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Climate change scenarios for Estonia based on climate models from the IPCC Fourth Assessment Report

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Abstract. Climate change scenarios were created for Estonia by employing the SRES (= Special Report on Emission Scenarios) emission scenarios and general circulation model (GCM) outputs used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) and presented at the IPCC Data Distribution Centre. Control simulations were explored for the estimation of the suitability of different GCMs to describe climatic conditions in Estonia. Comparing the modelled and observed monthly mean temperatures and precipitation during 1961–1990, better-quality GCM outputs were selected for further analysis. Climate change scenarios based on GCMs were created for Estonia for the period 2070–2099. The mean projected increase in air temperature was 3–4 K; it was slightly higher in winter than in summer. All models revealed some warming in all months. The projections of precipitation were more variable. The mean increase in annual precipitation was estimated to be mostly between 10% and 20%. An increase in precipitation was uniformly predicted for the cold season, while a variety of possible changes existed in summer. Some models projected even a decrease in precipitation in July, August and September.

Key words: climate change, climate scenario, air temperature, precipitation, general circulation model, Baltic Sea region, Estonia.

INTRODUCTION

Climate is an extremely variable component of the natural environment. It has always been changing in the past, it is changing nowadays and it will certainly change in the future. If different time periods are used for averaging, the mean values of climatic variables are usually not constant. Advances in the science and observations of climate change can provide a clearer understanding of the inherent variability of the climate system and its response to human and natural influences.

Large uncertainties exist in the forcings of the future climate changes and their responses. Climate change scenarios are used to explore potential consequences of different response options. They can be observed as descriptions of possible future climatic changes, which may be caused by different plausible future changes. Climate change scenarios are not climate predictions but storylines, alternative visions of future climatic conditions, which are possible, plausible, internally consistent but not necessarily probable (Schwartz 1991; Tol 2006). No probability has been attached to the scenarios. The purpose of climate change scenarios is to provide other scientists, stakeholders and policy-makers with possible future climatic conditions. Thus the scientists can analyse how different natural and social systems might respond to possible climate changes, and stakeholders and policy-makers can analyse the availability and usefulness of options to confront the climate changes in the future.

Climate change scenarios have been widely used since the introduction of the Intergovernmental Panel on Climate Change (IPCC) process, described in the IPCC reports, at the end of the 1980s (Houghton et al. 1990, 1992, 1996, 2001; Solomon et al. 2007). In the first step of scenario development emission scenarios for greenhouse gases and aerosols are worked out. The emission of carbon dioxide, methane and aerosols depend on various economic and social developments like population growth and advances in energy use and technology.

The concentrations of greenhouse gases are used as input data in the general circulation models (GCMs). They are also called global climate models, which are highly complex tools, embodying numerous processes and details, applicable on contemporary computers. General circulation models are based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources. These equations form the basis for complex computer programs commonly used for simulating the atmosphere and the ocean in GCMs. As a result, the possible, plausible and internally consistent future emissions are used to derive the estimates of future climatic conditions. Monthly or seasonal mean values, variability, spectra and patterns of air temperature, precipitation and other major climatic variables obtained as a result of GCM computations are considered as the global climate change scenarios (BACC Author Team 2008).

Comparisons of the GCM output data and results of meteorological measurements have been made for northern Europe already since the 1990s (Räisänen 1994). A detailed comparison of the monthly mean temperature and precipitation simulations by 20 GCMs with observations in the Baltic Sea Basin during the control period 1961–1990 is presented in the BACC book (BACC Author Team 2008). The variation between the modelled temperatures was very wide, in some cases differing from the observed values by up to 8–10 K. But the 20-model mean estimates were close to the observed temperatures except for the spring season, where an underestimation of about two degrees was found.

The seasonal cycle of precipitation is simulated by the models with much higher biases than those for temperature (BACC Author Team 2008). The highest variability of the model estimates occurred in summer. All models strongly overestimated precipitation in winter and spring, while some models overestimated and others underestimated precipitation in summer and autumn.

Regional climate models (RCMs) reproduce the actual climatic conditions downscaling the results of GCM runs (Jakob et al. 2007). Five RCMs were used for the comparison of modelling results for the Baltic Sea Basin (BACC Author Team 2008). The actual annual cycle of temperature was well represented with the ±2 K bias for single months. This bias is valid also for the modelled temperature for entire Europe (Giorgi et al. 2004). Regional climate models are successfully used for the reconstruction of climatic conditions in the Baltic Sea region for the whole of the last millennium (Schimanke et al. 2012). Using the RCM RCAO and two GCMs, the average annual bias for air temperature proved to be about 1 K in Estonia (Räisänen et al. 2003).

Comparison of the modelled by 10 RCMs monthly precipitation in the Baltic Sea region with the observed values revealed a mean error of 15% and a maximum error of single models of 25% (Kjellström & Ruosteenoja 2007). An extended study with a set of 16 RCMs, based on seven GCMs and four emission scenarios, was carried out for the representation and projection of seasonal mean temperature, precipitation and wind speed over Europe in 1961–2100 (Kjellström et al. 2011). Comparing the modelled and observed temperatures in 1961–1990, the biases were mostly below 2 K, while higher biases were seen in winter. The models overestimated winter precipitation in northern Europe.

Carter et al. (2004) described in detail the procedures of selecting GCM outputs and developing climate change scenarios for the future. Climate change scenarios for Finland, based on 15 GCM simulations, project an increase in annual mean air temperature by 2–7 K and in annual precipitation by 5–40% for the end of the 21st century (Jylhä et al. 2004). Detailed investigations on climate changes and climate change scenarios are implemented in many regions: the Netherlands (van den Hurk et al. 2006), Australia (CSIRO 2007), the Mediterranean (Somot et al. 2008), Switzerland (CH2011 2011).

The BACC book presents a 20 GCM outputs-based overview of climate change scenarios for northern and central Europe for the doubling of CO_2 concentration. The 20-model-predicted mean increase in annual mean temperature in northern Europe for the end of this century is 2.5 K. The warming in winter is higher than in summer and it increases from southwest to northeast (BACC Author Team 2008). In Estonia, the annual and summer increases were modelled to be 2–3 K and the winter increase was modelled to be 3–4 K. The corresponding mean increase in annual precipitation in northern Europe was about 10%, while in Estonia it was 10–15% in winter and 5–10% in summer.

A wide range of RCM outputs, using different SRES emission scenarios and GCMs presented in the BACC book, indicate a substantial warming for the Baltic Sea region. A warming by 4–6 K in winter (DJF) and by 3–4 K in summer (JJA) was projected for Estonia using the A2 scenario (BACC Author Team 2008). Regional climate models generally project a higher increase in precipitation in northern Europe than GCMs. First of all, it concerns winter precipitation, where an increase of 30–50% was estimated for Estonia by the A2 emission scenario for the end of this century. The precipitation change in summer is rather uncertain, varying between the 10–15% decrease and increase. A drying is more probable in southern and western Estonia (BACC Author Team 2008).

The objective of this study is to review the development of earlier climate change scenarios for Estonia and to create new scenarios using the SRES emission scenarios and the GCM outputs prepared for the IPCC Fourth Assessment Report from 2007 (AR4). It will give an overview of possible climatic changes in the 21st century.

PREVIOUS CLIMATE CHANGE SCENARIOS FOR ESTONIA

The first climate change scenarios for Estonia were developed in the 1990s. These studies were related to two large international projects for the assessment of climate change impacts. The first one was the 'U.S. Country Studies Program. Support for Climate Change Studies, National Communications and Technology Assessments', which was implemented in 1995–1996.

