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Changes in the water budget in the Baltic Sea drainage basin in future warmer climates as simulated by the regional climate model RCA3

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In this study we investigate three different regional climate change scenarios with respect to changes in the water budget over the Baltic Sea drainage basin. The scenarios are transient climate change scenarios in which the regional climate model RCA3 has been used to downscale results from two general circulation models, with three different emissions scenarios, for the years 1961–2100. First we show that the control climate in the late 20th century is too wet as compared with observations. This wet bias in the simulations is partly attributable to biases in the forcing global models but is also amplified in the regional climate model. The future climate change signal shows a gradually warmer and wetter climate during the 21st century with increased moisture transport into the region via the atmosphere. This leads to an intensification of the hydrological cycle with more precipitation and evaporation. The net precipitation increases in all scenarios in the entire region. The changes are of the order 15%–20% for annual and areal mean fluxes.

Introduction

The water cycle over the Baltic Sea drainage basin is in focus in the European continental-scale Baltic Sea Experiment (BALTEX) (e.g. Raschke *et al*. 2001). An early attempt to quantify water fluxes in this area, with the aid of a numerical weather prediction model, was made by Heise (1996). Since then, several regional atmospheric model systems have been used in process oriented studies of the water cycle over the Baltic Sea drainage basin (e.g. Jacob *et al*. 2001). Work with regional models in the area includes model development and evaluation of their performance in the present-day climate both for shorter relatively well-observed periods (e.g. Hagedorn *et al*. 2000) and for long 30- or 40-year climatologies (Hagemann *et al*. 2005, Kjellström *et al*. 2005, Lind and Kjellström 2009).

Forced by an enhanced greenhouse effect, climate models project future warming that is more pronounced in northern Europe, including the Baltic Sea drainage basin, than the global average (Christensen *et al*. 2007). A synthesis of global and regional climate change projections for the end of the 21st century, specifically for the Baltic Sea drainage basin, is presented in Graham *et al*. (2008). They show the largest temperature increases for winter in northern parts of the basin while changes in the seasonal cycle of temperature are less clear in the south. Precipitation is projected to increase in the entire area except in the southernmost parts during summer (Kjellström and Ruosteenoja 2007, Graham *et al*. 2008). The combined effect of changes in precipitation and temperature-driven changes in evaporation may change the entire water budget of the area by the end of the century.

Most regional climate change scenarios that have been reported (e.g. Graham *et al*. 2008) deal with time slice experiments, in which a future period (typically 2071–2100) under some emission scenario is compared with a reference period (typically 1961–1990). Recently, the advent of long, regional climate simulations covering the entire 21st century has made it possible to investigate the continuous transient climate change signal (Kjellström *et al*. 2005). Here we investigate how the water budget changes with time in three different regional climate-change simulations. First, we show how the regional climate model RCA3 (Kjellström *et al*. 2005) reproduces this budget with boundary conditions from two coupled atmosphere–ocean general circulation models (AOGCMs) for a control period, 1961–1990. This is done by comparing the components of the simulated water budget for the control period with other data sets including observations and reanalysis data that build on a combination of short-range weather forecasts and observational data. Next, we look at three simulations covering the 21st century with RCA3 downscaling the two AOGCMs. For one AOGCM we use one emission scenario and for the other we use two different emissions scenarios. Changes in the water budget are analyzed in terms of annual means and changes in the seasonal cycle. Finally, we discuss differences between the water budget components as simulated in RCA3 and in the forcing AOGCMs.

Material and methods

The Rossby Centre regional model

RCA3 is a regional climate model that contains a full description of the atmosphere and its interaction with the land surface. It includes a land surface model (Samuelsson *et al*. 2006) and a lake model, PROBE (Ljungemyr *et al*. 1996). Sea-surface temperature (SST) and sea-ice conditions are prescribed for all ocean areas including the Baltic Sea. Given realistic boundary conditions, such as the reanalysis products ERA15 (Gibson *et al*. 1997) and ERA40 (Uppala *et al*. 2005), RCA3 and its predecessor RCA2 reproduces regional scale climate conditions (Jones *et al*. 2004, Kjellström *et al*. 2005). Further documentation and evaluation of RCA3 can be found in Kjellström *et al*. (2005) and Lind and Kjellström (2009).

