of the present theme issue on the FINSKEN project (Developing consistent global change scenarios for Finland), this paper aims to meet these requirements expressed by potential climate scenario-users. The main objective is to update the climate scenarios constructed for Finland within SILMU, the Finnish Research Programme on Climate Change, in 1990–1995 (Carter *et al.* 1996). A new state-of-the-art set of climate scenarios for the 21st century, to be presented here, is based on the most recent climate change simulations by a number of coupled atmosphere–ocean general circulation models (AOGCMs). In accordance with the premise of FINSKEN, the scenarios are compatible with four narrative storylines of the future world, formulated in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Nakićenović *et al.* 2000) (*see* also Carter *et al.* 2004).

The primary goal of climate modelling is to assess how sensitive the climate system is to external disturbances, such as human-induced changes in atmospheric composition, and what kind of temporal and spatial climate response patterns may be expected. For a given externally-imposed disturbance, or radiative forcing, variations in the climate change patterns from one model simulation to another ensue from differences in model design and, to some extent, from random effects due to internal climate variability. Accordingly, the sources of uncertainty involved in climate change projections may be divided into three categories: uncertainties in future emissions (and in associated concentrations and radiative effects) of greenhouse gases (GHGs) and aerosols into the atmosphere, inaccuracies in model formulation, and the noise due to natural climate variability. All these aspects are deliberated upon in this paper. First, we utilize model simulations based on the SRES scenarios that cover a wide range of alternatives of how future emissions may develop. Second, we employ several models to get an idea of the uncertainties in climate projections due to differences in model formulation. We also explore how closely the models can reproduce the observed present-day climate in Finland. Third, we study the magnitude of internal variability of climate from one 30-year period to another on the basis of very long-term model simulations with a constant atmospheric composition.

The significance of the projected future climate changes is assessed relative to the abovementioned uncertainty sources. In addition, the projections are compared with observed trends in climate. We shall examine whether the observed trends are statistically significant and, if so, whether they agree with or contradict the projected future changes. According to the Third Assessment Report of the IPCC (2001: p. 10), most of the observed increase in the global average surface temperature over the last 50 years is likely to have been due to the growth in GHG concentrations. However, since natural variability is much larger at the regional than at the global scales, regional temperature trends can depart appreciably from a global average and are more difficult to attribute to GHG forcing.

Because of the influence of random noise, in climate scenario construction it is worthwhile taking an average over at least a few adjoining model grid boxes (*see* e.g., Räisänen and Joelsson 2001). The present analysis produces average climate scenarios over the whole country. Maps of projected climate changes in individual model simulations are available on the FINSKEN web site (*see* Appendix). When viewing horizontal distributions of the projected changes, one should keep in mind that the typical grid box sizes of AOGCMs are some hundreds of kilometres. For those impact assessment studies in which fine-scale climate information is essential, the spatial scale of AOGCM results tends to be too coarse. With the goal of providing spatially more detailed climate information, various regionalisation techniques have been developed, including regional climate models (RCMs). While the FINSKEN climate scenarios are founded on AOGCM simulations, some regionalisation results are briefly considered in this paper for the sake of comparison.

The climate variables that we focus on are surface air temperature and precipitation. Modelled present-day and future atmospheric flow patterns in Finland are also briefly discussed. The emphasis is placed on the analysis of changes in the mean climate, whereas changes in climate variability and extremes are only shortly considered on the basis of a literature review. This does not imply that only changes in the mean climate would be relevant; on the contrary, changes in variability and extremes may be even of more consequence than those in mean climate conditions.

The paper is organised as follows. First, the methods and data are described. Second, we examine the performance of AOGCMs in representing the present-day climate in Finland. After considering the observed trends in Finland during the 20th century, the projected future changes are presented. The projections are compared with results from previous model simulations under earlier emissions scenarios. Finally, we give guidance to researchers of climate change impacts on how to utilize climate change scenarios.

Methods and data

Construction of climate scenarios from general circulation model output

Experiments using AOGCMs produce time-dependent global distributions of climate variables, typically at a horizontal resolution of a few degrees in longitude and latitude. Employing data available from the IPCC Data Distribution Centre (Parry 2002) and the Climate Impacts LINK Project (Viner and Hulme 1997) (*see* Appendix), we conducted an analysis of seasonal and annual mean surface air temperature and precipitation change in fifteen global climate model experiments performed with six AOGCMs (Table 1). These comprehensive three-dimensional global models describe interactions between the atmosphere, oceans, cryosphere (snow and ice) and the land surface but, due to the relatively low horizontal resolution, the models represent land–sea distribution and topography rather coarsely.

The AOGCM experiments simulate the climate response to past and assumed future changes in atmospheric composition. The time-dependent concentrations of GHGs and anthropogenic aerosol particles are retrieved from historical data up to 1989. The effects of volcanic eruptions and variations in solar irradiance are neglected in the simulations considered here. From 1990 onward, the concentrations are based on the IPCC SRES emissions scenarios. As an example, the SRES-based concentrations of CO_2 are presented in Fig. 1. All models in Table 1 simulate climate responses to SRES scenarios A2 and B2, which define intermediate levels of future emissions. Additionally, the HadCM3 model has employed the most extreme SRES marker scenarios, A1FI and B1. The B1 scenario has also been used by the CSIRO-Mk2 model.

Some model simulations of present-day climate have a tendency to drift away from the observed climate. A common technique to correct for this is to artificially modify interactions between the atmosphere and the underlying ocean surface (the so-called flux-adjustment). Only two AOGCMs considered in this paper (HadCM3 and NCAR-PCM) do not use such artificial corrections. These models are hence

Table 1. The coupled atmosphere–ocean general circulation models (AOGCMs) considered in this paper. The model resolution and the number of grid boxes covering Finland are given in cols. 2 and 3. The use of flux adjustment is indicated in col. 4. Parameterisations of aerosol-climate interactions include the direct radiative effect of aerosol particles due to scattering and absorption of solar radiation (D) and in certain models the indirect cloud albedo effect (IN1) (col. 5). The simulated increases in global mean surface temperature from 1961–1990 to 2070–2099 for the SRES A1FI, A2, B2 and B1 emissions scenarios are given in cols. 6–9 (when available). A value in parentheses is based on the MAGICC model and indicates that the pattern-scaling technique has been employed. The modelling centres, key references and information on substitution of missing data are given in the footnotes.

Model	Grid box size at 65°N (km × km)	No. of grid boxes for Finland	Flux adjustment	Aerosol effects	Global ΔT (°C) by the 2080s			
					A1FI	A2	B2	B1
HadCM3[1]	180 × 280	8	no	D, IN1	4.0	3.2	2.4	2.1
ECHAM4/OPYC3[2]	130 × 310	8	yes	D, IN1	(3.4)	3.3	2.5	(1.7)
CSIRO-Mk2[3]	260 × 350	5	yes	D	(4.6)	3.4	2.7	2.5
NCAR-PCM[4]	130 × 310	9	no	D	(2.9)	2.4	1.9	(1.4)
CGCM2[5]	180 × 410	6	yes	D	–	3.5	2.5	–
GFDL-R30[6]	170 × 250	9	yes	D	–	3.1	2.3	–

[1] Hadley Centre for Climate Prediction and Research (Gordon *et al.* 2000, Pope *et al.* 2000); a millennial control simulation is available. [2] Max Planck Institute für Meteorologie (Roeckner *et al.* 1999); data from the ECHAM4 GSDIO experiment were used for the baseline period 1961–1990. [3] Australia's Commonwealth Scientific and Industrial Research Organisation (Gordon and O'Farrell 1997). [4] National Centre for Atmospheric Research (Washington *et al.* 2000); data from the NCAR-PCM historic run experiment were used for the baseline period 1961–1990. [5] Canadian Center for Climate Modelling and Analysis (Flato and Boer 2001); a millennial simulation is available. [6] Geophysical Fluid Dynamics Laboratory (Delworth *et al.* 2002).

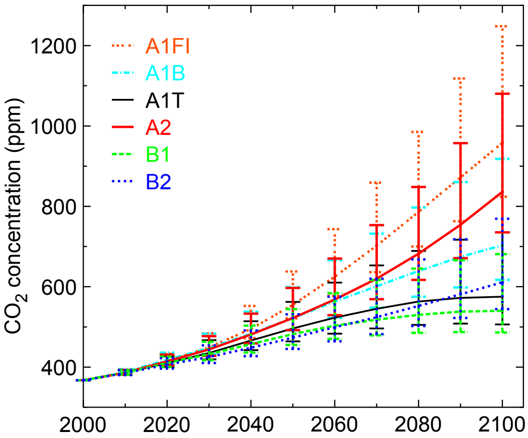

Fig. 1. Atmospheric concentrations of CO_2 in the period 2000–2100 resulting from the six SRES emissions scenarios on the basis of the Bern-CC carbon cycle model (IPCC 2001: p. 221). Curves represent the concentrations corresponding to mid-range estimate of the models. The error bars give assessed ranges due to uncertainties in the carbon cycle. All estimates assume a climate sensitivity of 2.5 °C for a doubling of CO_2 (for details, *see* IPCC (2001: appendix II).

more physically self-consistent than the flux-adjusted models but, as shown later, they are less capable of reproducing the observed climate. Nonetheless, the two categories of models appear to produce comparable changes in climate.

The FINSKEN climate change scenarios were constructed from model data by calculating annual and seasonal temporal means and area-averages over the land grid boxes representing Finland, relative to the modelled 1961–1990 baseline period. Temperature changes are given in absolute terms; precipitation changes are percentages. Somewhat inconsistently with the thermal seasons in various parts of Finland, we here define "winter" as December–February, "spring" as March–May, "summer" as June–August and "autumn" as September–November. The changes by the 2020s, 2050s and 2080s were derived from the 30-year averages in 2010–2039, 2040–2069 and 2070–2099, respectively.

Modelled internal climate variability

In addition to alterations in man-made and natural (solar activity, volcanism) external forcing, the climate system experiences unforced internal variability on various time scales. Internal climate variability is induced by non-linear interactions between various components of the climate system having different inertia. In order to assess the significance of the model-simulated response of the climate system to changes in the atmospheric composition, we have to estimate the magnitude of the noise.