Following the joint methodology for the programme, a very simple emission scenario was used – a doubling of CO_2 concentration in the atmosphere by the end of the 21st century in comparison with the 1961–1990 mean level (Jaagus 1996).

Using five GCMs, the global mean temperature increase by 3.5–4.2 K was modelled for the end of the 21st century. The same indicators for Estonia were higher, ranging annually between 3.9 and 5.0 K. The highest increase was projected for the cold half-year, while it was much lower for summer. Changes in precipitation were much more variable across the models. In most cases an increase in precipitation was expected; in some cases it could be up to 50%. The projected precipitation increase was also the highest in the cold season (Jaagus 1996).

The second international project on climate change was 'Country Case Study on Climate Change Impacts and Adaptation Assessment in the Republic of Estonia. UNEP/GEF project GF/2200-96-45', carried out in 1996–1998. The emission and climate model MAGICC 2, in combination with the scenario generator SCENGEN (SCENario GENerator), was used to provide a wide range of possible climate scenarios (Keevallik 1998). MAGICC (short for Model for the Assessment of Greenhouse-gas Induced Climate Change) is a set of coupled gas-cycle, climate and ice-melt models that allows the user to determine the global mean temperature and sea-level responses to user-defined greenhouse gas and sulphur dioxide emissions. It was developed at the Climate Research Unit, University of East Anglia, UK (Hulme et al. 1995). The central IPCC scenario IS92a as well as the lowest (IS92c) and highest (IS92e) scenarios (Leggett et al. 1992) were applied to creating climate change scenarios for Estonia (Keevallik 1998).

The scenario generator SCENGEN included outputs of 14 GCMs that have been stored as patterns of monthly mean changes in climatic variables. The combinations of MAGICC and SCENGEN climatic changes for the end of the 21st century were calculated in comparison to the baseline period 1961–1990. For the particular study, two GCMs were selected: HadCM2 (moderate scenario) and ECHAM3TR (warm and wet scenario). The projected monthly temperature increase by the HadCM2 central scenario was 1.7–3.0 K, while higher values were modelled for winter months and lower values for summer months (Keevallik 1998). In the case of a low emission scenario the warming was 0.7–1.0 K and in the case of a high emission scenario it was 3.1–5.6 K. The model ECHAM3TR projected a much higher temperature increase, up to 4.2–11.5 K.

Precipitation changes calculated for the year 2100 were mostly positive. The model HadCM2 projected a moderate increase in precipitation of 10–30%, while ECHAM3TR modelled a much higher increase of 30–50% on average, especially for the period from October to May (Keevallik 1998).

The methodology for creating climate change scenarios (Smith & Hulme 1998), applied in previous research, was further used for the analysis of all possible changes available in the MAGICC/SCENGEN software (Kont et al. 2003). Three emission scenarios (IS92a, IS92c and IS92e) were combined with the outputs of all 14 GCMs using the climate sensitivity of 2.5 K. Climate change scenarios for Estonia were obtained for two grid points (57.5°N/22.5°E and 57.5°N/27.5°E) describing the territory of Estonia. As a result, a large variability of possible climatic changes was obtained (Kont et al. 2003). In the case of the IS92a emission scenario, the GCMs mostly project an increase in annual mean temperature of 2.3–4.7 K. Some models, however, indicate an extremely high warming for IS92e that exceeds the limits of the observed natural variations in Estonia. The highest warming is supposed to take place during the cold half-year. During June to September the modelled increase in air temperature is much lower. In almost every case the temperature increase is higher in the continental part of Estonia and lower in the coastal zone.

Changes in annual precipitation are related to changes in air temperature. All the GCM results indicate an increase in annual precipitation in Estonia, varying between 4% and 46% but more often averaging around 10–20%. The models that project a higher increase in air temperature also produce a higher increase in precipitation. Changes in monthly precipitation percentages are much more uncertain. They vary between a 20% decrease and a 50% increase. In general, the increase in monthly precipitation of 10–50% is projected for the cold half-year and the change by –10% to +20% is expected for the period from June to September (Kont et al. 2003).

DATA AND METHODS

All data concerning the SRES (short for Special Report on Emission Scenarios) emission scenarios-based GCM outputs were obtained from the IPCC Data Distribution Centre web page (http://www.ipcc-data.org/ar4/gcm_data.html). We used the results from the IPCC Fourth Assessment Report 2007 (AR4).

The report AR4 provides results from a wide range of different GCM runs. We used results from 22 GCM runs available on the IPCC Data Distribution Centre web page (Table 1). Thereby, three SRES emission scenarios (A1B, A2, B1) were applied. The A2 scenario represents the highest increase in the concentration of greenhouse gases, B1 indicates the lowest increase and A1B is the medium scenario with a moderate increase.

Table 1. General circulation model outputs from AR4 with different SRES emission scenarios available on the IPCC Data Distribution Centre web page

Climate research centre (abbreviation)	Climate model	SRES emission scenarios
Bjerknes Centre for Climate Research, Norway, (BCCR)	BCM2.0	A1B, A2, B1
Canadian Centre for Climate Modelling and Analysis, Canada, (CCCMA)	CGCM3 (T47)	A1B
	CGCM3 (T63)	A1B, B1
National Centre for Meteorological Research, France, (CNRM)	CM3	A1B, A2, B1
Australia's Commonwealth Scientific and Industrial Research Organisation, Australia, (CSIRO)	Mk3	A1B, A2, B1
Max-Planck-Institute for Meteorology, Germany, (MPIM)	ECHAM5-OM	A1B, A2, B1
Meteorological Institute, University of Bonn, Germany; Meteorological Research Institute of KMA, Korea; Model and Data Group at MPI-M, Germany, (MIUB, METRI, M&D)	ECHO-G	A1B, A2
Institute of Atmospheric Physics, China, (LASG)	FGOALS-g1.0	A1B, B1
Geophysical Fluid Dynamics Laboratory, USA, (GFDL)	CM2.0	A1B, A2, B1
	CM2.1	A1B, A2, B1
Goddard Institute for Space Studies, USA, (GISS)	AOM	A1B, B1
	EH	A1B, B1
	ER	A1B, A2, B1
Institute for Numerical Mathematics, Russia, (INM)	CM3.0	A1B, A2, B1
Institute Pierre Simon Laplace, France, (IPSL)	CM4	A1B, A2, B1
National Institute for Environmental Studies, Japan, (NIES)	MIROC3.2 hires	A1B, B1
	MIROC3.2 medres	A1B, A2, B1
Meteorological Research Institute, Japan, (MRI)	CGCM2.3.2	A1B, A2, B1
National Centre for Atmospheric Research, USA, (NCAR)	PCM	A1B, A2, B1
	CCSM3	A1B, A2, B1
UK Meteorological Office, UK, (UKMO)	HadCM3	A1B, A2, B1
	HadGEM1	A1B, A2

In the first step, the model outputs of the control run for 1961–1990 were compared with the observation data. We assume that the GCMs that correctly represent the main features of the current climate are also able to project the future climate more truthfully. Clearly non-adequate results were omitted from the analysis. The comparison was made for the modelled data concerning the grid cells located between 57 and 60 degrees north and 20 and 30 degrees east. This box embraces the territory of Estonia and its neighbouring areas. Depending on the model resolution, the number of grid cells within the box varies greatly. In some cases, when the resolution was quite high and the number of grid cells was also high, some marginal grid cells located far from the territory of Estonia were omitted.