Changes with time of the radiative forcing in RCA3 are prescribed to follow the forcing history in the driving global model. As RCA3 does not explicitly account for different greenhouse gases and/or aerosols this is accomplished for by changing the equivalent CO_2 concentration. For further details of the application of the forcing conditions in the experiments described below *see* Kjellström *et al*. (2005) and Persson *et al*. (2007).

RCA3 was run at 0.44° × 0.44° (approximately 49 km × 49 km) horizontal resolution with 24 levels up to 10 hPa in the vertical direction at a time step of 30 minutes. The model domain covers Europe (Fig. 1).

Boundary data from global models and climate change scenarios

Lateral boundary conditions and SSTs needed in RCA3 were updated every six hours from the reanalysis product ERA40 and from either of two AOGCMs. These were ECHAM4/OPYC3 (Roeckner *et al*. 1999), and ECHAM5/MPIOM (Jungclaus *et al*. 2006, Roeckner *et al*. 2006). For brevity, in the following we denote these by their atmospheric components only, i.e. ECHAM4 and ECHAM5. RCA3 was first used to simulate a control period in the late 20th century, both with an AOGCM or ERA40 data on the boundaries. Subsequently, three climate change experiments were performed for the 21st century. Future changes in radiative forcing follow the A2, A1B and B2 emission scenarios from the Special Report on Emission Scenarios (SRES) by the Intergovernmental Panel on Climate Change (Nakićenović *et al*. 2000). The A2 and B2 scenarios were used in the ECHAM4 simulations and the A1B scenario in the ECHAM5 simulation. Table 1 summarizes the experiments and introduces abbreviations used in the text.

Evaluation data

Simulated near-surface temperature and precipitation are compared with the global, land-only, gridded observational data from the Climate Research Unit, University of East Anglia (CRUTS2.1, Mitchell and Jones 2005). Precipitation fluxes in CRUTS2.1 are based on gauge measurements. ERA40 data on precipitation and near-surface temperature are also used. The ERA40 data are partly based on observations as these have an influence on the model forecast through the process of data assimilation. Particularly near-surface temperature is heavily dependent on observations. However, the precipitation fluxes in ERA40 are predicted variables. As the forecast model underestimates precipitation during the first hours (Hagemann *et al*. 2005) we choose to use precipitation fluxes for the forecast interval 12–24 hours to obtain a more realistic climatology. In the following ERA40 and CRUTS2.1 refer to these two data sets for the years 1961–1990.

Calculation of terms in the water budget

Precipitation (*P*) and evaporation (*E*) were stored at high temporal resolution in the model calculations. We did not store information about atmospheric moisture convergence (MC) explicitly in any region. The MC into the Baltic Sea drainage basin and the Baltic Sea (Fig. 1) was instead calculated as a residual, i.e. taken as the difference between *P* and *E* integrated over that area. To calculate MC we assumed that the water content of the reservoirs does not change over long periods of time. For comparisons of water fluxes in RCA3 and the corresponding AOGCMs results

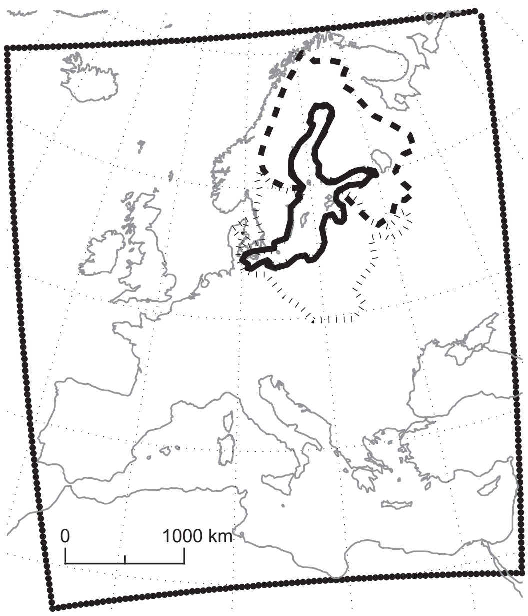

Fig. 1. The domain used in RCA3. Shown are also the Baltic Sea (full line) and its drainage basin divided into the northeastern (dashed) and southwestern (dotted) parts as used here.

Table 1. Experiments. The initial R in the experiment names stands for RCA3, if omitted we refer to the corresponding global model. ERA/E4/E5 represents different sources of boundary data. CTRL stands for control period while B2/A2/A1B indicates which emission scenario that is used.

