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Future trends and variability of the hydrological cycle in different IPCC SRES emission scenarios — a case study for the Baltic Sea region

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Global climate change is also affecting the Baltic Sea and its surrounding areas. Therefore, it is of great importance to understand decadal variability and future trends as they are projected by global and regional climate change simulations. In this paper, trends and variability of hydro-meteorological quantities are investigated in simulation results for the period 1900 to 2100. Special attention is paid to the differences in the climate change signals which are simulated within three individual simulations of one IPCC SRES scenario (here: three realisations of A1B) as compared with those in three simulations of different IPCC SRES scenarios (one realisation each for A2, A1B and B1). In addition results from a validation run for 1958 to 2002 which are compared with observations, show the capability of the regional model to simulate today's climate. From the 200-year simulations it can be concluded that in all of them the differences in the hydro-meteorological quantities are of similar order, despite of significant differences in temperature trends. The relation between an increase in temperature and an intensification of the hydrological cycle is also analysed. This study shows that the differences in the IPCC SRES emission scenarios lead to significantly different temperature developments until the end of this century, but they do not stimulate significant differences in the developments of the hydrological cycles. At present this behaviour cannot be explained and needs further investigations.

Introduction

During BALTEX (http://www.baltex-research.eu) phase I, the focus was mainly on process understanding and modelling of the water and energy cycles of the Baltic Sea basin. This focus is carried on in BALTEX phase II, objective 1. In addition, within objective 2, climate variability, climate change since 1800 and future climate projections are introduced into the BALTEX activities. An overview of observed and simulated long-term changes has been published in the BACC report (BACC 2008), in which it is stated that the warming during the last century in the Baltic Sea basin is slightly stronger than the global mean temperature increase of 0.75 °C (IPCC 2007). The air temperature increased approximately 1 °C in the northern areas and 0.7 °C in the south of the Baltic Sea region. Climate scenarios project further warming of 3–6 °C until the end of this century depending on the region and the emission scenario. Associated with changes in temperature, precipitation changes are expected. Unfortunately they are much more difficult to detect and to analyse due to the high spatial and temporal variability of precipitation. Beck *et al*. (2005) identified an increase of precipitation for 1976–2000 as compared with that for 1951–1975. They clearly show non-uniform pattern of changes with regional differences. An overview of observed regional precipitation changes is also presented in the BACC (2008).

Both BALTEX phase II objectives are linked via the variability of the hydrological cycle, which is strongly influenced by the large scale flow. Westerly winds from the Atlantic dominate during autumn and winter with humid and mild air advected into the region. The climate can be characterized as maritime in the south and southwest, while it is sub-arctic in the north and east. However, local and regional processes are able to modulate the hydrological cycle, which has also been presented by Kjellström and Ruosteenoja (2007) and Jacob *et al*. (2007) within the PRUDENCE project (http://prudence.dmi.dk).

Possible changes in the hydrological cycles due to the changing climatic conditions can involve different time scales, from seasonal to centennial. Closely related to the variability are possible trends in hydro-meteorological quantities like temperature, precipitation and runoff. An overview of today's knowledge about the variability of hydro-meteorological variables on different time scales is given in the BACC (2008). Within the BALTEX programme, the runoff to the Baltic Sea during 1921 to 1998 was analysed (BACC 2008: fig 2.32) from which estimates for dry and wet decades can been extracted. The 1970s was the driest decade, while the last two decades can be seen as wet from the runoff level. There is no clear trend visible in the runoff records, but strong inter-annual variability, with high runoff levels since the late 1970s.

Hansson and Omstedt (2007) analysed the annual maximum ice extent and annual water temperature on centennial time scale. They concluded from the maximum ice extent that the 17th and 19th centuries were the coldest ones, while the 20th century was the warmest. Eriksson *et al*. (2007) stated that the Baltic region experiences changes on centennial and decadal time scales, often with rapid transitions. They found that in addition to the 20th century also the first half of the 18th century could be characterized as warmer and that warm periods are associated with low variability on shorter time scales. Cold periods often display greater variability on inter-annual time scales. Following Erikson *et al*. (2007), it can be stated that the climate in the Baltic Sea region is characterized by centennial, inter-decadal, and decadal time scales, showing no strong periodicities. Large decadal variability was found in the 20th century (Hansson and Omstedt 2007, Eriksson *et al*. 2007) with the 1930s, 1950s and 1990s being warm periods regarding water temperatures. The 1940s, 1960s, late 1970s and early 1980s, and 1990s were identified as cold decades. Note that the results are mostly related to the Baltic Sea itself, analysed from water temperatures and sea ice extends.

In this paper, an ensemble of regional climate change simulations for the period 1900–2100 is presented. This period allows for investigating the relation between an increase in temperature and an intensification of the hydrological cycle. For this, the change in decadal variability in several hydro-meteorological quantities during the 200 years is analysed. Special attention is paid to the differences in the climate change signals which are simulated within three individual simulations of one IPCC SRES scenario (here: three realisations of A1B) as compared with those in three simulations of different IPCC SRES scenarios (one realisation each for A2, A1B and B1).

Experimental setup

Climate change projection experiments have been carried out using the regional climate model (RCM) REMO (Jacob 2001, Jacob *et al*. 2001). REMO is a hydrostatic RCM. The model domain used within this study covers whole Europe on a rotated coordinate system (Fig. 1) and has been defined within the European Union project ENSEMBLES. This domain covers 109 × 121 grid points horizontally with a grid spacing of 0.44° (~50 km) and on 27 vertical levels.