The statistical properties of the internal variability were inferred separately from two 1000-year AOGCM simulations, in which the composition of the atmosphere was kept constant. The control simulations were run by HadCM3 and CGCM2 (Table 1). For both models, we computed a time series of overlapping 30-year running averages of annual and seasonal mean precipitation and temperature in Finland. Thereafter, the standard deviation of temperature (σ_T) was calculated from these sets of 30-year averages. For precipitation, the standard deviation was divided by the time mean, giving the percentage standard deviation σ_P.

Assuming that the 30-year means of temperature obey the normal distribution, $\pm 1.96\sigma_T$ defines a range within which 95% of the probability density is concentrated (from the 2.5 to 97.5 percentiles). In order to assess the statistical significance of model-projected changes in annual and seasonal mean temperature, we have to take into account the fact that there is internal variability both in the baseline and in the future climate. Ignoring possible changes in σ_T due to climate change, the 95% confidence interval for temperature changes is given by $\pm 2^{0.5} \times 1.96\sigma_T$, i.e., by $\pm 2.77\sigma_T$. Analogously, the confidence interval for precipitation changes is $\pm 2.77\sigma_P$. In several figures to be presented in this paper, bars showing these confidence intervals give a measure of the model-generated noise on a 30-year temporal scale.

In addition, the 1000-year control simulations by HadCM3 and CGCM2 were used to assess the probability distribution of 100-year annual and seasonal temperature trends in Finland. Assuming that the models can describe natural, internal variability of the climate system reasonably well, one can use the results to evaluate the statistical significance of the observed trends.

An important point to be made here is that a lack of statistical significance does not necessarily imply the absence of a substantial change in climate. Even signals of climate change not exceeding the level of statistical significance may have impacts of practical importance.

Pattern scaling

For a majority of the AOGCMs given in Table 1, climate change simulations were conducted only for scenarios A2 and B2. Thus the full range of uncertainty arising from alternative emissions scenarios is generally not captured by the AOGCM outcomes alone. In order to cover the most extreme SRES marker scenarios, A1FI and B1, we used a pattern-scaling method (Santer *et al.* 1990). The method combines results from AOGCMs and the simple global climate model MAGICC (*see* IPCC 2001: p. 577, Raper *et al.* 2001). The MAGICC model can calculate time series of the annual mean global surface air temperature for any given emissions scenario, but does not produce any spatial information. In this study we used MAGICC model data tuned to emulate the behaviour of three AOGCMs, namely ECHAM4/OPYC3, NCAR-PCM and CSIRO-Mk2 (S. Raper pers. comm.).

Pattern scaling assumes that the amplitude of the regional climate response to a given emissions scenario is linearly proportional to the global mean temperature change (e.g., Hulme and Carter 2000, Carter *et al.* 2000). Therefore, by multiplying an existing AOGCM outcome by an appropriate horizontally constant scaling factor, one can obtain an approximation to the climate change in an emissions scenario not actually simulated by the AOGCM. Slightly modifying the techniques used by Hulme and Carter (2000) and Carter *et al.* (2000), we first calculated 30-year temporal averages of global mean temperature changes simulated by the simple model and then defined the scaling factors as ratios of these temporal averages under alternative emissions scenarios (*see* Ruosteenoja *et al.* 2003). In practice, pattern-scaled approximations of climate change for the missing SRES scenarios were calculated from the closest existing AOGCM simulations, i.e., from A2 for A1FI and from B2 for B1. Thus the pattern-scaled approximations for A1FI (B1) have exactly the same spatial pattern as the climate change projections for A2 (B2), only the amplitude of the response being different.

For the sub-continental scale, the pattern-scaling approach is justified by the recent findings of Giorgi and Mearns (2002), Mitchell (2003) and Ruosteenoja *et al.* (2003). The applicability of the pattern-scaling method for a relatively limited area, i.e., the Finnish region, is evaluated in Fig. 2, which shows the AOGCM-simulated and pattern-scaled seasonal temperature and precipitation responses to the B2 forcing scenario for the period 2070–2099. Patterns were scaled from a stronger radiative forcing (A2) to a weaker one (B2), as recommended by Mitchell (2003).

Figure 2 indicates that the scaling method produced in most cases close approximations to the actual AOGCM simulations. The error bars around the scatter points, giving a measure of the modelled variability on a 30-year time-scale, generally intersect the diagonals. This suggests that it is possible to explain the differences between the pattern-scaled approximations and the actual AOGCM results by internal climate noise. As compared with the projected changes, the differences for the time slices 2010–2039 and 2040–2069 (not shown) are somewhat larger than those shown in Fig. 2. This may be attributed to the greater contribution of the unevenly distributed aerosol forcing (IPCC 2001: pp. 398 and 822) for these two time slices than for the more distant period. In the early periods, there are a few cases in which the differences between the modelled and pattern-scaled climate responses are statistically significant with a confidence level of 95%. Accordingly, the technique does not seem to perform quite as well for the earlier periods as for the last one.

Regional climate modelling

Because of the relatively coarse horizontal resolution of AOGCMs, various regionalisation — or downscaling — techniques have been developed by which results from AOGCMs are utilized to produce more detailed regional information. The methods include high or variable resolution atmospheric general circulation models (AGCMs), regional climate models (RCMs) and

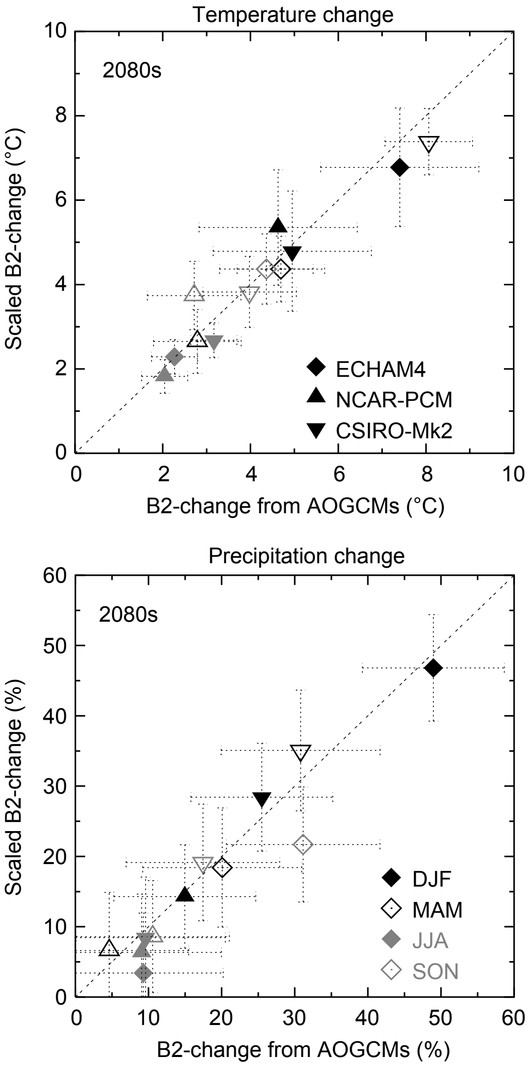

Fig. 2. Applicability of the pattern-scaling method to calculate seasonal mean temperature and precipitation changes for Finland for the SRES B2 emissions scenario. The pattern-scaled changes from 1961–1990 to 2070–2099 are shown as a function of the values derived directly from the three AOGCMs (indicated in the legend). Changes for winter (DJF) and spring (MAM) are indicated by black solid and open symbols, and for summer (JJA) and autumn (SON) by grey solid and open symbols. The error bars depict estimates of internal climate variability on a 30-year temporal scale on the basis of a millennial unforced HadCM3 simulation (*see* text for details).

statistical downscaling (for a review, *see* e.g., Giorgi *et al*. 2001). Inherently, climate data produced by regionalisation are influenced by the AOGCM employed. Regionalisation is generally regarded as most useful in studies dealing with areas of complex topography and land-water distribution and in research into future climate extremes. In contrast, when time mean changes of climate variables over relatively wide areas with a reasonably homogeneous topography are to be examined, it is more relevant to consider a number of different AOGCMs and levels of radiative forcing than to rely on regionalisations of one or two AOGCM experiments. Since only a few regionalisations for northern Europe of SRES-based AOGCM simulations were completed during the FINSKEN project (Jones *et al*. 2001, Räisänen *et al*. 2003, Christensen and Christensen 2003), we accordingly decided not to base the FINSKEN mean climate change scenarios on regionalisation results. Instead, outcomes from RCMs are used in this paper for two purposes. First, they offer comparison material for the scenarios. Second, we refer to RCM results in a literature review of potential changes in climate variability and extremes, to be presented later.

For the first purpose, we both reviewed earlier investigations and explicitly analyzed a set of RCM experiments. The set included two climate change experiments, each consisting of a 10-year control run and a 10-year scenario run made with the Rossby Centre regional model RCA1 with a horizontal resolution of 44 km (Rummukainen *et al*. 2001, Räisänen and Joelsson 2001). One experiment (denoted RCA1-H) used boundary data from the global HadCM2 model (Johns *et al*. 1997) while the other (RCA1-E) used data from ECHAM4/OPYC3 (Roeckner *et al*. 1999). In contrast to other simulations considered in this paper, these experiments were not based on the SRES emissions scenarios but on the earlier IS92 scenarios (IPCC 1996). Moreover, the effect of aerosols was not included.

Originally the two RCA1 experiments simulated climate changes over different time intervals. Following the approach of Christensen *et al*. (2001), we harmonized the results in time on the basis of the global mean warming in the driving AOGCM simulations (Mitchell and Johns 1997, Roeckner *et al*. 1999). Thereby, the RCA1 results became comparable with the FINSKEN scenarios.

Observations of temperature and precipitation

Observational data over Finland were used in this study for two purposes: for examining model performance in representing present-day climate and for comparing projected future changes to past trends and variability. Consequently, we needed 30-year mean values of the present climate and observational time series extending throughout the 20th century.