Experiment name	Boundary data	Emission scenario	Simulated period
RERA	ERA40	Linearly increasing CO_2 (1.5 ppm_v per year)	1961–2002
RE4CTRL	ECHAM4	*See* Kjellström *et al.* 2005 for details	1961–1990
RE5CTRL	ECHAM5	*See* Kjellström *et al.* 2005 for details	1951–2000
RE4B2	ECHAM4	SRES B2	1991–2100
RE4A2	ECHAM4	SRES A2	1991–2100
RE5A1B	ECHAM5	SRES A1B	2001–2100

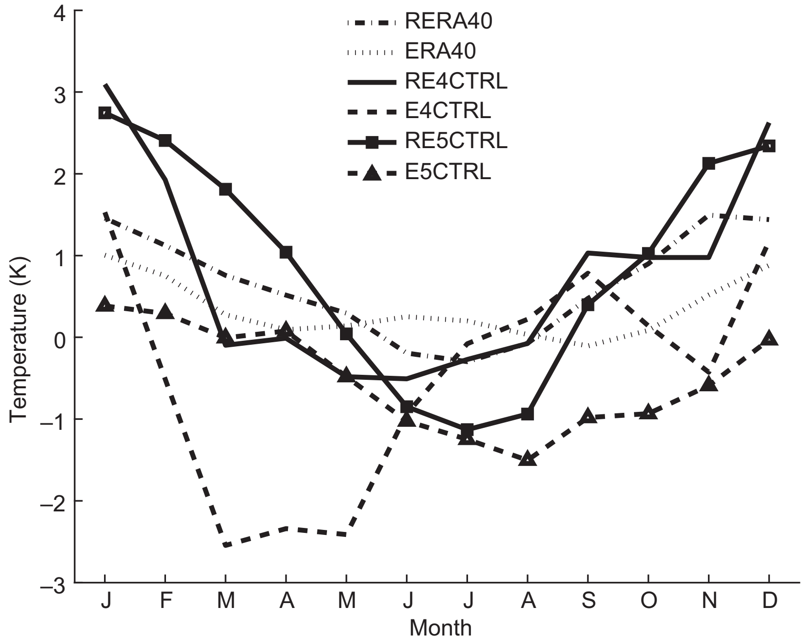

Fig. 2. Monthly mean biases in near-surface (2-metre level) temperature over all land in the Baltic Sea drainage basin in the three simulations with RCA3 and in the corresponding AOGCMs (*see* Table 1 for abbreviations) and in ERA40. All data are averages for the years 1961–1990.

from the latter were first interpolated into the RCA3 grid (Fig. 1).

RCA3 does not include river routing implying that we could not directly calculate river discharge into the Baltic Sea. Further, the land surface scheme in RCA3 calculates runoff generation (R) explicitly only for the land fraction of each grid box in the model domain. P and E, on the other hand, are calculated for the entire grid box, including land, lake and sea fractions. Therefore, R could not be directly compared with the $P - E$ in terms of describing the integrated river discharge into the Baltic Sea. Instead, river discharge into the Baltic Sea was estimated as the residual between P and E over the land areas in the Baltic Sea drainage basin. Here it is assumed that there are no long-term changes in the storage of water in the ground.

To close the water budget of the area the outflow of water from the Baltic Sea to the North Sea is taken as $P - E$ over the entire area (land and sea). Assuming no changes in the freshwater storage in the Baltic Sea this outflow is by definition equal to the MC into the Baltic Sea drainage basin. All fluxes in the budget calculations were aggregated by averaging over the years 1961–1990 and 2071–2100 for control and scenario periods, respectively.

Results

The control climate

The area average differences in near surface temperature between ERA40 and CRUTS2.1 are generally less than ±1 K as monthly averages over land points within the Baltic Sea drainage basin (Fig. 2). Forced by ERA40 on the boundaries RERA40 follows the near surface temperature climate in ERA40 to within ±0.5 K for all months. A systematic difference is a weaker seasonal cycle in RERA40 by almost 1 K as compared with that in ERA40. A similar feature, with a relatively mild winter half of the year in RERA40 as compared with that in ERA40, is also seen for RE4CTRL and RE5CTRL as compared with that for the corresponding AOGCMs. With CRUTS2.1 as the reference, RE4CTRL/RE5CTRL show temperature biases peaking at almost 3 K in December and January. These biases are larger than the corresponding biases in RERA40.