The regional climate change projections were all initialized and driven at the lateral boundaries with data from coupled global climate change experiments simulated by the global ECHAM5/

MPIOM atmosphere/ocean model system (Roeckner *et al.* 2003, Jungclaus *et al.* 2006). The coupled global model runs, which have been conducted for the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC), were carried out without flux correction at T63 horizontal spectral resolution (~200 km grid spacing) with 31 vertical levels in the atmosphere and about 1.5 horizontal resolution on 40 vertical levels in the ocean. Observed concentrations of greenhouse gases were prescribed for past climate simulations (1860–2000, the so-called control runs). For the projection of future climate evolution, greenhouse gas concentrations were prescribed according to the IPCC SRES scenarios B1, A1B and A2 (Nakicenovic *et al.* 2000).

Three realisations (members), differing in slightly changed initial conditions, were performed for each of the before mentioned IPCC SRES scenarios. Out of the coupled global simulations, the following ones have been downscaled by the REMO model:

— Three members for control climate (1900–2000).
— Three members for a changing climate (2000–2100) under the SRES A1B emission scenario conditions.
— One member for a changing climate (2000–2100) under the SRES A2 emission scenario conditions.
— One member for a changing climate (2000–2100) under the SRES B1 emission scenario conditions.

Additionally, a so called "validation experiment (REMO-ERA40)", a REMO simulation forced at the lateral boundaries by the ERA-40 reanalysis (Uppala *et al.* 2005) data from the ECMWF have been carried out for the period 1958–2002. Experiments driven by reanalysis data are considered as so-called "perfect boundaries" RCM simulations, as the results are not influenced by any possible bias from the coupled global climate model results.

In all experiments, REMO was initialized and driven at the lateral boundaries by the results of the global model of reanalysis data interpolated to the grid of the regional model. REMO was applied in the so-called climate mode: except for sea surface temperature and sea-ice fraction, which are prescribed for the whole integration period by interpolated results from the global model of reanalysis data, the regional model simulates all variables within the interior of the model domain by itself without any kind of re-initialization.

For comparison with observations the CRU dataset (Mitchell and Jones 2005) was used for 2-m temperature and precipitation for the land part of the Baltic Sea catchment. CRU is developed by the Climate Research Unit of the University of East England, U.K.

Analyses

For the analysis of the decadal variability of the hydrological cycle, decadal area sums of precipitation (P), evaporation (E) and runoff (RO) were calculated for the land part of the Baltic Sea catchment area (*see* solid line in Fig. 1) and for the area of the Baltic Sea itself (except for runoff) for all simulations. The runoff values are directly calculated within the regional climate model in each land-grid box from precipitation, evaporation and change in soil moisture content. The long-term mean runoff is very close to $P - E$. With these values, residual budgets like net transport of Baltic Sea water through the Kattegat were computed (under the assumption that the mean sea level in the Baltic Sea does not change). The unit of all computed quantities is km^3 year^{-1}. Here the net transport through the Kattegat is defined as runoff to the Baltic Sea plus precipitation minus evaporation over the Baltic Sea itself.

Additionally, decadal means of near-surface (2-m) air temperature were constructed for the land and water fractions of the Baltic Sea catchment area.

Furthermore, for all quantities mean values for the three decades from 1961 to 1990 and from 2071 to 2100 were calculated for the control runs and climate change scenario simulations, respectively. Climate change signals were derived from the difference between mean values for the future period 2071–2100 and mean values for the control period 1961–1990 (*see* also Hagemann *et al.* 2008).

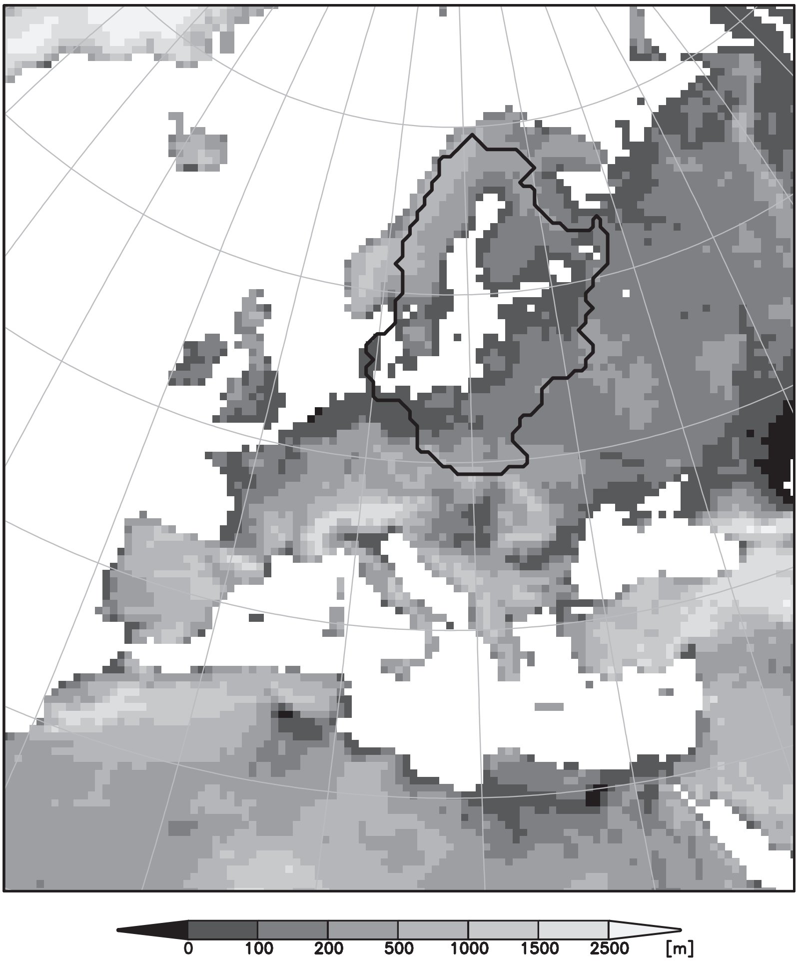

Fig. 1. Model domain with orography (m) and Baltic Sea catchment (solid line).