In the next step, the monthly mean air temperature and precipitation values from the control run at the grid cells for 1961–1990 were compared with the mean values measured at 17 meteorological stations in Estonia (Fig. 1) during the same period. Data from the nearest station were used for each grid cell. Root-mean-square errors (RMSE) were found for the estimation of the adequacy of the GCMs in describing climatic conditions in the past. We assume that if a model describes more or less adequately the current climate, it can also give reasonable projections for the future climate.

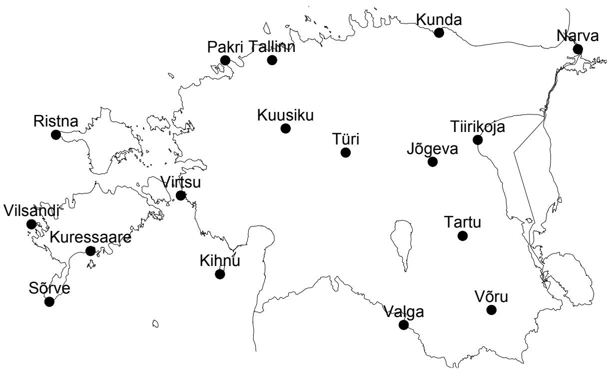

Fig. 1. Location map of meteorological stations used in this study.

In the last stage of this study, climate change scenarios were created using results of the model runs provided by reliable GCMs. Differences between the air temperatures modelled for 2070–2099 and for 1961–1990 were calculated. The future temperature projections were found using the so-called delta-change method by adding these temperature differences to the baseline climatic values measured at the stations.

The delta-change method was applied also to the calculation of precipitation changes. The percentage change of precipitation was found from the model simulations for 2070–2099 and for the baseline period 1961–1990. Then, the observed 1961–1990 mean precipitation values r_{obs} were modified by the projected per cent change Δp to get the precipitation projection r_{proj}

$$r_{\mathrm{proj}} = r_{\mathrm{obs}} \left(1 + \frac{\Delta p}{100} \right),$$

where Δp is given in per cent.

The baseline climatological values were calculated separately for western Estonia with a maritime climate and for eastern Estonia with a much more continental climate. Western Estonia is represented by mean data from the Sõrve, Vilsandi, Kuressaare and Ristna stations. In eastern Estonia, mean values were found by averaging observation data from Valga, Võru, Jõgeva and Narva.

The modelled values are presented separately for western (or maritime) Estonia with the longitude of the corresponding grid points mostly 22.5°E (for one model output 22°E and for two outputs 23.75°E) and for eastern (or continental) Estonia with a longitude between 26.25°E and 28.25°E. The latitude of the grid points varies between 57°N and 60°N, depending on the resolution of the GCM output.

In addition to the results of single models, a multi-model mean approach is used in this study. The mean change values averaged by all reliable GCMs are provided for western and eastern Estonia. The multi-model mean values give a good synthesis of all GCMs available. We compared multi-model mean estimates calculated using the 12 best GCMs and using all 22 GCMs. This will show how the results will change if less reliable models for description of climatic conditions in Estonia are omitted.

There are quite large differences between western and eastern Estonia. Temperature in the western part of the country is higher in autumn and winter, while in the eastern part it is higher in spring and at the beginning of summer. In continental Estonia, precipitation has a clear maximum in July and August. In western Estonia, the seasonal distribution of precipitation is more equal with a weak maximum in November.

SELECTION OF GCM OUTPUTS

Supporting data obtained from AR4 present a wide range of GCM results for developing climate change scenarios. Quite large differences in RMSE were revealed in the comparison of the modelled and observed temperatures and precipitation for the control run during 1961–1990 (Table 2). The output of one GCM – LASG_FGOALS-G1_0 – has many times higher values of RMSE than that of the others.

Four model runs (NCAR_CCSM3, MPIM_ECHAM5, NIES_MIROC3_2-HI, UKMO_HADGEM1) for temperature have much lower RMSE values than the other GCM outputs (Fig. 2). Thereby, MPIM_ECHAM5 and UKMO_HADGEM1 indicate a negative bias of temperature in winter and autumn, and NCAR_CCSM3 has a negative bias of temperature in summer. The model NIES_MIROC3_2-HI is the only one of all the 22 GCM outputs to reveal higher temperature in Estonia throughout a year in comparison with the observed values in 1961–1990. Other GCMs mostly indicate negative biases in the model-simulated temperature in Estonia, especially in winter (Fig. 2).

The RMSE values of precipitation in Table 2 vary largely between the GCMs. The best representations of the annual precipitation curve are presented in Fig. 3. The four GCMs with the lowest RMSE values for precipitation are not the same four GCMs that indicate the lowest errors for air temperature. Consequently, none of

Table 2. Root-mean-square errors (RMSEs) of monthly mean air temperature and precipitation calculated between the modelled for AR4 and the observed monthly mean values for 1961–1990

General circulation model	RMSE-temperature, K	RMSE-precipitation, mm
BCCR_BCM2	9.8	16.7
CCCMA_CGCM3_1-T47	6.1	13.3
CCCMA_CGCM3_1-T63	6.5	14.0
CNRM_CM3	6.2	17.0
CONS_ECHO-G	6.7	15.7
CSIRO_Mk3	7.1	11.4
GFDL_CM2	6.8	16.1
GFDL_CM2_1	4.9	13.9
INM_CM3	7.0	10.1
IPSL_CM4	8.6	19.3
LASG_FGOALS-G1_0	15.1	35.3
MPIM_ECHAM5	2.5	14.5
MRI_CGCM2_3_2	7.5	11.2
NASA_GISS-AOM	6.5	10.3
NASA_GISS-EH	9.3	26.0
NASA_GISS-ER	9.7	26.5
NCAR_CCSM3	1.7	24.3
NCAR_PCM	7.1	11.9
NIES_MIROC3_2-HI	2.6	19.4
NIES_MIROC3_2-MED	5.3	19.2
UKMO_HADCM3	8.2	11.8
UKMO_HADGEM1	3.4	14.1