Precipitation in RCA3 and the forcing global models show some differences in their respective seasonal cycles (Fig. 3). In winter, when there is a strong forcing from the lateral boundaries, RCA3 follows the global models relatively

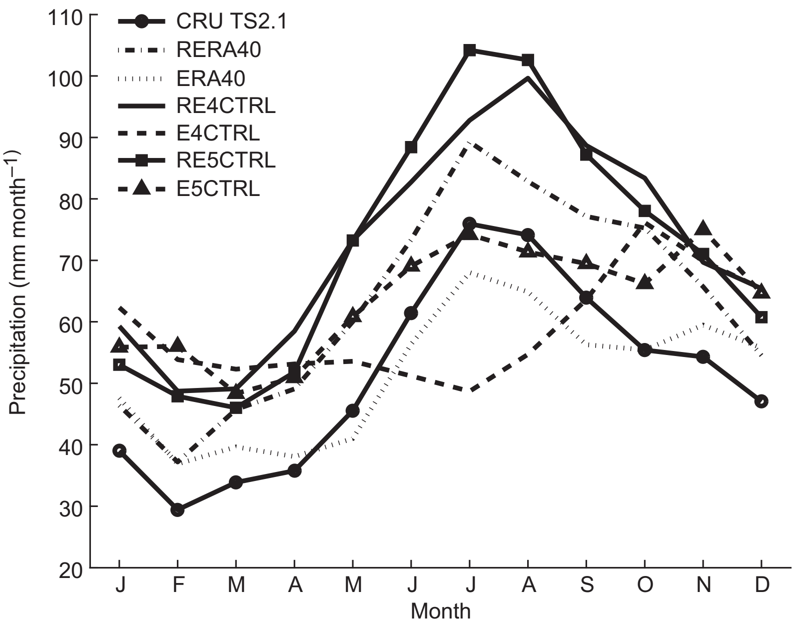

Fig. 3. Monthly mean precipitation integrated over all land in the Baltic Sea drainage basin in the three simulations with RCA3 and in the corresponding AOGCMs (*see* Table 1 for abbreviations). Observational data are the ERA40 and the CRU TS2.1 data. All data are averages for the years 1961–1990.

closely. As a consequence both RE4CTRL and RE5CTRL show more precipitation as compared with the RERA40 simulation in the Baltic Sea drainage basin (20%–30%). In summer, when RCA3 is freer to develop its own climate in the interior model domain, it systematically produces more precipitation than the corresponding global models. The largest difference is seen for RE4CTRL as compared with that for E4CTRL for July when precipitation is higher by almost a factor of two.

The climate in the Baltic Sea drainage basin is wetter in RE4CTRL/RE5CTRL as compared with that in RERA40 (Fig. 4). Annually, 40%–50% more water is transported over the area through the atmosphere yielding approximately 15% more precipitation. Evaporation over land in RE5CTRL (RE4CTRL) is about equal to (or smaller than) RERA40. As a result, the river discharge into the Baltic Sea is considerably larger (35%–45%) in both experiments than in RERA40 which in turn is very close to the observed discharge, i.e. less than 5% from the observations (Lind and Kjellström 2009). Also, over the Baltic Sea, RE4CTRL/RE5CTRL give more precipitation than does RERA40. Simultaneously evaporation is lower, related to lower SSTs during summer as prescribed by the AOGCMs.

As compared with that in the forcing global models, the water cycle over the land areas in the Baltic Sea drainage basin is more vigorous in RCA3. The differences in *P* and *E* are about 10%–15% (25%) for RERA40 and RE5CTRL (RE4CTRL). Over the Baltic Sea, differences between RCA3 and the global models are smaller than 10% for precipitation and up to almost 25% for evaporation in RERA40.