The observed monthly and annual mean temperature and precipitation for the period 1961–1990 were inferred from Finnish Meteorological Institute (FMI) data that were collected from about 100 temperature and 400 precipitation stations. Before calculating area-averages, the data were interpolated onto a 10 km × 10 km grid taking into account the climatic effects of the topography, coastlines and water bodies (Henttonen 1991, Venäläinen and Heikinheimo 2002). The area-average over Finland for temperature can be regarded as accurate. The measured precipitation is an underestimate, since rain gauges considerably undercatch precipitation, especially snow in windy conditions. Therefore, mean precipitation totals over Finland were corrected using a method introduced by Hyvärinen *et al.* (1995) to get unbiased estimates.

The observed trends and inter-annual variability of area-averaged annual mean temperature over Finland were calculated from time series consisting of data from eight stations for the period 1901–2001. For precipitation, the time series is based on a 24-station network in operation since 1910. Data up to the year 1995 were described by Tuomenvirta and Heino (1996); an update to the year 2001 has since been made. Details concerning the homogenization of the time series can be found in Tuomenvirta (2002).

The linear annual and seasonal trends were calculated with two techniques — the non-parametric Sen's trend estimate and the least-squares method (Gilbert 1987) — and their statistical significance at the 95% level was tested with suitable tests (the Mann-Kendall test and the *t*-test, respectively). Both methods appeared to give practically similar results. Furthermore, in order to evaluate whether the observed trends can occur by chance due to long-term natural climate variability, we utilized the 1000-year AOGCM control simulations to assess the probability distribution of the trend values, as described previously.

Geostrophic wind

While in this paper the emphasis is placed on the analysis of temperature and precipitation, we also briefly discuss present-day and future atmospheric flow patterns. The flow patterns were simply described by determining seasonal and annual mean geostrophic wind components over two thirty-year periods, 1961–1990 and 2070–2099. The wind components were calculated from monthly mean sea-level air pressure fields, after which averages were taken over an area covering Fennoscandia and its neighbouring areas (55–70°N, 2.5–35°E). For the former period, we used two sources of data: reanalysed observations from the NCEP/NCAR reanalysis project (Kalnay *et al.* 1996; *see* also Appendix) and the AOGCM experiments. For the future period, we considered changes in the model-estimated wind components relative to the means of 1961–1990. One of the models (GFDL-R30) could not be included due to the absence of appropriate data.

Model performance in Finland

This section compares AOGCM simulations of present climate with observations. The comparison gives an idea of the models' performance in representing present-day climate in Finland but, as discussed below, does not necessarily tell anything about their ability to project future anthropogenically-forced climatic changes. At larger spatial scales, the important topic of model evaluation has been discussed thoroughly by, e.g., McAvaney *et al.* (2001). They found that no single coupled model can be considered to be the best and, accordingly, recommended use of a range of coupled models.

In attempting to reproduce the observed annual mean temperature in Finland in 1961–

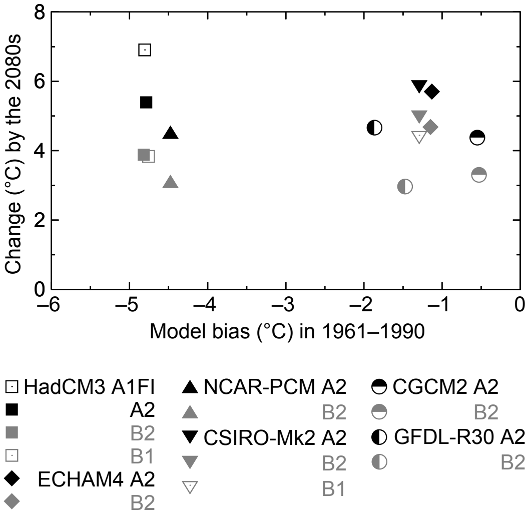

Fig. 3. Projected annual mean temperature changes in Finland by the 2080s, relative to the baseline period 1961–1990, as a function of the bias in the simulated mean temperature for the baseline period.

1990, the two AOGCMs without artificial flux-adjustment (HadCM3 and NCAR-PCM) do not succeed, in terms of systematic bias, as well as the flux-adjusted models (Fig. 3). Nevertheless, these two models appear to produce changes in temperature that are comparable with the other models. Thus for the model simulations analysed here, there are no distinct relationships between biases and projected changes in annual mean temperature. This also holds true for the annual mean precipitation in Finland and for the area-mean geostrophic wind components over Fennoscandia, for which the two groups of models do not deviate in terms of systematic biases, either (not shown). In the seasonal analysis, however, it was found that the largest biases in spring temperature (given by the CSIRO-Mk2 model with flux-adjustment) were connected with the largest projected future changes; this will be shown later.

Temperature and precipitation

The time series shown in Fig. 4 represent observed and simulated annual mean temperature and precipitation anomalies in Finland, relative to 1961–1990. Although concentrations of GHGs and anthropogenic aerosols are retrieved from historical data up to 1989, the observed and simulated anomalies cannot be expected to generally coincide in individual years. The inability of AOGCMs to reproduce the observed year-to-year climate fluctuations follows first of all from the random nature of internal climate variability. Besides, variations in past natural external forcing are ignored in the simulations, and there are uncertainties in model formulation and initialization.

In order to find out to what extent model simulations can reproduce the observed statistical features of regional climate in Finland, we studied the observed and simulated 30-year means and inter-annual variability, as well as annual cycles. We can see (Fig. 4) that the scatter of the modelled annual mean temperature and precipitation is of a similar magnitude to that of the observations. During the period 1961–1990, the observed standard deviation of the annual mean temperature was 1.1 °C (corresponding to the 95% interval of ±2.2 °C, *see* the black bar in Fig. 4a), while the modelled standard deviations ranged from 0.9 °C (ECHAM4/OPYC3) to 1.3 °C (GFDL-R30). The observed inter-annual percentage standard deviation of precipitation, was 12% (*see* the black bar in Fig. 4b), the corresponding figures from the model simulations ranging from 8% (HadCM3) to 13% (CSIRO-Mk2).

All the AOGCMs simulated an annual cycle of temperature that is qualitatively similar to the observations (Fig 5a): July is the warmest and January or February is the coldest month. The main deficiency of the simulations is that the temperatures are mostly too low. From October to May, the six-model average is more than 2.5 °C lower than observed, the maximum error occurring in March–April. During the remaining four months, about half of the models overestimate and the rest of them underestimate mean temperatures. The difference between the highest and lowest monthly mean temperatures is also biased. According to Heino (1994), the observed annual range varies from 22 °C in south-western coastal Finland to 29 °C in Lapland. AOGCM area-averages for Finland vary from 27 °C to 33 °C; accordingly, the models tend to simulate too continental a temperature climate.

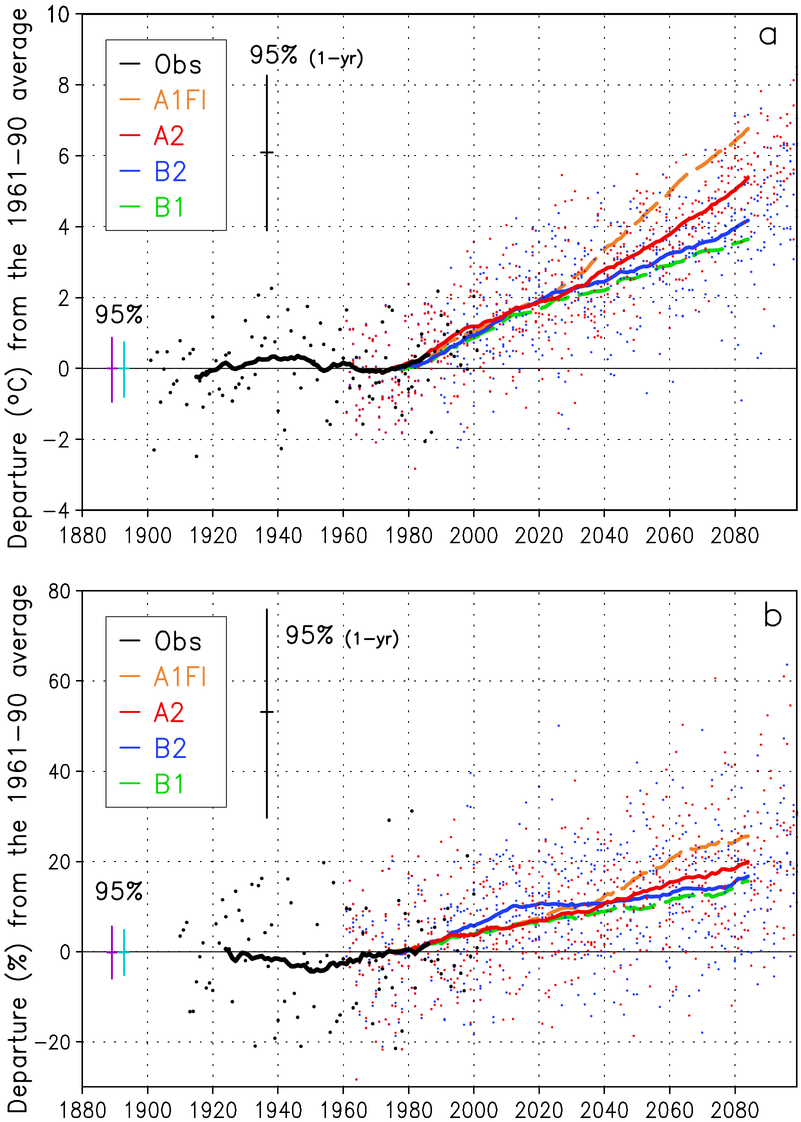

Fig. 4. Annual mean (**a**) temperature and (**b**) precipitation anomalies in Finland relative to the mean of 1961–1990 on the basis of observations and model projections employing four SRES emissions scenarios. Annual values are shown by dots: observations are in black; projections from four models (HadCM3, ECHAM4/OPYC3, NCAR-PCM, CSIRO-Mk2) for the A2 and B2 scenarios are in red and blue, respectively. Curves are 30-year running means: solid black depicts observations, solid red and blue show four-model average responses to the A2 and B2 scenarios, respectively, while dashed orange and green denote modelled or pattern-scaled average responses to the A1FI and B1 scenarios, respectively. The coloured bars indicate the 95% confidence intervals of statistical significance for changes in the 30-year mean values on the basis of two millennial unforced AOGCM simulations (purple for HadCM3 and cyan for CGCM2). The black bars, showing the 95% range of the observed inter-annual variability in 1961–1990, can be taken as a measure of the plausible year-to-year variations around the curves for the A1FI and B1 scenarios, since no annual values were plotted for them due to the lack of actual AOGCM data.