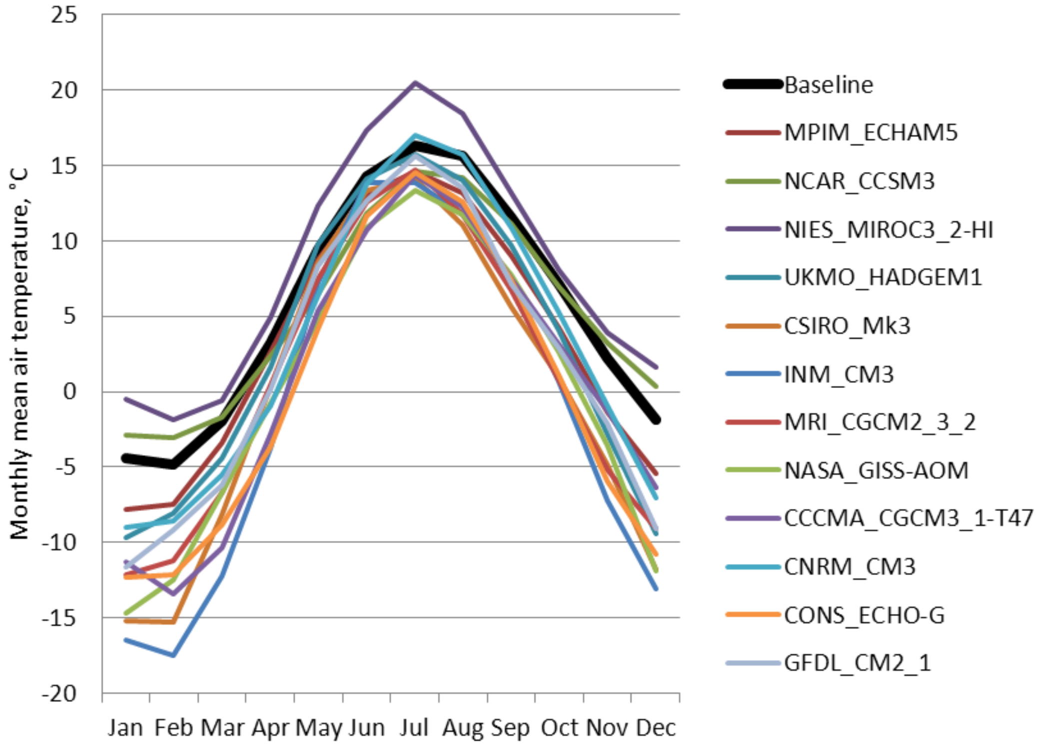

Fig. 2. Observed monthly mean temperatures (baseline) and the modelled values in western Estonia using 12 selected GCM outputs from AR4 during the control period 1961–1990.

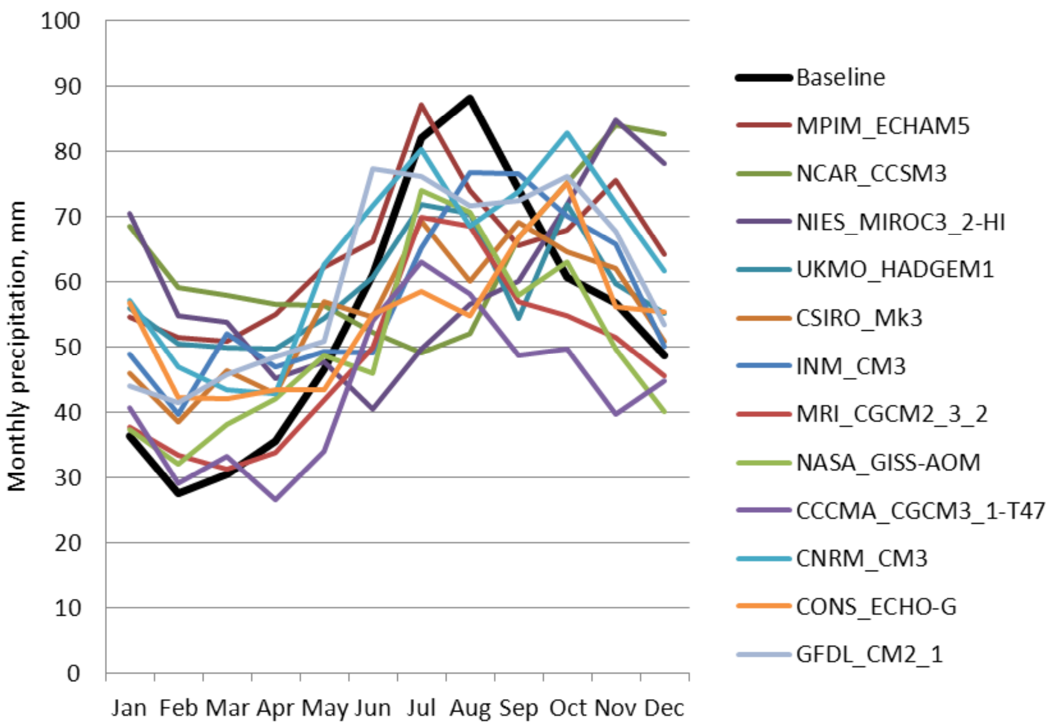

Fig. 3. Observed monthly mean precipitation (baseline) and the modelled values in eastern Estonia using 12 selected GCM outputs from AR4 during the control period 1961–1990.

the models is able to produce a good simulation for both variables. Generally, winter and spring precipitation in Estonia is overestimated, except by MRI_CGCM2_3_2, and summer and autumn precipitation is underestimated, except by CSIRO_Mk3 and INM_CM3 in autumn (Fig. 3).

We selected 12 GCM outputs for the creation of climate change scenarios up to the end of the 21st century: four best GCMs in describing temperature (NCAR_CCSM3, MPIM_ECHAM5, NIES_MIROC3_2-HI, UKMO_HADGEM1), four best in describing precipitation (INM_CM3, NASA_GISS-AOM, MRI_CGCM2_3_2, CSIRO_Mk3) and four more GCMs with more or less adequate results (CCCMA_CGCM3_1-T47, CNRM_CM3, CONS_ECHO-G, GFDL_CM2_1). The annual curves of control runs of these models are presented in Figs 2 and 3. At the same time we compared multi-model mean values calculated using the 12 best GCMs and using all 22 GCMs.

TEMPERATURE CHANGE SCENARIOS FOR ESTONIA

All together 12 GCM outputs from the AR4 supporting database were selected for developing climate change scenarios for Estonia. Annual average change values for these GCM outputs regarding three SRES emission scenarios are presented in Table 3. The values are given separately for western (or maritime) and eastern (or continental) Estonia. In addition, multi-model mean change values are presented for the 12 selected GCMs and for all 22 GCMs. Thereby, not all models have provided outputs for all three emission scenarios. Therefore, these multi-model mean values are not fully comparable with each other.

The mean change values for the A1B, A2 and B1 emission scenarios calculated by the use of the 12 models were 3.9, 4.5 and 2.7 K in eastern Estonia.

Table 3. Annual mean temperature changes and percentage change of precipitation in western and eastern Estonia projected for 2070–2099 according to the SRES emission scenarios and the general circulation models (GCMs) used for AR4

GCM	Temperature change, K			Precipitation change, %		
	A1B	A2	B1	A1B	A2	B1
Western Estonia						
CCCMA_CGCM3_1-T47	2.5	–	–	18.6	–	–
CNRM_CM3	2.8	3.2	1.6	4.7	10.7	–
CONS_ECHO-G	4.9	5.5	–	21.4	21.6	–
CSIRO_Mk3	4.2	5.2	2.2	11.9	15.4	9.8
GFDL_CM2_1	3.6	3.6	2.6	28.0	22.4	6.7
INM_CM3	4.1	5.2	3.3	23.7	32.1	19.2
MPIM_ECHAM5	3.9	3.7	2.7	17.2	17.5	13.4
MRI_CGCM2_3_2	3.2	3.5	2.5	21.1	24.7	10.7
NASA_GISS-AOM	2.9	–	1.9	25.4	–	23.6
NCAR_CCSM3	3.6	4.6	2.7	20.4	11.2	8.2
NIES_MIROC3_2-HI	5.8	–	4.2	23.5	–	24.7
UKMO_HADGEM1	5.1	–	–	8.2	–5.6	–
12 multi-model mean	3.8	4.3	2.6	18.7	17.9	14.5
22 multi-model mean	4.0	4.7	3.0	18.8	20.2	14.7
Eastern Estonia						
CCCMA_CGCM3_1-T47	2.8	–	–	20.2	–	–
CNRM_CM3	3.3	4.1	2.1	12.9	16.4	–
CONS_ECHO-G	4.9	5.5	–	26.0	26.9	–
CSIRO_Mk3	4.0	5.1	2.3	10.6	13.4	4.8
GFDL_CM2_1	3.9	4.0	2.6	29.1	22.3	8.3
INM_CM3	4.1	5.2	3.3	23.7	32.1	19.2
MPIM_ECHAM5	3.9	3.9	2.8	19.2	21.9	15.5
MRI_CGCM2_3_2	3.2	3.4	2.5	22.9	30.1	13.3
NASA_GISS-AOM	2.6	–	1.7	18.3	–	16.6
NCAR_CCSM3	3.8	4.8	2.9	16.6	15.2	9.2
NIES_MIROC3_2-HI	5.6	–	4.3	16.9	–	22.7
UKMO_HADGEM1	5.1	–	–	6.3	–4.3	–
12 multi-model mean	3.9	4.5	2.7	18.6	20.3	13.7
22 multi-model mean	4.1	4.9	3.1	18.3	21.2	13.8