Finally, simple trends using a linear regression were computed for the 20th and 21st centuries for the control and climate change projection runs, respectively.

Results and discussion

Temperature

The comparison of the results from the ERA40 driven REMO validation run against CRU observations (only available over land areas) allows judgements regarding the performance of REMO as mentioned above. For the land area of the Baltic Sea catchment (Fig. 2) it is clearly visible that the REMO-ERA40 results are very close to CRU data, but the decadal means are slightly higher in all 4 decades (1961–2000). In the observations, the last decade is the warmest, which is also true for REMO, but REMO-ERA40 is still about 0.25 °C warmer. In addition, the first decadal mean of REMO-ERA40 is about 1 °C warmer than the observed climatology for the land area of the Baltic Sea region. This might be due to the spin-up processes in the soil, which is initialized from soil equilibrium in the ERA40 data and which needs about one decade to find its own equilibrium. This long period is needed due to freezing and thawing processes in the soil, which also influence the soil temperature profile. Note that the CRU data for winter time possibly have a cold bias in Scandinavia (Christensen *et al*. 1998) and that the CRU mean temperature is only claimed to be accurate within approximately 1 K (Jacob *et al*. 2007)

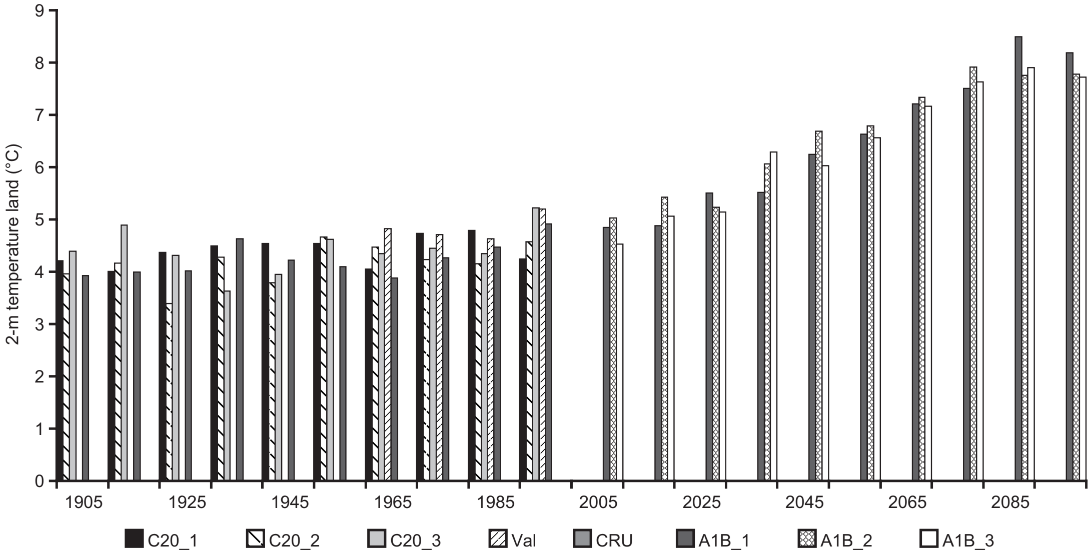

Fig. 2. Decadal-mean 2-m temperature (°C) for the land part of the Baltic Sea catchment area for the three members of the control run (C20_#), for the three members of the A1B scenario (A1B_#), for the REMO-ERA40 validation run (Val), and for CRU observations (CRU).

The comparison of the 100-year record of CRU against the three members of the control climate simulations shows that the decadal means of the CRU climatology are colder than the ones from all three members of REMO driven by ECHAM5/MPI-OM, except for 1931 to 1940. However, the warm bias of the REMO results is very small and mostly less than 0.5 °C, which is in the same order as the internal variability between the three members and clearly indicates the importance of considering many members due to the non-linear character of climate. The multi-decadal variability is very similar in the simulations and observations.

From the CRU climatology the calculated linear trend in the 2-m temperature over the land area of the Baltic Sea catchment for 1900 to 2000 amounts to 0.67 °C. The three trends simulated with REMO for the last 100 years are: 0.38 °C for member 1, 0.68 °C for member 2 and 0.44 °C for member 3 and they present the internal variability in the calculated trends. The trend in member 2 is extremely close to the observed one and shows that the modelling chain ECHAM5-MPIOM and REMO is well capable of simulating the observed temperature climatology for the land part of the Baltic Sea area.

For 1900 to 2100 the time series of the 2-m temperatures over the land area of the Baltic Sea catchment (Fig. 2) shows a small warming trend of less that 1 °C during the first 100 years, but with a clear decadal variability. This decadal variability seems to be similar from 2000 to 2100; however, clear warming trends are visible for all three IPCC SRES scenario simulations (Figs. 2 and 3). Until about 2050 all three scenario trends develop similarly, but in the second half of the century they differ considerably. The trends in the three members of A1B scenario are 4.29 °C, 3.53 °C and 3.9 °C during 2000 to 2100. A trend of 4.3 °C can be calculated from the results of the A2 scenario and from the B2 run only a trend of 2.61 °C is evident. For the land area of the Baltic Sea catchment the three members of A1B and the A2 simulation project very similar temperature changes until the end of this century with a range of about 0.7 °C between the individual member trends. The projected temperature change until 2100 following the B2 scenario however leads to a trend which is clearly weaker by about 1.5 °C.