In contrast to the annual temperature cycle, the models are unable to reproduce even qualitatively the observed annual cycle of precipitation (Fig. 5b). Both observations and model simulations do have a minimum in precipitation during February–April, but it is much more difficult for the models to capture the observed maximum in August. Some models display a

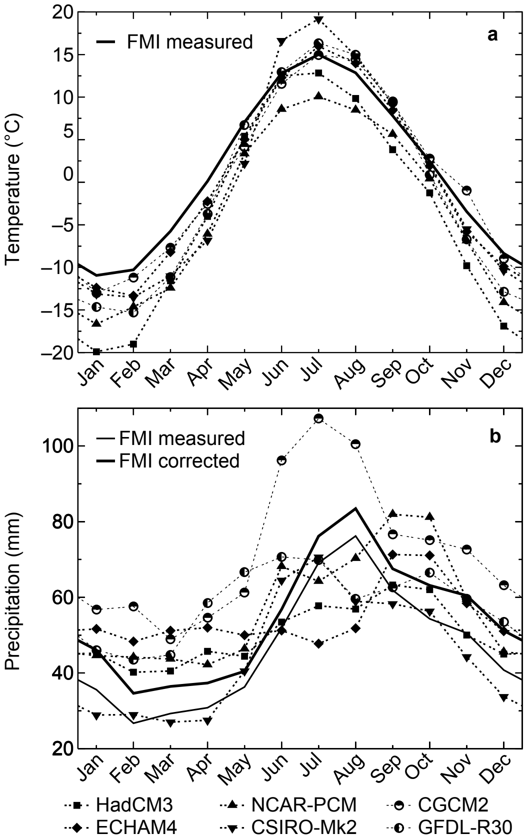

Fig. 5. Comparison of the modelled and observed monthly mean climatological (1961–1990) (**a**) temperature and (**b**) precipitation in Finland. Solid lines are area-averages inferred from observations by the Finnish Meteorological Institute (FMI). "FMI corrected" in panel **b** refers to precipitation totals adjusted for undercatch in precipitation measurements (*see* text). Symbols connected with dotted lines denote estimates from AOGCMs (*see* legend).

maximum in June or July, whilst others locate it in September–October. Most of the models overestimate precipitation during the first half of a year; in late summer the situation is generally reversed.

Several factors may account for the differences between the observed and modelled climate. On large spatial scales, models have problems in reproducing the observed atmospheric circulation (*see* below). For example, any errors in the position and strength of the North Atlantic wintertime storm track affect the simulated climate of Finland. In addition, the coarse model resolution does not allow a detailed description of the Scandinavian mountains and the Baltic Sea, both factors probably contributing to errors in precipitation. Parameterisation techniques employed in the models also affect the performance. Although not possible to quantify here, one might hypothesize that the maximum cold bias in the six-model average in March–April could be related to a delayed "melting snow and decreasing albedo" feedback.

Atmospheric flow patterns

Westerly winds bringing moist air from the Atlantic typically cause abundant precipitation and mild wintertime (cool summertime) temperatures in Finland, while dry continental air flows from the east have opposite effects (e.g., Tuomenvirta and Heino 1996). Consequently, the levels of agreement between observed and simulated temperatures and precipitation are partially dependent on the skill of AOGCMs in simulating the basic features of the atmospheric flow.

To cursorily address this issue, we studied seasonal and annual mean zonal (west–east) and meridional (south–north) components of the geostrophic flow (Fig. 6). The location of a point with respect to the origin gives the direction and magnitude of the mean seasonal geostrophic flow vector. Both in the observations and in the model simulations, the wintertime mean flow is stronger than the summertime one. While three of the models reproduce the mean wintertime west-south-westerly flow fairly well, HadCM3 and CSIRO-Mk2 depict a substantially weaker zonal component than observed. The mean westerly components simulated by the remaining two models are also typically too weak both in other seasons and annually (not shown). The mean southerly component is in most cases well captured or slightly overestimated.

With only five models available, it was not possible, on the basis of the model-to-model differences, to make any definite inferences on how the biases in modelled circulation affected other aspects of the simulated surface climate. Annually and seasonally, excluding summer, the bias in the mean westerly component was positively correlated with the bias in the mean precipita-

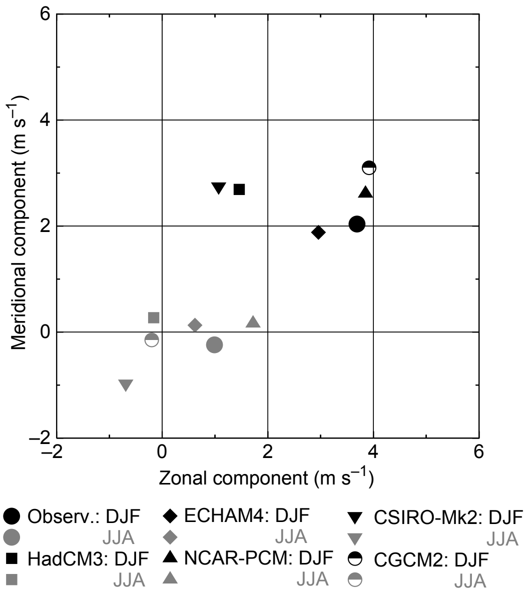

Fig. 6. Mean zonal and meridional components of the geostrophic wind over Fennoscandia (55–70°N, 2.5–35°N) in 1961–1990. The components are calculated from monthly mean sea level air pressure fields in reanalysed observations (NCAR-NCEP) and AOGCM simulations (Table 1), separately for winter (DJF) and summer (JJA).

tion, but only in spring was the relationship statistically significant at a confidence level exceeding 95%, the linear correlation coefficient being 0.91. The annual correlation value of 0.86 had a confidence level of 94%.

Fluctuations in the geostrophic flow over Scandinavia are linked with sea-level pressure variability over the North Atlantic, which particularly in winter is dominated by the North Atlantic Oscillation (NAO). AOGCMs generally reproduce the NAO pattern reasonably well, but when forced with anthropogenic increases in GHGs and sulphate aerosols, they underestimate the magnitude of the observed upward trend in NAO over the past few decades (Gillett *et al.* 2003).

Observed climate trends in the region

An analysis of the observations (*see* Fig. 4) indicates that annual mean temperatures in Finland increased by about 0.7 °C in 1901–2000. This increasing trend, which happens to be close to the best estimate of the global mean warming of approximately 0.6 ± 0.2 °C over this period (IPCC 2001: p. 26), is statistically significant (95% confidence level) from the point of view of trend analysis. However, while most of the observed global warming over the last 50 years is likely to have been caused by increased concentrations of GHGs (IPCC 2001: p. 61), we cannot exclude the large natural climate variability at regional scales as a potential explanation for the trend in Finland. On the basis of the frequency distributions of linear 100-year trends in the millennial HadCM3 and CGCM2 simulations without any external forcing, the observed trend of annual mean temperatures is not very uncommon, as equally or more strongly increasing trends occurred with a probability of about 10%.

Seasonally, the observed linear temperature trend is statistically significant at the 95% confidence level in spring (+1.4 °C/100 years) and summer (+0.7 °C/100 years). Based on the two control simulations, the smaller trend in summer is slightly more uncommon than the larger one observed in spring, as the probability of similar or more steeply increasing trends in the simulations was 2%–3% in spring and 0.5%–2% in summer. Autumns show only a modest, statistically insignificant, warming and winter temperatures have large fluctuations on the time-scale of a decade without any trend. In the 1990s the December–March mean temperature was exceptionally high, that is, about 1.7 °C higher than the preceding 30-year period average. In Sweden, Räisänen and Alexandersson (2003) estimated that the recent increase in winter (annual) mean temperature had about a 3% (6%) chance of occurring solely as a result of natural variability. These mild winter temperatures were related to unusually strong geostrophic westerly flow over Fennoscandia.

In contrast to temperature, the annual mean fluctuations of precipitation anomalies (*see* Fig. 4b) do not show any statistically significant national-scale trends over the 20th century. Nonetheless, particularly in the northern part of the country there were somewhat larger precipitation amounts during the latter than during the former half of the 20th century (*see* also Hyvärinen 2003). Increasing annual precipitation trends were observed for regions in Norway (Hanssen-Bauer and Førland 1998), for Sweden (Räisänen and Alexandersson 2003) and for an average of all land areas between latitudes 55°N and 85°N (Folland *et al*. 2001).

Projected future climate changes

Scenarios for mean temperature and precipitation changes

Because the anthropogenic radiative forcing for all the illustrative SRES emissions scenarios increases in time up to at least the 2080s (IPCC 2001: p. 66), climate change is anticipated to continue during the 21st century. The modelled climate change signal, as compared with the noise due to internal variability, is hence likely to become more apparent as the century proceeds. For estimates of climate change in the near future, it is more difficult to distinguish signal from noise.

A method to partly filter the noise due to random variability consists of calculating temporal and spatial means as well as the averages of several model simulations. In the following, we focus on multi-model averages and ranges of 30-year means of national-scale climate changes, although individual projections are also shown.

Annual changes

Projected annual mean responses to the A2 (B2) emissions scenarios suggest a distinct trend towards a warmer climate with more precipitation (*see* the red (blue) dots in Fig. 4). The projected future changes also indicate that the inter-annual variability is likely to remain large. As discussed previously, the simulated standard deviations of annual mean temperature and precipitation during 1961–1990 were close to those observed (*see* the black bars in Fig. 4). A comparison between two time slices, 1961–1990 and 2070–2099, indicated that the simulated standard deviations changed only slightly in time: from a range across all simulations of 0.9–1.3 °C to 0.8–1.6 °C for temperature and from 8%–13% to 7%–12% for precipitation. In individual simulations the standard deviations changed from –0.2 to +0.4 °C and ±3%, respectively. Note that these values of standard deviation include the contribution due to the trend. Since no significant changes of the inter-annual variability were found, it is obvious that the increasing scatter towards the end of the 21st century in Fig. 4 mainly results from model-to-model and scenario-to-scenario differences in long-term mean climate change.