The responses were virtually the same in western Estonia. The highest warming was projected by the NIES_MIROC3_2-HI, UKMO_HADGEM1 and CONS_ECHO-G models, while a comparatively lower increase was modelled by the CCCMA_CGCM3_1-T47, CNRM_CM3 and NASA_GISS-AOM models.

It is interesting to recognize that the multi-model mean change values for all 22 models are systematically higher than that for the 12 selected models. It can be concluded that the models representing the current temperature curve in Estonia with lower bias project lower increase in temperature for the end of the 21st century than the other climate models.

The multi-model mean annual curves of monthly mean temperature changes for 2070–2099 in comparison with the baseline period 1961–1990 in western Estonia (Fig. 4A) and in eastern Estonia (Fig. 4B) demonstrate a clear warming during the whole year. The change estimates do not vary much between the both parts of Estonia.

The expected warming is higher in winter than in summer. The emission scenarios A1B and A2 show more or less similarly a warming by 5–6 K in winter and by 3 K in summer. The scenario A2 projects higher change values for winter months and A1B for summer months. The fact that the A2 emission scenario would produce smaller temperature responses than A1B for summer months is evidently due to the smaller ensemble size (9 models for A2 and 12 for A1B). There are some models that simulate a large warming for A1B but for which the A2 simulation is not available. The winter warming in eastern Estonia is projected to be about one degree higher than in western Estonia. The emission scenario B1 indicates a moderate warming – by 2 K in summer and by 3–4 K in winter.

Extreme change values modelled by single GCMs are also presented in Fig. 4. They show a large variability. The highest change values in winter (above 10 K) are modelled by CONS_ECHO-G and CSIRO_Mk3, while the lowest increase in mean air temperature in summer is obtained by MRI_CGCM2_3_2 and GFDL_CM2_1.

The change estimates of monthly mean temperature of single models for the period 2070–2099 in the case of the emission scenario A1B vary within five degrees (Fig. 5). Mean temperature in summer months is projected to be 17–22 °C. The same modelled values for winter are different in western and eastern Estonia: from 0 °C to +5 °C for western Estonia with maritime climate (Fig. 5A) and from –5 °C to 0 °C for eastern Estonia with much more continental climate (Fig. 5B). Among the models, NIES_MIROC3_2-HI projects the highest warming during the warm half-year, and CONS_ECHO-G and INM_CM3 show the highest warming during the cold half-year. The model CCCMA_CGCM3_1-T47 indicates explicitly lower winter temperatures for continental Estonia than the other model outputs.

PRECIPITATION CHANGE SCENARIOS FOR ESTONIA

The climate change scenarios for precipitation are usually much more variable, showing unequal direction of change. The mean change values of annual precipitation for the 12 selected GCM outputs regarding three SRES emission scenarios are presented in Table 3. The multi-model mean change values of annual precipitation for the A1B, A2 and B1 emission scenarios in western Estonia were 18.7%, 17.4% and 14.5% and in eastern Estonia 18.6%, 20.3% and 13.7%. Higher change values were observed in the case of INM_CM3 and GFDL_CM2_1, while a small change was projected by UKMO_HADGEM1 and CNRM_CM3.

The differences between the multi-model mean annual curves of monthly mean precipitation changes for 2070–2099 using three SRES emission scenarios are not significant (Fig. 6). Only in winter the GCM outputs using the emission scenario A2 indicate a higher mean increase in precipitation of about 30%. At the same time, in the case of the scenario B1, the projected increase in precipitation in winter was only between 10% and 20%. The modelled mean changes in the warm half-year were between 0 and 10%. Precipitation increase was higher in winter and lower in summer in eastern Estonia (Fig. 6B) than in western Estonia (Fig. 6A).

The variability of precipitation projections for 2070–2099 among single GCM outputs is very high. They vary between –30% and +60% (Fig. 6), reflecting a large uncertainty in precipitation estimations between different models. All model outputs agree with an increase in winter precipitation but disagree in the prediction of summer rainfall. The highest positive change values above 50% were provided by CCCMA_CGCM3_1-T47 and NIES_MIROC3_2-HI in April, by GFDL_CM2_1 in May and by INM_CM3 in June. The highest negative precipitation changes below –20% were projected by CNRM_CM3 in August and September and by UKMO_HADGEM1 in September in the case of the A2 scenario.

In the case of climate warming, an increase in winter precipitation could be expected. Higher temperature is usually caused by cyclonic weather conditions with clouds, strong wind and high precipitation in Estonia. The warmed atmosphere is able to contain more water vapour than present. Cold weather is mostly related to anti-cyclonic weather with a clear sky and intense radiative cooling.

Possible precipitation changes corresponding to climate warming in summer and autumn are more uncertain (Fig. 7). Most of the GCM outputs project an increase, in some cases even a large increase in precipitation. In some models the monthly mean values cross the 100 mm line in July and August. At the same time, the GFDL_CM2_1 and NASA_GISS-AOM models show a clear decrease in precipitation in July, August and September.

Differences in the annual curves of precipitation between the western and eastern parts of Estonia remain in precipitation change scenarios for the end of the 21st century. In the majority of the model projections the maximum precipitation in eastern Estonia is observed in August (Fig. 7B), but in November in western Estonia (Fig. 7A).

DISCUSSION

Comparison of the modelled temperatures and precipitation with the observed data enables evaluation of the adequacy of single models to describe current climatic conditions. The main characteristic used for this purpose was RMSE. The calculations demonstrate that the RMSE for monthly mean surface air temperature for Estonia with the AR4 model outputs is highly variable, rising up to 15 K, but in the best cases being 1.7–3.4 K (Table 2). There are many reasons for such errors. In the case of a low grid resolution of a GCM, the nearest meteorological station may be located quite far from the grid point. Here, the error is natural and not primarily caused by the model bias. However, mostly, this was not the case.

Generally, GCMs underestimate temperature in Estonia, especially in winter, but there were still some exceptions. Among the AR4 GCM outputs, only NIES_MIROC3_2-HI modelled higher than actual temperatures throughout a year (Fig. 2). In addition, the NCAR_CCSM3 output indicated higher temperature in western Estonia in winter, but other results from the 12 GCMs used in this study modelled much lower temperatures.

For the majority of the GCMs, the annual curve of precipitation in Estonia is not modelled adequately. Only the best AR4 models represent it more or less reliably (Fig. 3). The winter and spring values are mostly overestimated and the summer and autumn values are underestimated. Biases were much larger in the case of the other GCMs.