The temperature increases only by about 2.4 °C in the B1 scenario, while it increases between 3.2 °C and 3.5 °C in the A1B and A2 simulations for 2071–2100 as compared with 1961–1990. This is most likely related to the different developments of emissions which are

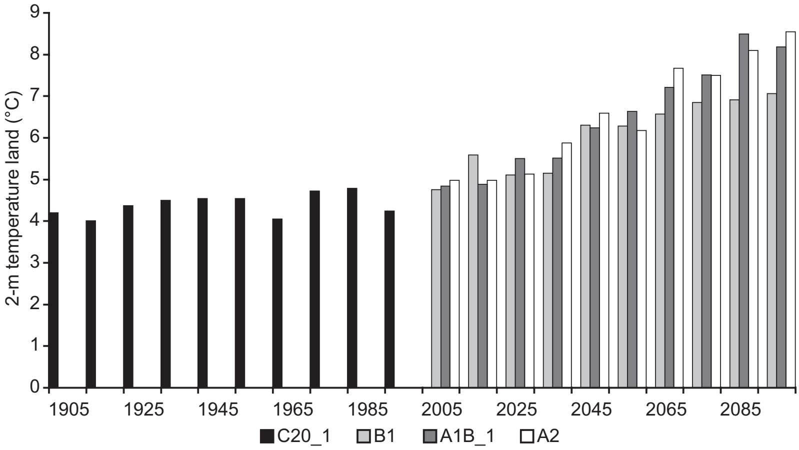

Fig. 3. Decadal-mean 2-m temperature (°C) for the land part of the Baltic Sea catchment area for the first member of the control run (C20_1) and for the three runs with different emission scenarios (B1, A1B_1, A2).

prescribed in the simulations. Until about 2050 the projected CO_2 concentrations are relatively similar (~450 to 500 ppm) in all scenarios, but large differences are projected until the end of this century. Until 2100 for B1 only about 540 ppm are prescribed, while the CO_2 concentrations increase for A1B to about 700 ppm and for A2 up to 840 ppm. The projected changes of the 2-m temperature over the land area for 2071–2100 as compared with those in 1961–1990 are in agreement with the earlier studies summarized in the BACC (2008).

The projected temperature trends over the Baltic Sea itself are very similar and therefore not shown.

Hydrological quantities

The comparison of the decadal precipitation sums from CRU data and REMO-ERA40 for 1961 to 2000 shows about 20% larger values in REMO-ERA40 results (Fig. 4). This overestimation — a common model problem (Hagemann *et al*. 2004) — can partly be influenced by too efficient precipitation formation within REMO. It can also partly be explained by the underestimation of precipitation in the CRU data, which are not corrected for undercatch (rain drops and snow particles drifting around the rain gauge due to winds; Forland and Hanssen-Bauer 2000). The lack of accurate precipitation measurements for the Baltic Sea region was studied by Bumke and Clemens (2001). Another sampling problem for precipitation is the high variability in space and time which was investigated by Rubel (1996, 1998) in general and by Clemens and Bumke (2002) for the Baltic Sea area. Rubel and Hantel (2001) stated that the annual average precipitation deficit of the raw rain gauge data is about 13% for the land area of the Baltic Sea catchment area. More details about the difficulties to determine the accuracy of precipitation data for the Baltic Sea area are given in the BALTEX Phase I State of the Art report (BALTEX 2005). Jones and Ullerstig (2002) and Räisänen *et al*. (2003) applied the correction model from Rubel and Hantel (2001) to the CRU climatology quantifying the correction effect to about 20% in the annual mean for the Baltic Sea land area. For winter the correction increases to about 40%. It is stated in the BACC (2008) that for the CRU climatology the annual mean precipitation varies between 610 mm year^{-1} (1062 km^3 year^{-1}) (uncorrected) and 720 mm year^{-1} (1253 km^3 year^{-1}) after applying correction factors for 1961–1990. For 1960–2000 the uncorrected CRU value amounts to 634 mm year^{-1} (1103 km^3 year^{-1}) whereas within REMO-ERA40 766 mm year^{-1} (1333 km^3 year^{-1}) is simulated over land.

For the entire Baltic Sea catchment area (land and sea) Arpe *et al*. (2005) discussed the CMAP climatology (Climate Prediction Centre Merged Analysis of Precipitation), which sums up to an annual mean of 1352 km^3 year^{-1} (620 mm year^{-1}) and GPCP (based on the Global Precipitation Climatology Project) with an annual average