During the first decades of the 21st century, the four SRES emissions scenarios produce nearly the same radiative forcing (IPCC 2001: p. 66) and, accordingly, yield almost similar temporally-smoothed multi-model average annual mean climate change scenarios (*see* the coloured curves in Fig. 4). Only thereafter do the multi-model averages start to deviate, with higher increases in the A1FI and A2 scenarios than in the B1 and B2 scenarios. Owing to averaging, the curves in Fig. 4 fluctuate less than corresponding curves based on single simulations. Even so, many details in the curves, especially those for near-term precipitation estimates, are evidently due to the model-generated noise. In climate change impact studies the near-term scenarios should therefore be treated with a high degree of caution, keeping in mind the low signal-to-noise ratio.

The 95% confidence intervals of statistical significance for changes in the 30-year mean values in Finland, derived from the millennial HadCM3 and CGCM2 control simulations, are ±0.89 and ±0.75 °C for temperatures and ±5.5 and ±4.8% for precipitation, respectively (*see* the coloured bars in Fig. 4). By comparing the confidence intervals with the projected annual mean climate change scenarios for three 30-year time periods, centred on the 2020s, 2050s and 2080s (Table 2), one can make the following remarks. The multi-model average precipitation changes for the first time interval are comparable with the modelled internal climate variability on a time-scale of three decades. Subsequently, the average changes exceed the random noise, but some individual model results are hardly statistically significant even by the 2080s (Table 2). In contrast, all the projected 30-year mean temperature changes, including the smallest changes by the 2020s, are statistically significant at a confidence level of 95% or higher. Compared with the projected globally-averaged mean temperature changes by the 2080s (Table 1), the warming for Finland in individual simulations is 60% ± 30% greater. This is consistent with the fact that the strongest warming is generally expected to take place in high-latitude land areas.

The temporally-smoothed time series of temperature change for the individual emissions scenarios are nearly linear in time (Fig. 4). The larger deviations from linearity in the precipitation changes may result from internal variability, which affects precipitation more strongly than temperature. If the projected alterations in the climate by the 2080s for the various emissions scenarios are expressed simply by linear trends, the AOGCM-averaged mean changes (*see* Table 2) correspond to a trend of 0.3–0.6 °C per decade for temperature and 1%–2% per decade for precipitation, depending on the emissions scenario. These rates of future temperature change exceed the observed trend during the past century by a factor of between four and nine.

The ranges given in Table 2 reflect the uncertainty due to the different model formulations, varying emissions scenarios and, to some extent, the internal variability of climate. However, they do not cover the whole uncertainty extent, which also includes the influence of externally-induced natural climate variations (e.g., volcanism and solar activity) and potential surprises, i.e., strong non-linear climate responses to anthropogenic emissions. An example of such a low-probability but high-impact response would be a substantial weakening or total collapse of the large-scale thermohaline circulation (THC) in the Atlantic Ocean. The warming and freshening of high-latitude surface water associated with global warming are expected to weaken the North Atlantic THC and thereby reduce the heat transport into high latitudes of Europe (Stocker *et al.* 2001, Cubasch *et al.* 2001). As shown by fig. 9.21 in IPCC (2001), all the AOGCMs that we have used, except ECHAM4/OPYC3, show some weakening of the THC. For the period 2070–2099, the fifteen experiments considered by us produced either a local minimum in the warming or a small area of cooling over the North Atlantic — and simultaneously considerable warming over Finland. A complete shutdown of the THC would profoundly influence the climate around the North Atlantic, but none of the current AOGCMs projects such an event during the 21th century. As stated by the IPCC (2001: p. 73), it is too early to say with confidence whether an irreversible shutdown of the THC is likely during subsequent centuries (*see* also Knutti and Stocker 2002).

Table 2. The projected annual mean temperature and precipitation changes in Finland for three 30-year time periods, relative to the baseline period 1961–1990. In addition to the multi-model means, the upper and lower ranges are shown (parentheses). Changes for the SRES A2 and B2 emissions scenarios are derived from AOGCM output, those for the A1FI and B1 scenarios are generally pattern-scaled*. The AOGCMs used are shown in Table 1. The right-hand column contains estimates of the range of uncertainty across all scenarios.

Time slice	A1FI*	A2	B2	B1*	All scenarios
Temperature changes (°C)					
2010–39	2.1 (1.5–3.1)	1.8 (1.3–2.8)	2.0 (1.5–2.8)	1.9 (1.5–2.4)	(1.3–3.1)
2040–69	4.5 (3.8–5.2)	3.3 (2.9–4.0)	2.6 (2.1–3.7)	2.7 (1.8–3.5)	(1.8–5.2)
2070–99	6.8 (5.6–7.4)	5.1 (4.4–5.9)	3.8 (3.0–5.0)	3.6 (2.4–4.4)	(2.4–7.4)
Precipitation changes (%)					
2010–39	9 (4–14)	6 (2–13)	8 (3–16)	7 (3–14)	(2–16)
2040–69	18 (9–28)	12 (7–21)	9 (1–20)	10 (4–17)	(1–28)
2070–99	26 (14–37)	15 (8–29)	14 (6–28)	16 (8–22)	(6–37)

* No results from CGCM2 and GFDL-R30 are available for A1FI and B1 since the pattern scaling factors were missing for these models. HadCM3 results for A1FI and B1, and CSIRO-Mk2 results for B1 were directly derived from model output.
Since there were six values for A2 and B2 and four values for A1FI and B1 from which the ranges and means were calculated, the results for A1FI and B1 are not precisely comparable with those for A2 and B2.

Seasonal changes

In order to illustrate the seasonal features of the climate change, we created scatter diagrams of seasonal mean changes in temperature and precipitation for the three time slices (Fig. 7). Each scatter point represents a single model-simulated temperature–precipitation response to one radiative forcing scenario. As a measure of the model-generated natural variability, included in the scatter plots are horizontal and vertical bars around the origin that illustrate the 95% confidence intervals for changes in the two variables, derived from the two millennial AOGCM control simulations. The statistical significance of the climate change can be assessed relative to these model-based confidence limits, which vary seasonally and from model to model.

The projected mean temperatures increase in all seasons and time intervals (*see* also Table 3). For precipitation, there is a qualitative inter-model disagreement in summer: two models show a decrease and the others an increase or little change (Table 4). The correlation between the projected summertime temperature and precipitation changes is close to zero or slightly negative. In the other seasons the mean precipitation total is projected either to increase or to remain practically unaltered, and changes in the two variables tend to be correlated positively.

For the first time slice, most of the scatter points are located only slightly outside the horizontal range delimited by the 95% confidence intervals, many of them lying within the vertical range. This implies that the projected seasonal precipitation changes are generally statistically insignificant and that the temperature change signals are near in magnitude to natural variability. The differences between the scatter points depend more on the model than on the emissions scenario. Still, the scatter is rather small, suggesting that a considerable portion of the differences may result from random variability. The largest uncertainties in predicting the climate change in Finland during the first decades of the 21st century are hence related to the natural variations in temperature and precipitation, and to the limited ability of the global models to describe correctly the regional distribution of the climate change.

Further into the future, the projected changes increase and become statistically more significant. In the course of time, however, the spread of the points tends to widen. This manifests the growing uncertainty in climate scenarios due to differences in emissions scenarios and AOGCM disagreement on the regional scale. Seasonally, the projected changes are largest in winter and smallest in summer. The multi-model mean pre-

Table 3. Same as Table 2 but for seasonal temperature changes (°C).

Time slice	A1FI*	A2	B2	B1*	All scenarios
Dec–Feb					
2010–2039	2.7 (1.6–5.0)	2.2 (1.2–4.5)	2.6 (1.8–4.4)	2.5 (1.8–3.8)	(1.2–5.0)
2040–2069	6.2 (4.2–7.8)	4.6 (3.4–6.0)	3.2 (2.0–5.7)	3.3 (2.3–4.8)	(2.0–7.8)
2070–2099	9.1 (7.6–10.9)	6.8 (5.9–8.7)	5.1 (3.8–7.4)	4.9 (3.7–6.0)	(3.7–10.9)
Mar–May					
2010–2039	2.4 (1.1–3.7)	2.1 (1.1–3.4)	2.2 (1.1–4.2)	2.2 (1.3–3.7)	(1.1–4.2)
2040–2069	4.8 (2.9–7.8)	3.6 (2.3–6.2)	3.0 (1.7–5.9)	3.2 (1.5–5.9)	(1.5–7.8)
2070–2099	7.4 (4.4–11.7)	5.6 (3.5–9.4)	4.4 (2.8–8.1)	4.1 (2.2–6.9)	(2.2–11.7)
Jun–Aug					
2010–2039	1.2 (0.7–1.6)	1.2 (0.6–1.6)	1.3 (1.1–1.5)	1.2 (1.0–1.5)	(0.6–1.6)
2040–2069	2.8 (2.0–3.9)	2.1 (1.6–2.5)	1.9 (1.3–2.2)	1.8 (1.1–2.2)	(1.1–3.9)
2070–2099	4.1 (3.0–5.5)	3.4 (2.4–4.3)	2.5 (2.0–3.2)	2.4 (1.6–3.1)	(1.6–5.5)
Sep–Nov					
2010–2039	2.2 (1.5–2.8)	1.8 (1.1–2.6)	1.7 (0.9–2.9)	1.8 (1.3–2.5)	(0.9–2.9)
2040–2069	4.1 (3.5–5.2)	2.9 (2.1–4.0)	2.4 (1.5–3.6)	2.4 (1.8–3.0)	(1.5–5.2)
2070–2099	6.4 (6.0–7.1)	4.5 (2.9–5.6)	3.3 (2.1–4.4)	3.0 (2.2–3.6)	(2.1–7.1)

* No results from CGCM2 and GFDL-R30 are available for A1FI and B1 since the pattern scaling factors are missing for these models. HadCM3 results for A1FI and B1, and CSIRO-Mk2 results for B1 are directly derived from model output.