The control simulations showed that no GCM is much better than the others. This statement is well known and has been pointed out by many studies (BACC Author Team 2008). The models having the lowest errors in temperature and in precipitation were not the same. At the same time, some GCMs presented obviously weaker results for Estonia, for example LASG_FGOALS-G1_0.

A large variety of climate change scenarios, created by different GCM-based sources, as well as multi-model mean values enable the discussion of possible future climatic conditions in Estonia. All scenarios project a temperature increase as they predict an increase in greenhouse gas concentrations during the 21st century. The mean increase in annual mean air temperature of 3–4 K was projected for Estonia already by the first climate change scenarios (Jaagus 1996; Keevallik 1998) and it was repeated by the further estimations by Kont et al. (2003), by RCM-based scenarios for Europe (Räisänen et al. 2004; BACC Author Team 2008; Kjellström et al. 2011) and by the results of the AR4 GCM outputs presented in this article. This estimation is valid under the A1B scenario or with somewhat smaller future emissions.

We can conclude that the mean warming by 3–4 K is the most probable and reliable estimation of climate change in Estonia for the end of the 21st century. Naturally, there are higher estimations, especially in the case of the A2 emission scenario, and lower ones, first of all in the case of the B1 scenarios. The results of different GCMs also vary greatly. Some models indicate a much higher warming (NIES_MIROC3_2-HI, UKMO_HADGEM1, CONS_ECHO-G) and some others a much lower one (CCCMA_CGCM3_1-T47, NASA_GISS-AOM).

The projected changes in the precipitation regime are much more uncertain. Generally, a significant increase in winter precipitation is projected by all models that we are using. Most of the GCM outputs foresee a moderate increase in annual precipitation in Estonia. The mean projected increase is about 10–20%. The first climate change scenarios predicted even a higher increase in annual precipitation (Jaagus 1996; Keevallik 1998). Later models, rather, show a moderate increase that is much lower than the inter-annual natural variability of annual precipitation.

At the same time, the model projections for summer precipitation are very different. Some models, for example CNRM_CM3 and UKMO_HADGEM1, suggest a drying in summer, i.e., a decrease in precipitation. The other models indicate a significant increase in summer precipitation (NCAR_CCSM3, CONS_ECHO-G, MRI_CGCM2_3_2).

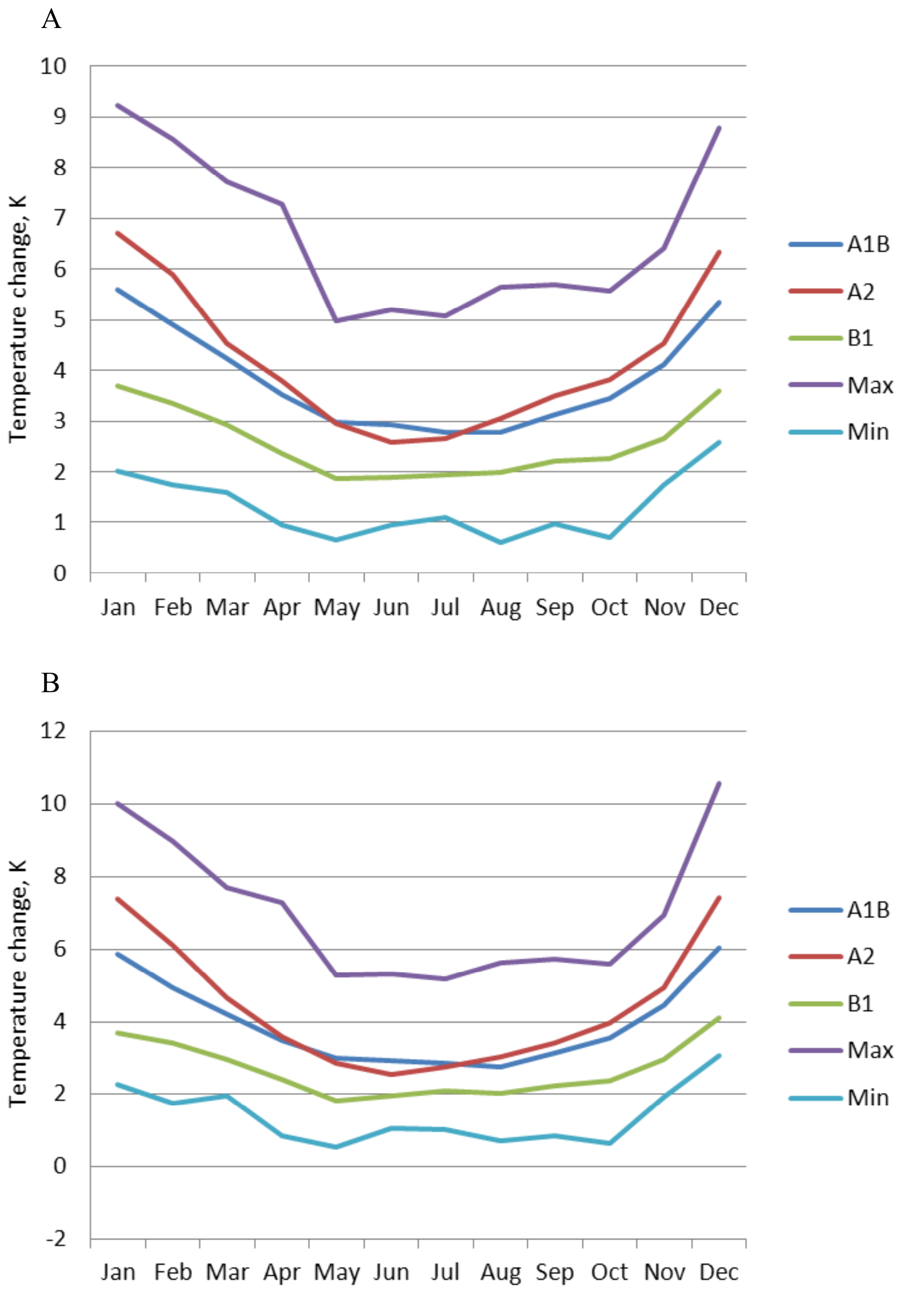

Fig. 4. Multi-model mean annual curves of monthly mean temperature changes for 2070–2099 (in comparison with the 1961–1990 baseline period) in western Estonia (**A**) and in eastern Estonia (**B**) using three SRES emission scenarios and 12 selected GCM outputs together with the absolute maximum and minimum estimates of these GCMs.

CONCLUSIONS

The main results of this study allow us to draw the following conclusions.

- The best control simulations of the GCMs from AR4 for the period 1961–1990 revealed the RMSEs of monthly mean air temperature between 2 and 3 K. The models mostly underestimated temperature. Control simulations gave different results for monthly mean precipitation. They mostly overestimated winter precipitation and underestimated summer precipitation.
- Climate change scenarios for air temperature in Estonia simulate an increase in annual mean temperature of 3–4 K for the end of the 21st century. The A2 emission scenario shows a higher increase and the B1 a lower increase.