The transient climate change experiments

All three scenarios (RE4B2/RE4A2/RE5A1B, *see* Table 1) display increasing temperatures with time in the Baltic Sea drainage basin in the future climate (not shown). Precipitation is projected to increase in all seasons except in summer in the southwestern part of the drainage basin where it decreases (Table 2). The projected increase in precipitation is largest in the northeastern part of the Baltic Sea drainage basin. Annually it amounts to 20%–25% in this area, with the largest change during winter (Table 2). Over the entire land area of the Baltic Sea drainage basin precipitation in summer is projected to remain similar to today's (RE5A1B), or decrease slightly (RE4B2 & RE4A2). The decrease in

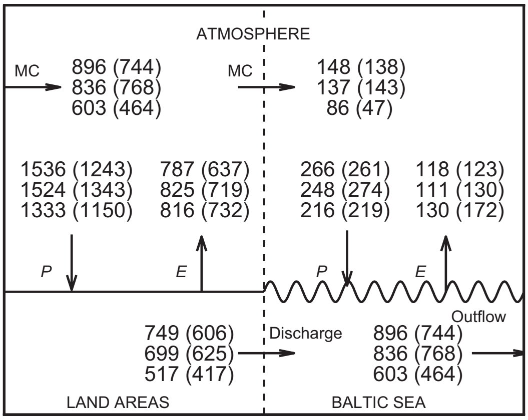

Fig. 4. Calculated fluxes in the annual mean water budget in the Baltic Sea drainage basin. The numbers are from RE4CTRL (top), RE5CTRL (middle) and RERA40 (bottom). Numbers in parenthesis are from the corresponding global model. Units are km^3 year^{-1}.

the southwest during summer is seen in all three simulations, while for the last 30-year period there is a decrease beginning in May/June until the end of August (Fig. 5).

Evaporation over land and sea increases in all seasons (Fig. 6 and Table 2). The absolute changes are largest in spring in the northeastern part of the area. In the southwestern part the changes are largest in winter and spring. In relative numbers the changes are much larger in winter in both areas. Evaporation increases as a result of higher air temperatures and a higher surface water availability. Consequently, the increase is smallest in summer in the southwestern part of the region due to decreasing precipitation there.

Runoff increases in autumn and winter and decreases during a few months in spring and/or summer (Fig. 7 and Table 2). The increase in winter is related both to the increase in $P - E$ and to the reduction in the amount of precipitation that is stored as snow (not shown). The reduction in snow storage during winter leads to less snowmelt in spring. As the reduction in snow storage is most prominent in the northeast, runoff decreases are also largest in this region. During June and July, the changes in runoff are small in the northeastern part of the area reflecting the fact that increases in precipitation are more or less balanced by increased evaporation. In the southwest, on the other hand, runoff also decreases in summer as a result of a small increase in evaporation combined with a reduction in precipitation.

Annual, area integrated changes in the water budget confirm the picture of a wetter future climate in the region (Fig. 8). Both moisture convergence into the area as well as net precipi-

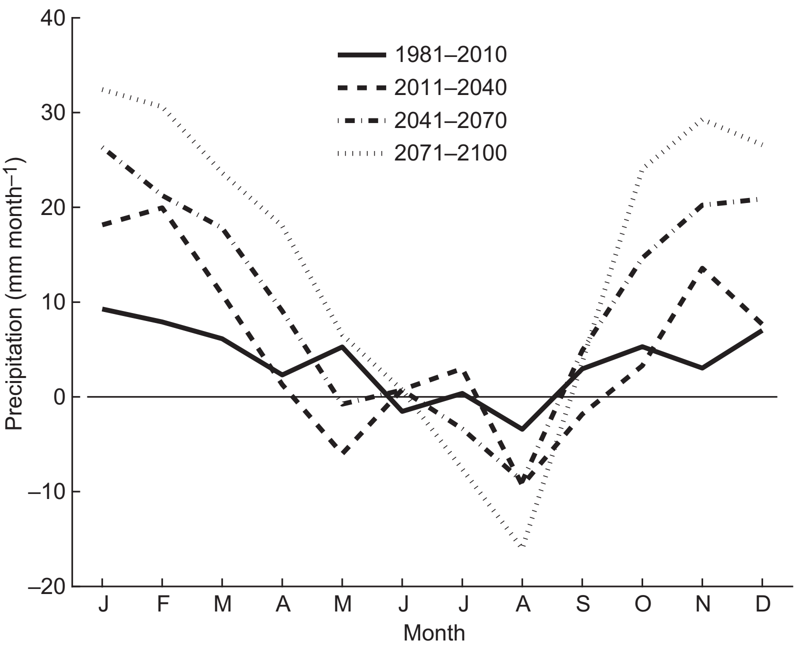

Fig. 5. Change in the integrated precipitation over all land in the Baltic Sea drainage basin. Results are from RE4A2 for four periods compared with the reference period (1961–1990).