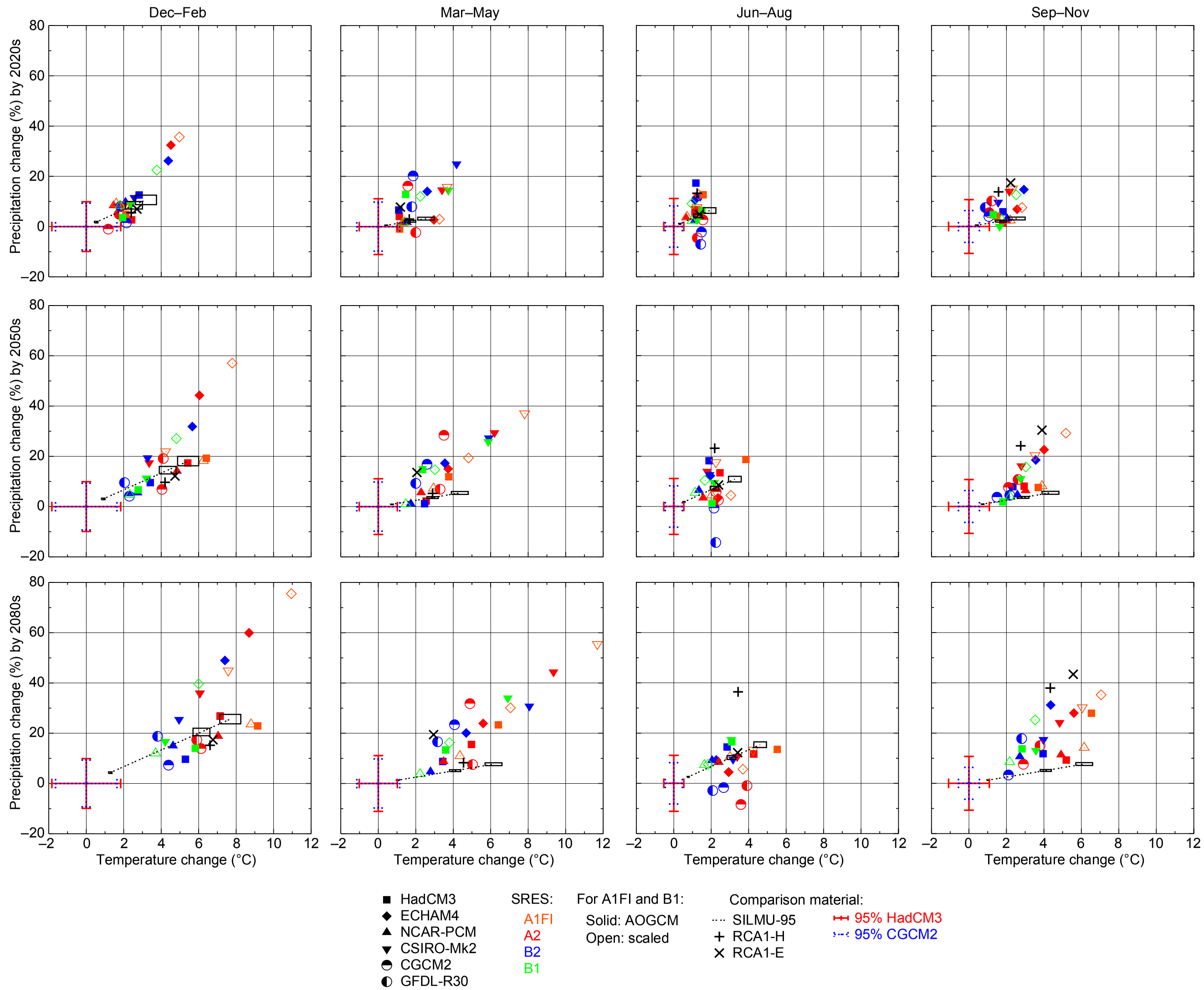

Fig. 7. Seasonal mean changes in temperature (horizontal axis) and precipitation (vertical axis) in Finland by the 2020s (top row), 2050s (middle row) and 2080s (bottom row) relative to the mean of 1961–1990. The FINSKEN scenarios are based on the SRES emissions scenarios. Coloured solid and half-solid symbols depict changes derived directly from AOGCM simulations, while open symbols denote results from pattern-scaling. Supplementary symbols in black are based on previous climate change projections. The horizontal and vertical dimensions of the symbols for the SILMU-95 policy-oriented central, low and high scenarios denote the uncertainty due to the temporal scaling (*see* text). The horizontal (vertical) coloured bars define the ranges near the origin inside which 95% of the probability density of natural variability in 30-year seasonal mean changes of temperature (precipitation) is concentrated on the basis of two millennial unforced AOGCM simulations.

cipitation changes, as well as the majority of the individual projections, appear to be statistically robust in winter and spring from the period 2040–2069 onwards and in autumn during the period 2070–2099 but insignificant in summer throughout the century. Since the random noise of mean temperature is greatest in winter and smallest in summer, the small summertime warming is statistically at least as significant as the larger warming in the other seasons. For all three time slices, the uncertainty ranges of the temperature and precipitation changes are larger in spring and winter than in summer and autumn.

An additional source of uncertainty for the A1FI and B1 climate scenarios arises from the use of pattern scaling. Whereas the differences between the forcing scenarios are fairly small for the first 30-year period and the scaling technique was inferred to work quite satisfactorily for the last period, the pattern-scaled A1FI and B1 climate scenarios for the period 2040–2069 should be treated with some degree of caution.

Comparisons with previous climate scenarios

In addition to the SRES-based FINSKEN scenarios, Fig. 7 presents a few supplementary climate change projections that have frequently been used in impact assessment in Finland (*see* below). The SILMU policy-oriented central, low and high climate change scenarios (Carter *et al*. 1996) were based on the IS92 emissions scenarios (IPCC 1996), which assumed higher concentrations (and hence stronger cooling effects) of anthropogenic sulphate aerosols than the current SRES emissions scenarios. The original SILMU results were given as linear trends between the years 1990 and 2100, instead of using the period 1961–1990 as a baseline. In order to make them comparable with the FINSKEN scenarios, the trends were simply extrapolated backward in time using two alternative assumptions: either a zero or a linear change from the year 1975 (the midpoint of 1961–1990) to the year 1990. These assumptions were regarded as yielding reasonable lower and upper estimates. Accordingly, the scatter marks for the SILMU scenarios (*see* Fig. 7) have dimensions that indicate the uncertainty ranges arising from the temporal harmonization.

As compared with the SILMU policy-oriented scenarios, the new FINSKEN scenarios generally project rather similar or larger increases in mean temperature and precipitation, and cover a wider range of uncertainty, particularly for precipitation changes. The SILMU-central scenarios still offer quite up-to-date estimates, except that

Table 4. Same as Table 2 but for seasonal precipitation changes (%).

Time slice	A1FI*	A2	B2	B1*	All scenarios
Dec–Feb					
2010–2039	16 (5–36)	9 (–1–32)	11 (1–26)	11 (4–23)	(–1–36)
2040–2069	31 (18–57)	20 (7–44)	13 (4–32)	13 (5–27)	(4–57)
2070–2099	43 (23–76)	28 (14–60)	20 (7–49)	22 (12–40)	(7–76)
Mar–May					
2010–2039	4 (–1–16)	6 (–2–16)	12 (2–25)	10 (1–14)	(–2–25)
2040–2069	18 (7–37)	14 (2–29)	12 (1–27)	13 (1–26)	(1–37)
2070–2099	28 (11–56)	21 (8–44)	17 (5–31)	16 (4–34)	(4–56)
Jun–Aug					
2010–2039	9 (4–13)	4 (–5–12)	4 (–7–17)	5 (2–9)	(–7–17)
2040–2069	11 (4–19)	7 (3–14)	4 (–14–18)	7 (1–10)	(–14–19)
2070–2099	11 (6–13)	3 (–8–12)	5 (–3–14)	12 (7–17)	(–8–17)
Sep–Nov					
2010–2039	7 (2–15)	6 (1–14)	7 (3–15)	5 (0–13)	(0–15)
2040–2069	16 (8–29)	12 (6–23)	8 (4–18)	8 (2–16)	(2–29)
2070–2099	26 (14–35)	15 (8–28)	15 (3–31)	15 (8–25)	(3–35)

* No results from CGCM2 and GFDL-R30 are available for A1FI and B1 since the pattern scaling factors are missing for these models. HadCM3 results for A1FI and B1, and CSIRO-Mk2 results for B1 are directly derived from model output.

in spring and autumn they lie at the lower end of the FINSKEN range for precipitation. The SILMU-low estimates give smaller temperature increases than any of the simulations analysed for FINSKEN in all seasons and all time slices, especially for the period 2070–2099. The new, considerably smaller sulphate emission scenarios for the latter half of the 21st century are the main cause of the differences. In winter and spring the SILMU-high scenarios are lower than the highest SRES-based simulations by several degrees for temperature and by tens of percentage units for precipitation.

The Rossby Centre regional climate model experiments RCA1-H and -E, described previously in this paper, generally produce intermediate or relatively weak mean seasonal warming, when compared with the FINSKEN scenarios (*see* the black crosses in Fig. 7). The projected precipitation changes are moderate in winter to spring. In summer the RCA1-H experiment and in autumn both simulations produce larger increases in mean seasonal precipitation than the FINSKEN scenarios. This might simply result from the fact that the 10-year-long RCA1 simulations are more strongly affected by internal climate variability and are therefore more likely to produce extreme mean precipitation changes in some seasons than the longer AOGCM simulations. The most recent SRES A2-based Rossby Centre simulations (RCAO) for changes between two 30-year periods (1961–1990 and 2071–2100), shown by Räisänen *et al.* (2003), do not yield such large increases in summer and autumn precipitation in Finland. In fact, one of the two RCAO simulations suggests a slight decrease in summer precipitation in southern Finland. Such a decrease is also produced by a few of the AOGCM simulations (*see* Fig. 7) and by two other recent SRES-based dynamical downscaling experiments, one conducted by the Hadley Centre model HadRM3H (Jones *et al.* 2001) and the other by the HIRHAM4 model of the Danish Meteorological Institute (Christensen and Christensen 2003).