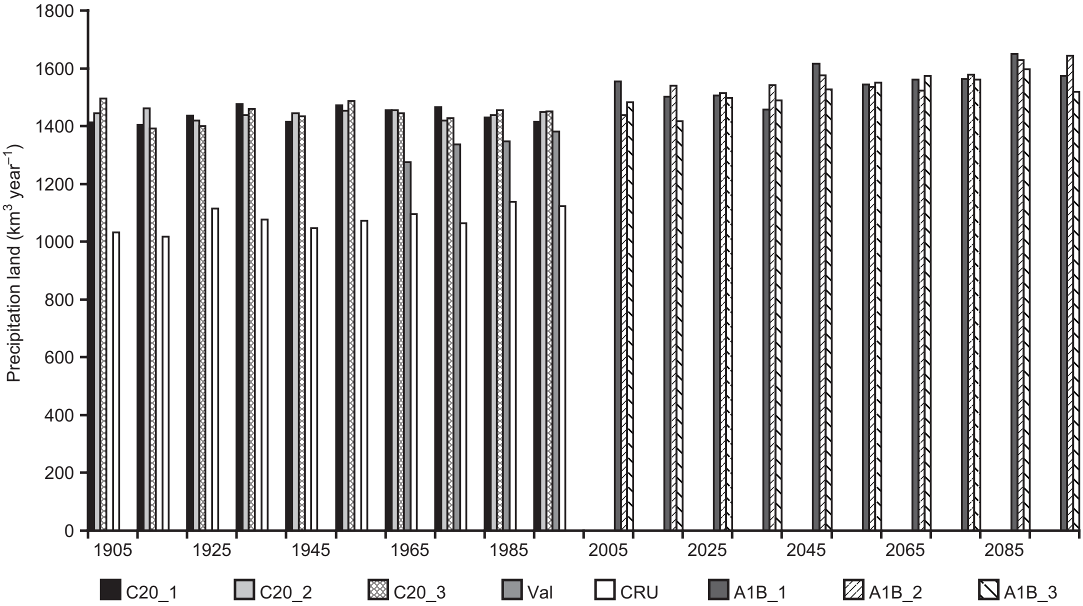

Fig. 4. Decadal precipitation sum (kg^3 year^{-1}) over the land part of the Baltic Sea catchment area for the three members for the control run (C20_#), for the three members of the A1B scenario (A1B_#), for the REMO-ERA40 validation run (Val) and for CRU observations (CRU).

of 1723 km^3 year^{-1} (790 mm year^{-1}). They conclude that GPCP is slightly overestimated while the CMAP data are significantly underestimated. Within the BACC (2008) it is stated that a reasonable mean for the current climate amounts to 1636 km^3 year^{-1} (750 mm year^{-1}). In the validation run this value sums up to 1654 km^3 year^{-1} (758 mm year^{-1}).

The comparison of CRU data to the precipitation sums resulting from the control climate runs show a similar behaviour. The calculated sums are even larger than those for the validation run and they are much wetter than the CRU climatology. This clearly shows the influence of the global model data, which are prescribed at the lateral boundaries thus dominating the flow of moisture into the REMO simulation domain.

During the last 100 years a small multi-decadal variability is visible in the observations and a very small trend of about 90 km^3 within 100 years. For all three members of the control run no clear trend is visible during this time (left half of Fig. 4). For each of the three realisations the magnitude of the inter-decadal variability during this century is of the same order as the differences between the three realisations of the control run for individual decades and very similar to the observed variability analyzed from CRU data. This is also the case when analysing the inter-decadal variability and differences for the three realisations of the A1B emission scenario (right half of Fig. 4), but there is an increasing trend evolving within the 21st century, which clearly outperforms the inter-decadal variability for each single run and the differences between the three members of the control run and A1B scenarios, respectively (Fig. 4). These findings for the future period are also valid when analysing the three different emission scenarios (B1, A1B_1, A2) for the period 2001–2100 (Fig. 5). Calculated trends for 2001–2100 sum up to 104, 161 and 132 km^3 for the members of the A1B projection, to 141 km^3 for the B1 simulation and to 212 km^3 for the A2 run.

It is very interesting to note that at the end of the century the differences between the decadal sums in precipitation of the three A1B members are of similar magnitude as the differences between the decadal sums in precipitation of the runs with three different emission scenarios. The magnitude of the simulated increase in precipitation over land is around 10% at the end of the

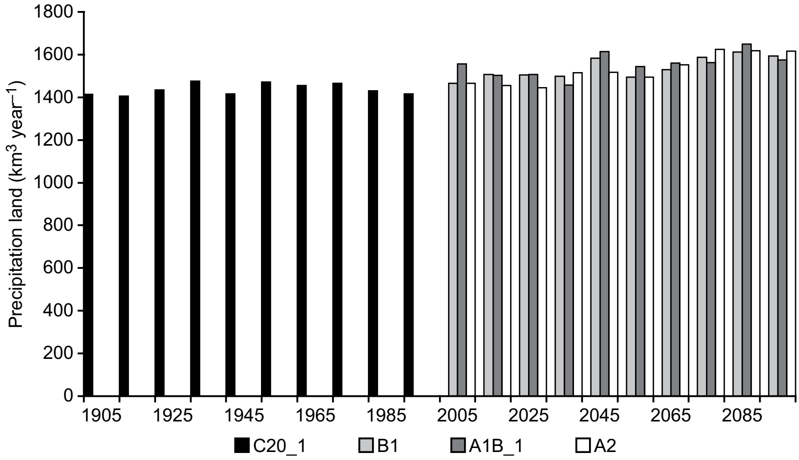

Fig. 5. Decadal precipitation sum (kg^3 year^{-1}) over the land part of the Baltic Sea catchment area for the first member of the control run (C20_1) and for three runs with different emission scenarios (B1, A1B_1, A2).