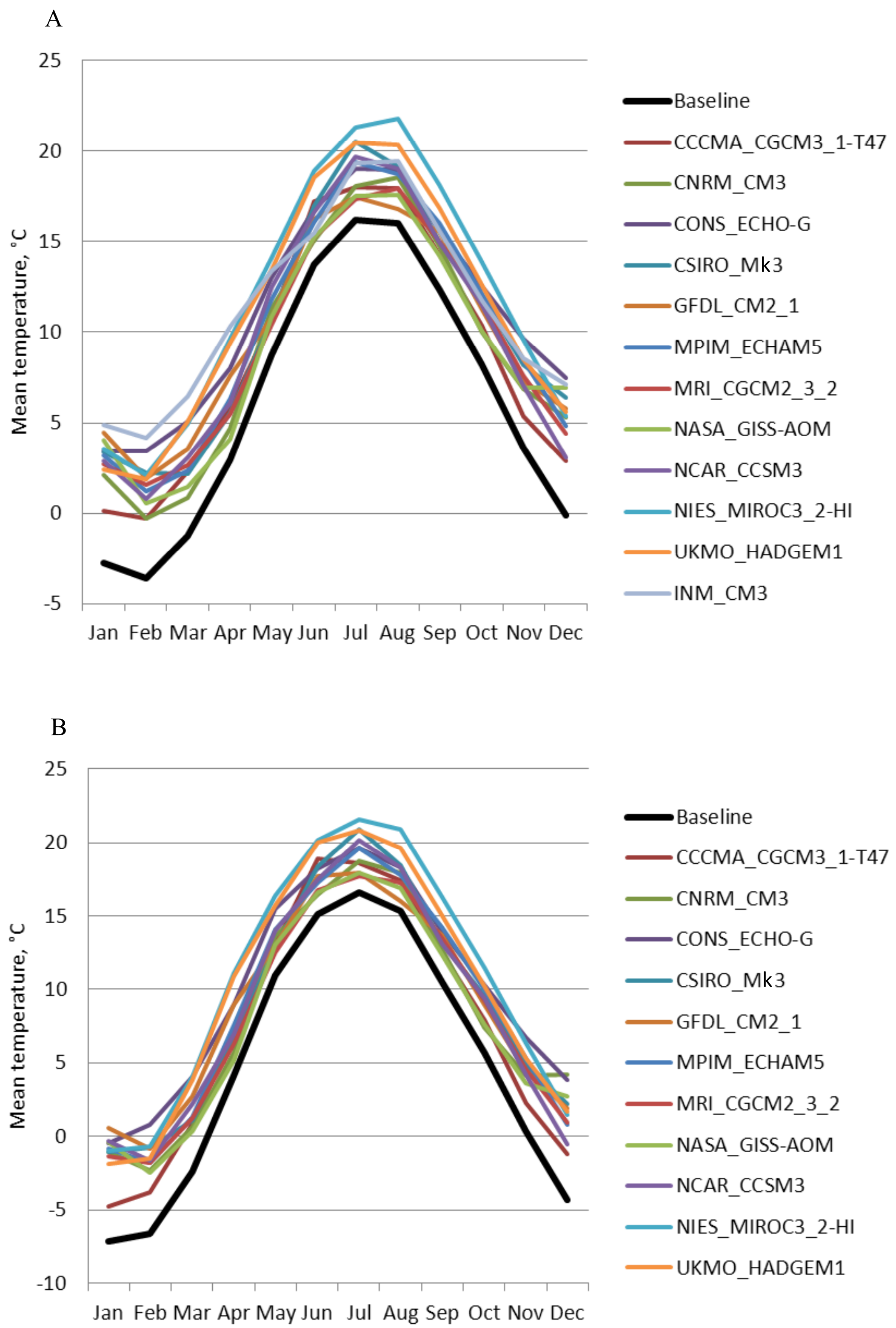

Fig. 5. Annual curve of monthly mean temperatures in western (**A**) and eastern (**B**) Estonia observed in 1961–1990 (baseline) and modelled for 2070–2099 using the A1B emission scenario and 12 GCM outputs.

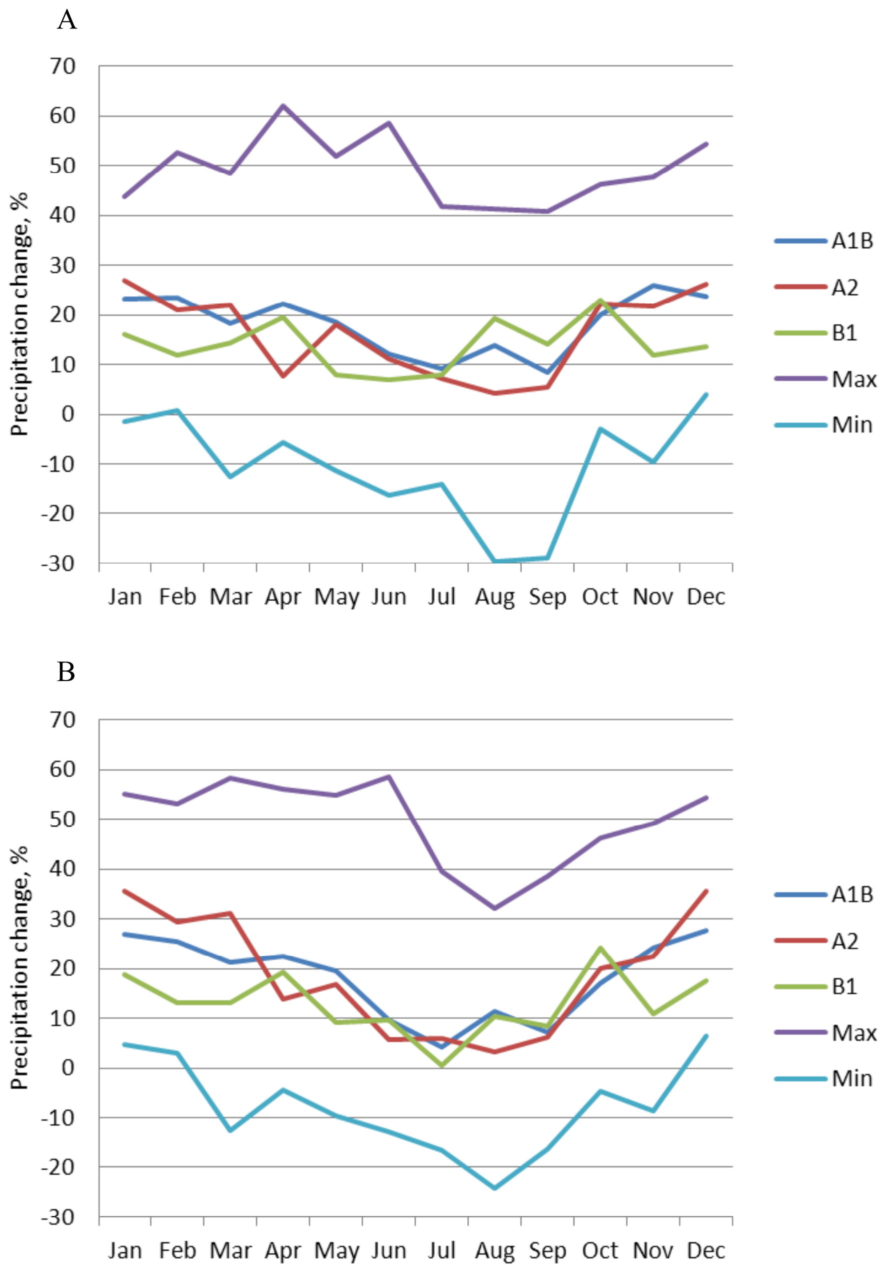

Fig. 6. Multi-model mean annual curves of monthly mean precipitation changes (in comparison with the 1961–1990 baseline period) in western Estonia (**A**) and in eastern Estonia (**B**) for 2070–2099 using three SRES emission scenarios and 12 selected GCM outputs from AR4 together with the absolute maximum and minimum estimates of these GCMs.