We examined briefly three sets of previous regional climate change scenarios (not shown), one based on the SRES emissions scenarios for the north European land area (Ruosteenoja *et al.* 2003) and the others employing non-SRES based emissions scenarios for the Scandinavian land area (Christensen *et al.* 2001, Räisänen 2001). Averaging over northern Europe instead of Finland was found to increase the signal-to-noise ratio of climate change projections, more clearly so for precipitation than for temperature. A cluster containing numerous models but using only one emissions scenario (Räisänen 2001) produced a range of annual mean temperature changes for the Scandinavian land area that was twice as wide as the range found here for Finland on the basis of fewer models but using several emissions scenarios (Table 2). This highlights the uncertainties in regional climate projections due to model formulation.

Projected changes in atmospheric flow patterns

Changes in atmospheric circulation may result from unevenly distributed man-made warming or from the natural variability of the climate system, or from both (*see* e.g., Gillett *et al.* 2003). In the model simulations considered by us, the annual and seasonal means of the geostrophic flow over Scandinavia in the 2080s were practically unaltered or had a direction more from the northwest than during the baseline period 1961–1990. The changes in the mean seasonal meridional component ranged from –1.1 to 0.6 m s^{-1}. The changes in the zonal component (*see* Fig. 8) were of the same magnitude or somewhat greater. The ECHAM4/OPYC3 model was the only one to produce strengthening of westerly and northerly components in all seasons. This tendency of ECHAM4/OPYC3 has also been noted by, e.g., Roeckner *et al.* (1999) and Räisänen *et al.* (2003).

In winter, particularly, the models simulated larger increases in the mean westerly component for the A2 forcing scenario than for the B2 scenario. However, the analysis carried out in the current work was not adequate to enable us to assess to what extent the projected changes in circulation are associated with a response to anthropogenic climate forcing. Apart from the summertime, models projecting the largest increases in the mean westerly component typically also produced the strongest warming. Although we could

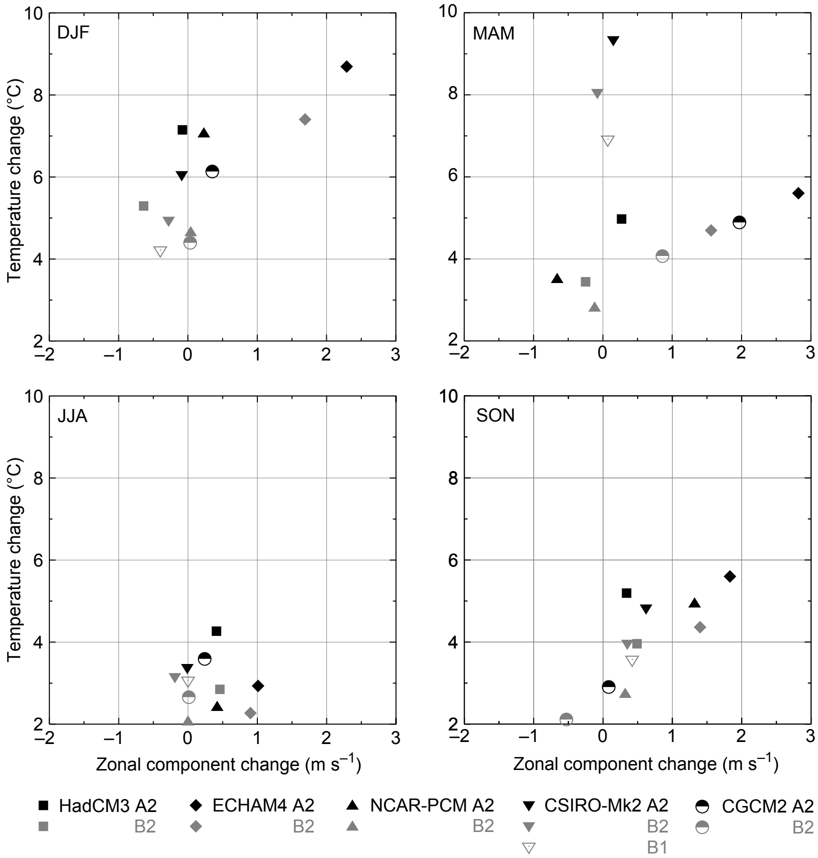

Fig. 8. Projected changes in seasonal mean temperature and geostrophic zonal flow component over Fennoscandia by the 2080s relative to 1961–1990. The symbols denote the various model estimates (*see* legend).

not find any statistically significant correlations, it is most likely that changes in the atmospheric circulation over Fennoscandia in the model climates contributed to the projected GHG-induced warming and enhanced precipitation in Finland.

An example of a negligible change in the time-mean geostrophic wind but a still considerable warming was given by the CSIRO-Mk2 model for the springtime (Fig. 8). The model severely underestimated the baseline period springtime mean temperature (Fig. 5), with a delayed snow season (not shown). Consequently, positive feedbacks between melting snow and decreasing albedo may have been particularly effective in that model during subsequent decades, causing strongly intensified warming of the model climate. In that particular case there was a clear connection between the biases and the projected changes in climate.

A literature review: changes in climate variability and extremes

In order to properly characterise the projected climate change, it is important not only to calculate changes in the temporal means of climatic variables, but also to look for changes in the width and shape of their frequency distributions. Cubash *et al*. (2001) reviewed several studies that report changes in climatic variability or extremes globally or in some regions of the world. Some of the results remained inconclusive. Unfortunately, only a few modelling studies on climate variability and extremes focus on northern Europe.

Räisänen *et al*. (2000, 2003) analysed changes in climatic extremes in Sweden on the basis of the downscaling experiments performed with the Rossby Centre regional climate model. The lowest annual minimum temperatures showed larger increases than the mean winter temperature. Changes in the highest annual maximum temperatures and in the highest 10-metre wind speeds, by contrast, did not differ from the corresponding changes in the mean values. For European land regions north of latitude 55°N, Räisänen and Joelsson (2001) found in RCA1 runs a shift towards larger daily precipitation amounts and a slight increase in the number of rainy days. The projected average annual maximum increased by 16%–19% for one-day precipitation and by more than 20% for six-hour precipitation, which indicates a decrease in the duration of heavy precipitation events. Similar findings suggesting stronger precipitation extremes in a warmer climate have been reported by several authors (e.g., Christensen and Christensen 2003). Concerning storms in the future climate, Cubash *et al*. (2001) pointed out that several AOGCMs produce less of the weak but more of the deep mid-latitude low-pressure areas, with a reduced total number of storms. However, there was a fairly large disagreement between models.

The ability of AOGCMs to simulate changes in extremes is limited by the coarse spatial resolution. RCMs have finer spatial resolution, but they are dependent on the driving AOGCMs, and the simulations generally cover a relatively short period for studies of extremes, typically one to three decades. In both RCMs and AOGCMs any model shortcomings may have a more detrimental effect on the extremes than on the mean values (Cubash *et al*. 2001).

Guidance on the use of climate change scenarios

This section gives some guidance for users of climate change scenarios in studies of impacts, adaptation and vulnerability. More information can be found from, e.g., Mearns *et al*. (2001), Carter *et al*. (2001) and the guidelines prepared by the IPCC Task Group on Scenarios for Climate Impact Assessment (*see* Appendix).

Climate models commonly exhibit biases in simulating the present-day climate (*see* Figs. 3, 5, 6). To minimize the influence of the bias on estimates of future impacts of climate change, it is recommended to use observed climatological means as a baseline and modify them with the simulated climate change. An implicit assumption in this procedure is that any model bias in a climate simulation is practically independent of the time evolution of radiative forcing, and hence remains unchanged in time.

In Tables 2–4 and Fig. 7 the temperature changes ΔT are given in absolute terms and precipitation changes ΔP as percentages. Thus, we can express the future annual and seasonal mean temperatures (T_{PROJ}) and precipitation totals (P_{PROJ}) as

$$T_{PROJ} = T_{OBS} + \Delta T \quad (1)$$
$$P_{PROJ} = P_{OBS}(1 + \Delta P/100) \quad (2)$$

where T_{OBS} and P_{OBS} are the observed baseline period climatological means. Some sources of baseline climate information are listed in the Appendix.

In the IPCC (2001) report, all SRES storylines are considered equally sound and are not assigned likelihoods. Accordingly, in climate impact studies the FINSKEN climate scenarios for the four marker emissions scenarios should be regarded as equal alternatives. It is therefore advisable to apply all of them. The scatter diagrams in Fig. 7 are designed to provide a quick overview of the distribution of the climate change projections produced by the various SRES scenarios and climate models. Nonetheless, the possibility remains that the response of the real climate system could even fall outside the range in the scatter diagrams.

In impact assessments, the simplest method to utilize the information given in the scatter plots consists of taking an average of all model-simulated temperature or precipitation changes for each forcing scenario (for multi-model averages *see* Tables 2–4) together with the range of the projected changes. The averages may also be weighted ones, the weights depending, for example, on the assessed reliability of individual models (*see* Giorgi and Mearns 2002) or on their spatial resolution.

The ranges of the projected changes (Tables 2–4) are useful for general scoping studies of potential climate change impacts, including sensitivity studies. However, because the ranges are composites of several models, they are not internally consistent. For example, the minimum estimates for temperature and precipitation changes may originate from different model simulations. If physically-consistent climate change scenarios are required for impact analysis, calculations should be performed one by one for the individual model projections depicted in the scatter diagrams. This is particularly relevant if the impact under consideration depends nonlinearly on temperature and precipitation changes. Due to the low signal-to-noise ratio in the climate change scenarios for the first decades of the 21st century, in near-term impact research it is advisable to use as many individual climate projections as possible. In this way one can also obtain an idea of the signal-to-noise ratio in the impact study.