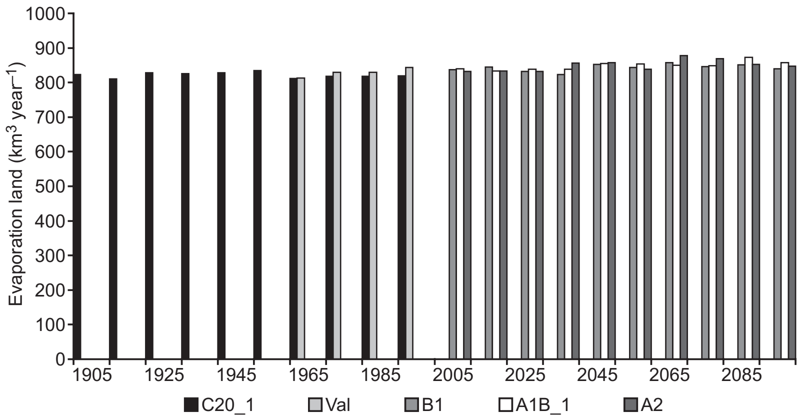

Fig. 6. Decadal evaporation sum (kg^3 year^{-1}) over the land part of the Baltic Sea catchment area for the first member of the control run (C20_1), for the three runs with different emission scenarios (B1, A1B_1, A2), and for the REMO-ERA40 validation run (Val).

projections (2071–2100) as compared with that for the period 1961–1990 of the control run for each future simulation (again Figs. 4 and 5).

Over the land part of the Baltic Sea catchment, the simulated decadal sums of evaporation cannot directly be compared with an observed climatology, since this unfortunately does not exist. Therefore, it is only possible to compare the results from the REMO-ERA40 validation run with the results from the control simulations (Fig. 6), which are very well in agreement. The general findings related to the inter-decadal variability and differences between the three A1B realisations (not shown) and three different emission scenario simulations (Fig. 6) are very similar as discussed for the precipitation over land. Furthermore, there is no general trend for the control period, but there is an increasing trend in all different future projections with a magnitude of around 5% at the end of the 21st century as compared with that for the control period in the 20th century (Fig. 6), again outperforming the inter-decadal variability and the differences between the realizations.

The comparison of the runoff results from the control runs (~620 km^3 year^{-1}) with those from the REMO-ERA40 validation run (~495 km^3 year^{-1}) shows larger values in the control climate. This is not surprising knowing that the evaporation over land areas is very similar in all simulations (Fig. 6), and that the precipitation in the control members is much larger than in the validation run (Fig. 4). A comparison of the simulated values against long term runoff data shows a good agreement for REMO-ERA40 data with 495 km^3 year^{-1} and 445 km^3 year^{-1} given in the BACC (2008). This long term average annual runoff results from observed data as they are collected in the BALTEX data base (*see* BACC 2008: fig. 2.32). The small overestima-

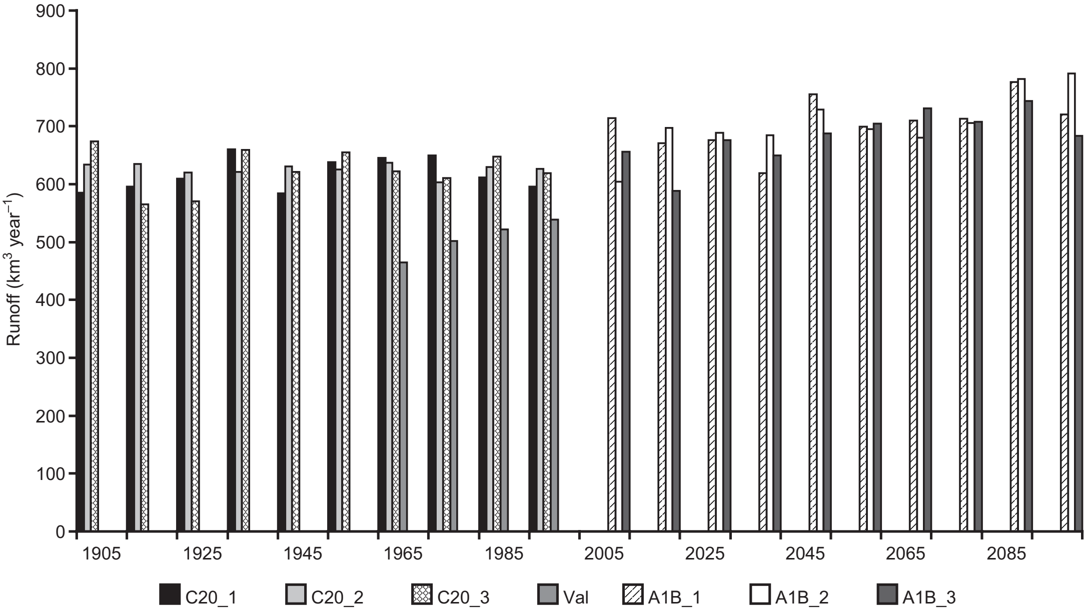

Fig. 7. Decadal total runoff sum (kg^3 year^{-1}) over the land part of the Baltic Sea catchment area for the three members of the control run (C20_#), for the three members of the A1B scenario (A1B_#) and for the REMO-ERA40 validation run (Val).

tion in REMO-ERA40 is most likely related to too much precipitation in the simulation. As reported above, the overestimation of precipitation in REMO-ERA40 is only partly influenced by the undercatch in the observation. The comparison with the observed runoff confirms that in REMO-ERA40 10% too much precipitation is produced.

The long-term runoff into the Baltic Sea is mainly controlled by precipitation and evaporation over land, therefore it is not surprising that again a similar evolution of the runoff time series for the three A1B members and the other two scenarios is projected: all scenario simulations show a relatively high variability and an increasing trend of total runoff into the Baltic Sea for the 21st century. The simulated increase at the end of the 21st century is between 15% and 21% as compared with the values for the end of the 20th century (Figs. 7 and 8). The calculated trends for the coming 100 years are 73, 140, 107 km^3 for the three A1B members, 126 km^3 for the B1 run and 180 km^3 for the A2 run. This is a considerable amount having in mind that the simulated long term mean runoff in the control climate is about 600 km^3 year^{-1}.