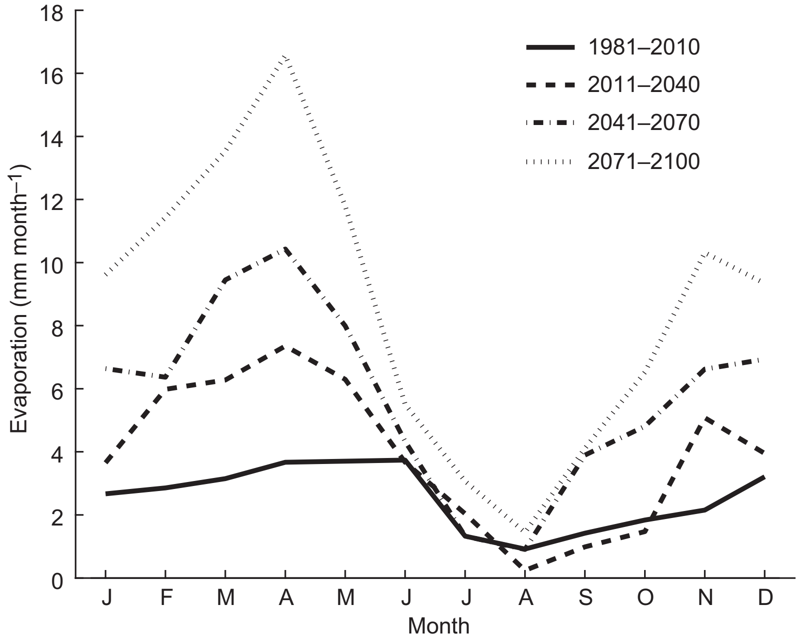

Fig. 6. Change in the integrated evaporation over all land in the Baltic Sea drainage basin. Results are from RE4A2 for four periods compared with the reference period (1961–1990).

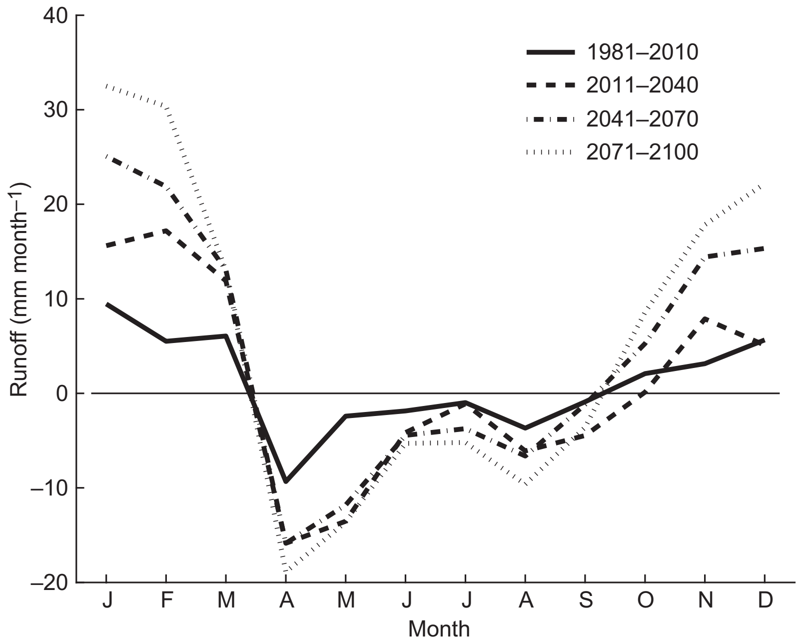

Fig. 7. Change in the integrated runoff over all land in the Baltic Sea drainage basin. Results are from RE4A2 for four periods compared with the reference period (1961–1990).

tation over land and sea increase. Consequently, discharge into the Baltic Sea and the net flux of freshwater from the Baltic Sea to the Atlantic Ocean also increase. Changes in most of the fluxes are between 15% and 20%, although larger relative changes of evaporation can also be seen (Fig. 8).