- For the end of the 21st century, the climate change scenarios for precipitation in Estonia project a mean 10–20% increase in annual precipitation. A higher increase is expected for winter, while some models show even a decrease in precipitation in July, August and September.

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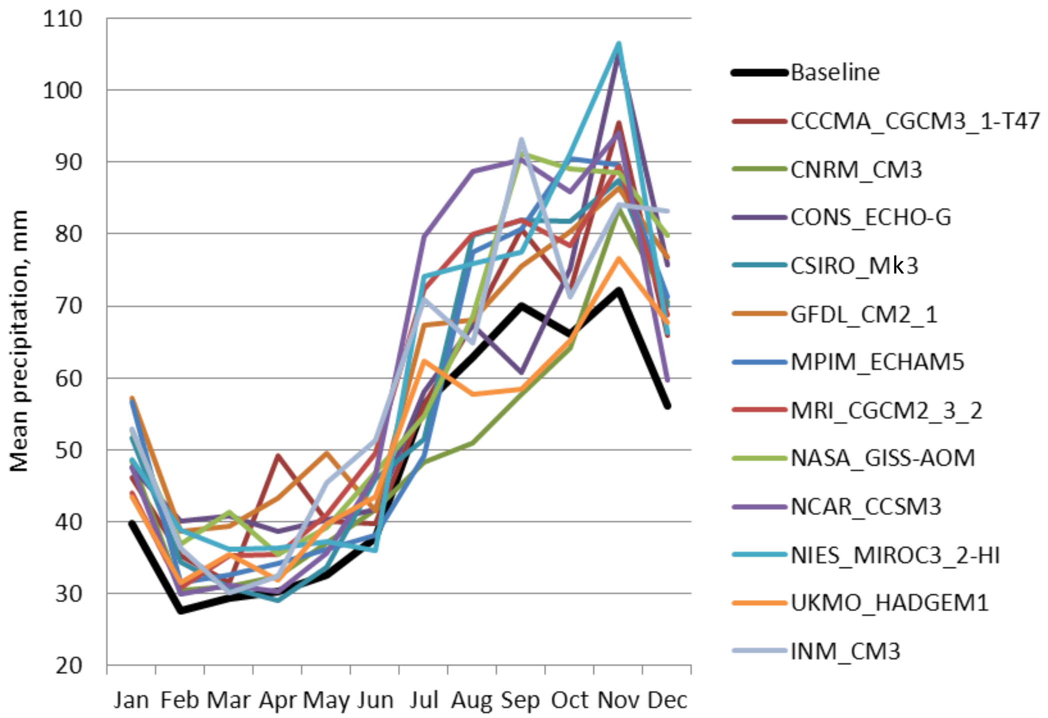
A



B

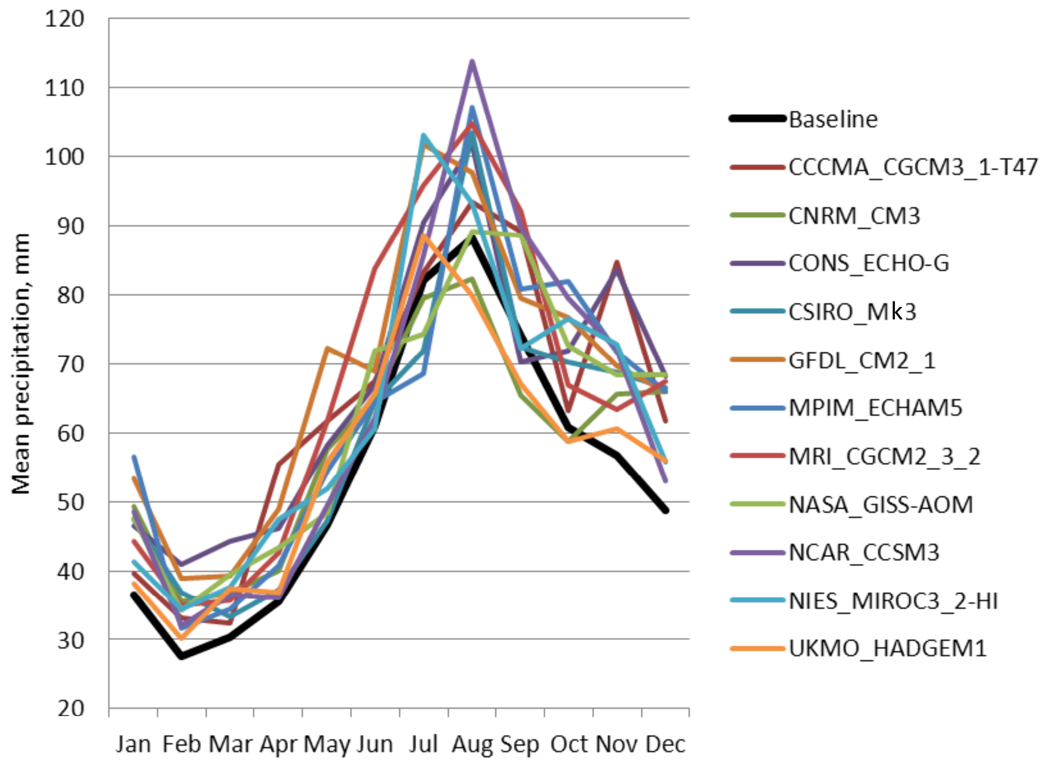


Fig. 7. Annual curve of monthly mean precipitation in western (**A**) and eastern (**B**) Estonia observed in 1961–1990 (baseline) and modelled for 2070–2099 using the A1B emission scenario and 12 GCM outputs from AR4.

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Kliimamuutuse stsenaariumid Eesti jaoks

Jaak Jaagus ja Kaupo Mändla

Kliimamuutuse stsenaariumid Eesti jaoks on koostatud, kasutades SRES-i emissiooni stsenaariume ja globaalsete kliimamudelite tulemusi, mida kasutati IPCC 4. aruandes ning mis on kättesaadavad IPCC andmekeskuse veebilehelt. Tehti kontrollarvutused, et hinnata erinevate kliimamudelite sobivust Eesti kliimatingimuste kirjeldamiseks. Võrreldes modelleeritud ja mõõdetud kuu keskmisi õhutemperatuure ning sademete hulki perioodil 1961–1990, valiti järgnevaks analüüsiks välja paremad mudelid. Kuu keskmise temperatuuri ruutkeskmised vead olid neil 2–4 K, sademetel aga 10–15 mm. Kliimamudelitel põhinevad kliimamuutuse stsenaariumid koostati perioodi 2070–2099 kohta. Keskmiseks eeldatavaks õhutemperatuuri tõusuks hinnati 3–4 K, mis on mõnevõrra suurem talvel ja väiksem suvel. Kõik mudelid näitasid soojenemist kõikidel kuudel. Sademete prognoosid on palju varieeruvamad. Aastase sademete hulga keskmine suurenemine jääb vahemikku 10–20%. Sademete hulga tõus külmal poolaastal on modelleeritud kõigi mudelite poolt, kuid suvised eeldatavad muutused on mudelitel vastukäivad. Mõni mudel eeldab isegi sademete vähenemist juulis, augustis ja septembris.