Over the area of the Baltic Sea itself, the general picture for precipitation over sea is very similar to precipitation over land, except that the projected increase is slightly stronger and has a magnitude of around 14% at the end of the simulations (Fig. 9). Again, an increase in evaporation is simulated for the area of the Baltic Sea, which is around 21% at the end of the 21st century and thus significantly higher than the projected increase over the land area (Fig. 10). Over water the comparison against the results of the validation run shows a very good agreement for decadal precipitation sums of the C20_1 run (Fig. 9) (over land precipitation was slightly overestimated), but the decadal sums of evaporation are much larger in the validation run (~180 km^3 year^{-1}) as compared with about 140 km^3 year^{-1} in the control simulation (Fig. 10). The very large evaporation over water in REMO-ERA40 might affect the precipitation formation over land leading to the overestimation of precipitation sums as compared with those in the CRU climatology. Omstedt *et al*. (2004) estimate the long-term mean of net precipitation ($P - E$) over the Baltic Sea itself to about 1500 m^3 s^{-1} (47 km^3 year^{-1}), but observed precipitation means over the Baltic Sea are still not exactly known (Bumke and Rubel 2005) and the uncertainties

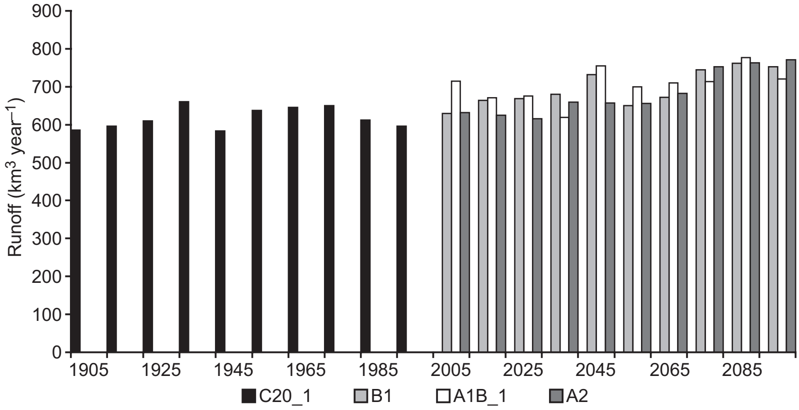

Fig. 8. Decadal total runoff sum (kg^3 year^{-1}) over the land part of the Baltic Sea catchment area for the first member of the control run (C20_1) and for the runs with different emission scenarios (B1, A1B_1, A2).

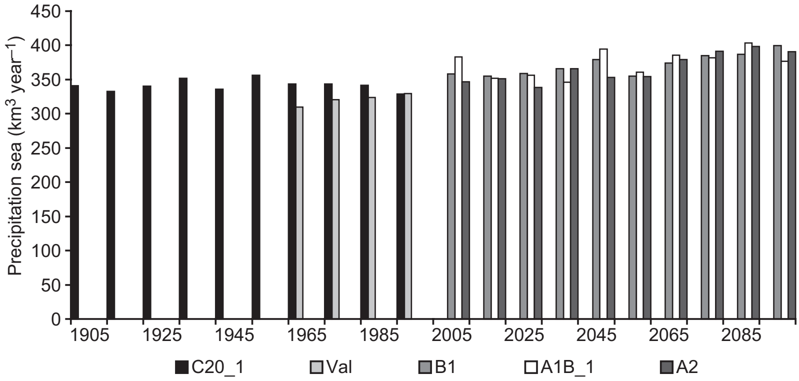

Fig. 9. Decadal precipitation sum (kg^3 year^{-1}) over the Baltic Sea (water part) for the first member of the control run (C20_1), for the three runs with different emission scenarios (B1, A1B_1, A2), and for the REMO-ERA40 validation run (Val).

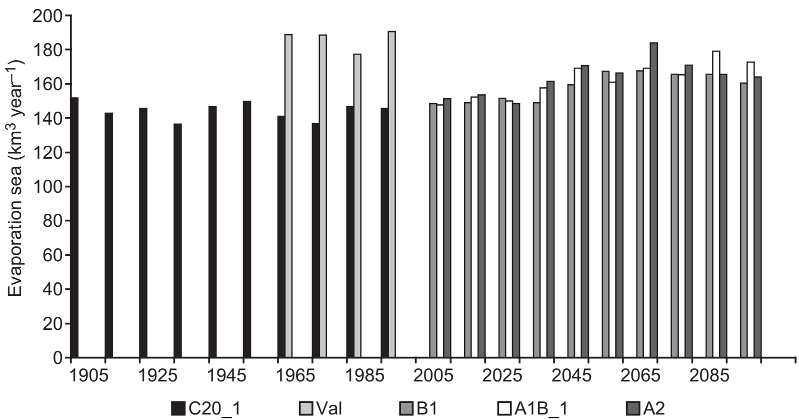

Fig. 10. Decadal evaporation sum (kg^3 year^{-1}) over the Baltic Sea (water part) for the first member of the control run (C20_1), for the three runs with different emission scenarios (B1, A1B_1, A2), and for the REMO-ERA40 validation run (Val).

are of the same order as uncertainties in evaporation estimates (Hennemuth *et al*. 2003).

All the before discussed quantities are influencing the net transport through the Kattegat. Increases in precipitation also lead to an increase of the net transport, but an increase in evaporation reduces the net transport, so that the before mentioned changes in precipitation and evaporation are partly compensating each other. Therefore, the variability of these quantities is the one with the highest inter-decadal variability and the highest differences between the different simulations (Figs. 11 and 12). Again, there is a clear trend visible for all simulations indicating an increase of the net transport through the Kattegat of about 15% at the end of the 21st century as compared with that for the control period.