Discussion

Given boundary conditions from two AOGCMs RCA3 simulates a too wet climate in the region for the years 1961–1990. This is to some extent reflecting biases in the boundary conditions from the AOGCMs that are also too wet in this area

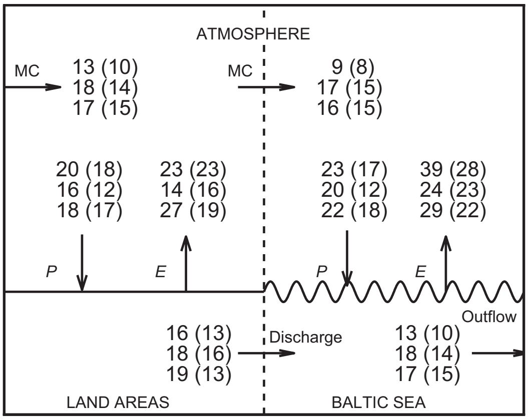

Fig. 8. Relative (%) changes in annual mean fluxes in the water budget in the Baltic Sea drainage basin in during 2071–2100 as compared with those during 1961–1990. The numbers are from RE4A2 (top), RE5A1B (middle) and RE4B2 (bottom). Numbers in parenthesis are from the corresponding global model.

during winter (Fig. 3). Previously Räisänen *et al*. (2003) showed that the general circulation over central and northern Europe in ECHAM4 is too zonal, leading to too much precipitation. An indication of a similar bias in ECHAM5 is found in Randall *et al*. (2007) who show that this model simulates too much precipitation over large parts of the north Atlantic and northern Europe. The overestimation of precipitation is even larger in RCA3. Part of this excess precipitation in RCA3 as compared with that in the AOGCMs stems from the fact that the horizontal resolution is higher. This implies that there is more orographically forced precipitation in the mountainous regions as these are more pronounced at higher resolution. Also, parts of the Baltic Sea drainage basin that are represented by land in the RCA3 grid are represented by sea in the AOGCMs due to their coarser resolution. In particular, ECHAM4 has a crude representation of the inlet to the Baltic Sea as large parts of Denmark and southern Sweden are not land covered in that model. An implication of this is that convective precipitation is not triggered during spring and summer as SSTs are lower than day-time temperatures over land. Locally, RCA3 simulates up to seven times as much precipitation as the corresponding AOGCMs for average July conditions (not shown). We note that discrepancies

Table 2. Change in precipitation (*P*), evaporation (*E*) and runoff (*R*) in land areas in the northeast (NE) and southwest (SW) parts of the Baltic Sea drainage basin. The numbers are given for all three simulations as the average change for the years 2071–2100 as compared with those for the years 1961–1990. Changes are given as absolute values (mm month^{-1}) and as relative values (%) in parentheses.

	NE			SW		
	P	*E*	*R*	*P*	*E*	*R*
RE4A2						
DJF	29 (57)	7.9 (147)	38 (230)	28 (46)	13 (104)	13 (35)
MAM	20 (35)	14 (56)	–10 (–16)	9.9 (16)	14 (33)	–2.1 (–6.1)
JJA	3.3 (3.6)	3.9 (5.7)	–3.2 (–8.6)	–21 (–24)	2.8 (3.6)	–11 (–45)
SON	22 (27)	7.5 (24)	15 (41)	14 (18)	6.1 (16)	–2.9 (–12)
ANN	18 (26)	8.3 (26)	9.8 (25)	7.9 (11)	8.9 (21)	–0.7 (–2.5)
RE5A1B						
DJF	16 (35)	5.2 (97)	25 (204)	19 (32)	8.7 (78)	10 (30)
MAM	11 (21)	7.8 (29)	–9.2 (–15)	10 (18)	6.2 (13)	2.1 (7.0)
JJA	11 (11)	5.1 (7.0)	2.6 (7.2)	–6.7 (–7.0)	2.2 (2.6)	–3.1 (–12)
SON	20 (26)	5.6 (18)	16 (47)	9.9 (13)	4.9 (13)	1.4 (5.7)
ANN	15 (22)	5.9 (17)	8.6 (25)	8.1 (11)	5.5 (12)	2.7 (9.6)
RE4B2						
DJF	23 (45)	5.5 (103)	31 (193)	24 (38)	9.3 (75)	15 (40)
MAM	13 (23)	10 (40)	–9.8 (–15)	7.9 (12)	9.5 (22)	–1.3 (–3.9)
JJA	3.2 (3.4)	3.1 (4.5)	–2.9 (–7.8)	–7.8 (–9.1)	2.1 (2.6)	–4.6 (–20)
SON	21 (26)	6.3 (20)	15 (43)	14 (18)	6.0 (16)	2.4 (9.7)
ANN	15 (21)	6.2 (19)	8.5 (22)	9.4 (13)	6.7 (16)	2.8 (9.3)

between the grids are problematic when comparing RCM and AOGCM results at a local scale. But, we also note that the finer grid in the RCM contributes to the added value of these models as compared with that in the AOGCMs at both local and regional scales.