If climate change scenarios are needed for some interval of time between the 2020s and 2050s or between the 2050s and 2080s, linear interpolation in time might be used. Some AOGCM results for the 2030s can be found in Tammelin *et al*. (2002). Many climate change impact assessments require information of the future climate with a daily or monthly resolution. A simple way to obtain approximations for monthly mean climate change consists of interpolating the seasonal mean changes (*see* Tables 3–4) linearly in time between the middle months of the four seasons, possibly using some smoothing. For daily resolution, the method is far more dubious because of changes in climate variability. If possible, scenario users should try to consider the effects of changes in variability by performing some sensitivity studies to find out whether there are large uncertainties arising from insufficient treatment of climatic extremes. An alternative is to use daily data from AOGCMs or RCMs, or a stochastic weather generator that produces synthetic weather time series (e.g., Carter *et al*. 1996).

Maps of the climate changes projected by individual model simulations are available on the FINSKEN web site (*see* Appendix), in cases where national-average climate scenarios over the whole country are of too coarse a spatial resolution. Original gridded monthly climate model outputs can be downloaded from the IPCC Data Distribution Centre (*see* Appendix). In addition to temperature and precipitation, climate model simulations produce information on many other climatic variables. A list of those commonly available from AOGCM simulations is given in the Appendix (Table A1). For some variables, e.g., precipitation, simulated changes on a grid-box scale are very noisy. In such cases spatial averaging of the original model results may be needed. However, one should avoid averaging over areas, e.g., land and sea, that are climatologically too disparate.

In addition to the general guidance and references given here, we encourage readers to consult scientists who have worked with climate observations and models and who have performed impacts research. During SILMU, numerous studies of possible climate change impacts were performed (*see* Roos 1996). Impact studies conducted in the early phases of FINSKEN have been reported by, e.g., Haapala *et al*. (2001), Tuomenvirta *et al*. (2000, 2001a), Venäläinen *et al*. (2001a, 2001b), Ilvesniemi *et al*. (2002), and Vajda *et al*. (2004). In these studies, use was made of climate scenarios based on AOGCM simulations with the IS92a emissions scenarios, often modified to represent the new SRES scenarios or dynamically downscaled with the Rossby Centre regional climate model RCA1. Recently, some impact assessments have applied the final FINSKEN climate change scenarios presented here (Tammelin *et al*. 2002). The current theme issue offers further references.

Concluding remarks

Fifteen experiments with six coupled atmosphere–ocean general circulation models were analysed to portray seasonal and annual mean climate change in Finland from the baseline period 1961–1990 up to 2100. The simulations were forced by projected changes in atmospheric concentrations of greenhouse gases and aerosols derived from a few SRES marker emissions scenarios. In order to cover a fuller range of radiative forcing, we combined information from the comprehensive climate models and a simple climate model by employing a pattern-scaling method. The method was found to apply better for the last 30-year period of the decade than for the earlier periods.

From the point of view of Finland, the main deficiencies in the models are their coarse resolution and their tendency to simulate a present-day temperature climate that is too cold and continental. To minimize the influence of the model deficiencies on impact assessments, it is advisable to add (multiply) projected temperature (percentage precipitation) changes to (with) the observed climatological means of the baseline period, rather than using the climate model output directly.

In the projections, there was a distinct trend towards a warmer future climate with more precipitation, while the simulated inter-annual standard deviations changed little in time. The simulated mean annual temperature increases for the SRES B1 and B2 scenarios were weaker than those for the A1FI and A2 scenarios, but still considerably stronger than the observed trend of 0.07 °C per decade during the 20th century. In addition to the enhanced greenhouse effect, modelled changes in atmospheric flow patterns contribute to the projected climate change in Finland, but the data analysed by us was insufficient to give any quantitative relationships that were statistically robust.

On the time horizon of the next few decades, the projected seasonal and annual mean precipitation changes, as well as the seasonal temperature changes, were generally below or close in magnitude to the natural variability. In contrast, the projected annual mean temperature changes were statistically significant. All emissions scenarios yielded nearly equal multi-model averages of annual and seasonal mean changes. This is because only later do the different emissions projections start to considerably diverge in their atmospheric concentrations of GHGs. Because GHGs generally have long lifetimes, their past emissions contribute most to the elevated concentrations. This implies that the uncertainty in the climate scenarios for Finland in the next few decades mainly results from the limited ability of the global models to properly describe the regional distribution of the climate change, and from the natural climate variability, rather than from alternative emissions scenarios. An important conclusion is that our possibilities of mitigating the near-term climate change by emission reductions are limited.

Later in this century, the ratio of noise due to natural climate variability to the magnitude of projected climate changes diminishes, making most of the seasonal scenarios statistically significant. The projected rather small summertime warming is at least as statistically significant as the larger warming in the other seasons. This is consistent with the fact that the observed seasonal temperature trend during the last century is statistically most significant for summer. In the course of time, the uncertainty range in climate scenarios widens, because differences in emissions scenarios and model disagreement on the regional scale increase. The fact that the high-emissions scenarios A1FI and A2 are anticipated to induce clearly stronger warming than the more moderate B1 and B2 scenarios suggests that reductions in emissions of GHGs, if realised, would have a real effect on climate change in this more distant period.

The IPCC (2001) report considers all SRES scenarios as possible images of the future. Following that premise, we did not attach any probabilities or levels of credibility to the climate change projections. The FINSKEN scenarios presented here replace the previous SILMU climate change scenarios for Finland. Progress in understanding climate processes, improving climate models, increasing computing resources and the employment of new methods, such as probabilistic approaches, will sooner or later make it necessary to update the FINSKEN climate change scenarios as well. Notwithstanding likely future advances in addressing climate change, some level of uncertainty is always inherently present in all climate change projections.

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Appendix

Some web sites and data sources

The web sites given here were accessed by the authors on 12 February 2004. The authors hope that the links prove useful to readers but cannot guarantee accessibility to them in the future.

— The web site of the FINSKEN project is http://www.finessi.info/finsken/.
— The web site of the IPCC is http://www.ipcc.ch/.
— The web site of the IPCC Data Distribution Centre (DDC) is http://ipcc-ddc.cru.uea.ac.uk/.
— Access to the AOGCM archive is via http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html.
— Guidance material provided by the IPCC DDC on the application of climate, socio-economic and environmental scenarios in climate change vulnerability, impact and adaptation assessments can be found at http://ipcc-ddc.cru.uea.ac.uk/guidelines/guidelines_home.html.
— The Climate Impacts LINK Project provides data from climate change experiments performed by the Hadley Centre for Climate Prediction and Research at http://www.cru.uea.ac.uk/link/.
— The Canadian Centre for Climate Modelling and Analysis (CCCma) provides data from a number of climate simulation models at http://www.cccma.bc.ec.gc.ca/data/data.shtml.
— The portal for a cluster of three EU-funded projects researching climate change and extreme events, namely PRUDENCE (Prediction of regional scenarios and uncertainties for defining European climate change risks and effects), STARDEX (Statistical and regional dynamical downscaling of extremes for European regions) and MICE (Modelling the impact of climate extremes) is http://www.cru.uea.ac.uk/projects/mps/.

Excluding upper-air variables, Table A1 gives the climate variables for which projected monthly means are commonly available at the IPCC Data Distribution Centre. Additional variables from modelling experiments by the HadCM3 and CGCM2 models are provided by the LINK project and the CCCma (*see* above), respectively.

Monthly and annual climatological means and extremes at Finnish stations for the periods 1961–1990 and 1971–2000 are presented by FMI (1991) and Drebs *et al*. (2002), respectively. The

Table A1. Monthly mean surface climatological data available from the six AOGCMs employed in this study (downloadable from the IPCC Data Distribution Centre).

Parameter	Unit	Availability
Mean surface air temperature	K	All
Mean maximum air temperature	K	All except ECHAM4, GFDL-R30
Mean minimum air temperature	K	All except ECHAM4, GFDL-R30
Total precipitation	mm d^{-1}	All
Large scale precipitation	mm d^{-1}	ECHAM4, NCAR-PCM
Convective precipitation	mm d^{-1}	ECHAM4, CSIRO, NCAR-PCM
Total incident solar radiation	W m^{-2}	All
Mean scalar wind speed	m s^{-1}	All
Humidity	% or kg kg^{-1}	All except ECHAM4, CSIRO
Dew point temperature	K	ECHAM4
Mean sea level pressure	Pa	All except GFDL-R30
Mean surface level pressure	Pa	GFDL-R30
Global mean sea level change	m	GFDL-R30
Surface skin temperature/SST	K	All except HadCM3
Soil moisture	mm, m or fraction	All
Snow melt	mm d^{-1}	ECHAM4, GFDL-R30
Snow amount or depth	kg m^{-2} or m	All except NCAR-PCM

former additionally contains daily mean and extreme values. Part of the statistical information is also available via the internet from the following web sites: http://www.fmi.fi/weather/climate_2.html by the Finnish Meteorological Institute and http://www.worldweather.org/061/m061.htm by the World Meteorological Organization. Time series of monthly means at 26 Finnish stations in 1890–2002 are presented by the Nordklim project (Tuomenvirta *et al*. 2001b) at http://www.smhi.se/hfa_coord/nordklim/.

Gridded climatological data sets are supplied by the Climate Research Unit (CRU) at the University of East Anglia (http://www.cru.uea.ac.uk/cru/cru.htm) and Willmott, Matsuura and collaborators in the University of Delaware (http://climate.geog.udel.edu/~climate/). The former data set covers the earth's land surfaces only. The Global Precipitation Climatology Centre (GPCC, http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/) and Global Precipitation Climatology Project (GPCP, http://wwwo.dwd.de/research/gpcc/e06.html) provide global precipitation analyses. In addition to precipitation gauges, GPCP has utilised satellite data.

While the above data sets are entirely based on observations, fields of numerous meteorological parameters have additionally been produced through reanalysis of observations. In this method, observational data are assimilated by an analysis/forecast system. Reanalyses have been performed by the NCEP/NCAR Reanalysis project (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html, http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html; *see* also http://www.cru.uea.ac.uk/cru/data/ncep/) and by ECMWF reanalyses ERA-15 and ERA-40 (http://www.ecmwf.int/products/data/). The NCEP/DOE AMIP-II Reanalysis (http://wesley.wwb.noaa.gov/reanalysis2/index.html) is based on the former.

Most of the data sets are freely available for scientific research provided that the sources are acknowledged. Additional observational and modelling datasets are available on request from several institutes.