Next we investigated the climate change signal in three different emission scenarios where the regional model has been forced by boundary data from two AOGCMs. Such a small set of experiments covers only a very limited range of possible outcomes for the region, but may still provide some information about uncertainties associated with emissions and choice of boundary data. The most definite result is that the climate in the region will get wetter according to all projections. The increase in precipitation is largest in RE4A2 followed by RE4B2 and smallest in RE5A1B. This may seem counterintuitive as the A1B emission scenario gives a stronger radiative forcing than the B2 scenario. However, the relatively small change in precipitation in RE5A1B is in line with an overall relatively weak regional climate change signal in E5A1B in the Baltic Sea drainage basin (annual mean temperature increase is 3.7 K) as compared with that in E4B2 (4.5 K) and E4A2 (5.7 K).

The moisture convergence into the Baltic Sea drainage basin increases by about 15% between the periods 1961–1990 and 2071–2100 (Fig. 8). For the northern hemisphere mid latitudes, Held and Soden (2006) reported an average increase in maximum poleward moisture transport of 4% per degree local warming. Our three regional climate change scenarios display annual average temperature increases of 2.5–4 K in large areas upwind of (to the southwest of and including the North Sea) the Baltic Sea drainage basin (not shown). Applying the Held and Soden ratio of 4% K^{-1}, these temperature increases correspond to a 10%–16% increase in moisture fluxes which is in qualitative agreement with the numbers in Fig. 8. Area integrated increases in precipitation are slightly larger (15%–20%) on an annual basis indicating a more vigorous hydrological cycle also within the Baltic Sea drainage basin. This is even more evident over the Baltic Sea, where relative increases in both precipitation and evaporation are even larger than over land areas. Seasonally and regionally changes in precipitation are occasionally very large, in the northeast winter precipitation is projected to increase by 35%–60%. The only exception to this increase in future climate conditions is found for summer in the southwestern part of the domain, where precipitation is projected to decrease in all simulations. These findings are in qualitative agreement with results presented in the IPCC fourth assessment report (Christensen *et al*. 2007) and in the Baltic Sea Assessment on climate change (Graham *et al*. 2008).

We compare the simulated changes in RCA3 with the corresponding changes in the respective AOGCMs. We note that RCA3 projects sligthly larger relative changes in the hydrological cycle than does the corresponding AOGCM (Fig. 8). The reason for this is not entirely clear but is consistent with the more intense hydrological cycle simulated during the control period. Furthermore, the temperature changes in the AOGCMs are about 0.5–1 K larger than in the corresponding RCA3 simulations by the end of the century (not shown). On an annual basis the relative increase in precipitation per degree warming is about 4.5%–5% K^{-1} over the Baltic Sea drainage basin in the three RCA3 experiments while the corresponding numbers in the AOGCMs are 3%–4% K^{-1}. It seems clear that the response of the hydrological cycle to the temperature increase is stronger in the regional model than in the two AOGCMs, at least for this area.

Conclusions

Acknowledging the fact that we sample just a part of the full uncertainty range by using only three different climate change scenarios for the 21st century, we show that the hydrological cycle in the Baltic Sea drainage basin will likely become more intense in the future. The more vigorous hydrological cycle is a consequence both of more water vapor being transported into the area through the atmosphere, but also due to localized increases of fluxes within the area. The calculations show increasing fluxes of water (atmospheric moisture convergence, precipitation, evaporation, runoff, river discharge) of about 15%–20% integrated for the entire Baltic

Sea drainage basin both over land and sea by the end of the century. We have also shown that both the hydrological cycle in the recent past climate and projected changes in the future are stronger in the regional climate model as compared with those in the AOGCMs. The full reason for this is not clear but the results indicate that the higher resolution in the regional model contributes to the differences. It remains to check the generality of this result by also investigating other regional climate models.

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