The net transport through the Kattegat calculated from the results achieved within the validation run is approximately 20% smaller (~650

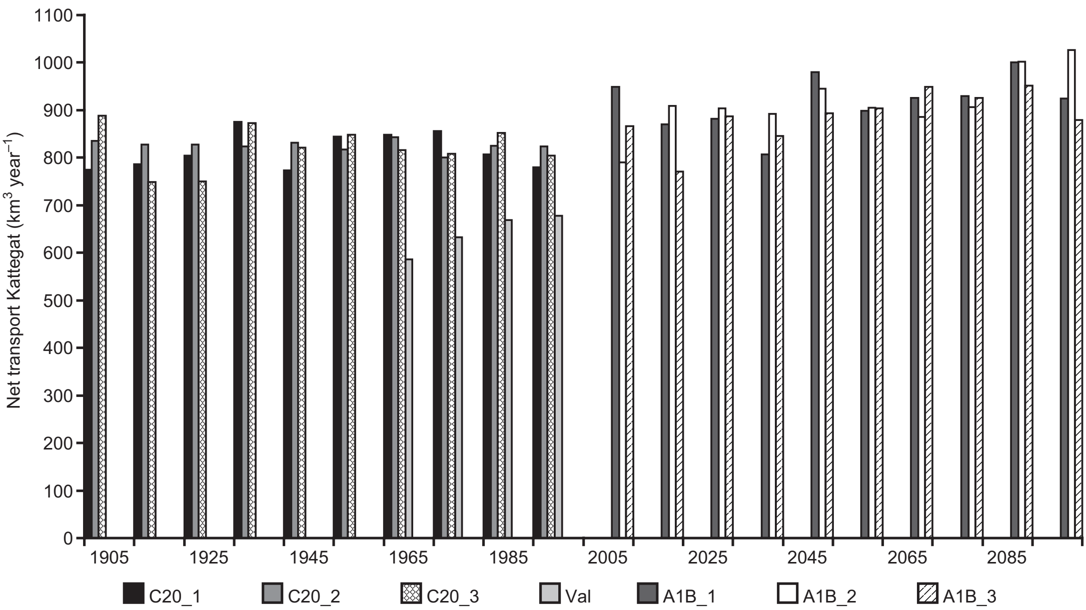

Fig. 11. Decadal net water transport through the Kattegat (kg^3 year^{-1}) for the three members of the control run (C20_#), for the three members of the A1B scenario (A1B_#) and for the REMO-ERA40 validation run (Val).

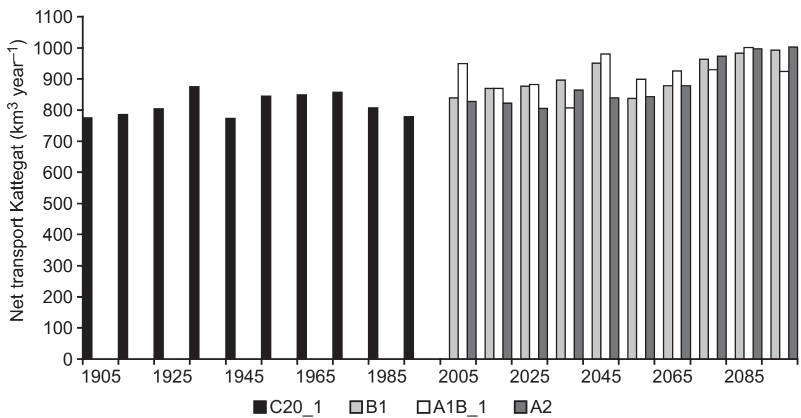

Fig. 12. Decadal net water transport through the Kattegat (kg^3 year^{-1}) for the first member of the control run (C20_1) and for the three runs with different emission scenarios (B1, A1B_1, A2).

km^3 year^{-1}) than the ones in the control simulations (~800 km^3 year^{-1}). Omstedt *et al*. (2004) stated that the long-term mean of the outflowing water from the Baltic Sea is estimated to about 80 000 m^3 s^{-1} (2523 km^3 year^{-1}) resulting in a net flow through the Kattegat of 15 000 m^3 s^{-1} (473 km^3 year^{-1}).

The BALTEX box

A comprehensive overview of recent estimates of the individual terms in the water budget over the Baltic Sea itself gives the BALTEX box (Omstedt *et al*. 2004: table 3). Table 1 presents the individual terms for the water budget as they result from the simulations. In the validation run the long term mean runoff for 1961–1991 amounts to 15 700 m^3 s^{-1}, which is in very good agreement with values given by Omstedt *et al*. (2004) ranging from about 14 000–16 500 m^3 s^{-1}. As discussed above, the calculated net outflow from REMO-ERA40 is slightly larger (~20 000 m^3 s^{-1}) than the recent estimates in Omstedt *et al*. (2004), with values between 15 000 and 17 300 m^3 s^{-1}. This is most probably due to an overestimation of $P - E$ with 4210 m^3 s^{-1} as compared with the estimates between 700 m^3 s^{-1} and 2400 m^3 s^{-1} presented by Omstedt *et al*. (2004).

The comparison of the different components in the three members of the control climate shows only small differences among each other, but a clear underestimation of evaporation (~140 km^3 year^{-1}) as compared with that in the validation run (185 km^3 year^{-1}), leading to a much larger $P - E$ and net transport. Here it becomes obvious that reliable estimates of evaporation over the Baltic Sea are clearly missing, if changes in all components of the water budget are to be analyzed.

The intensification of the hydrological cycle until the end of this century is easily detectable in all components (Table 1). The long term means of runoff increase by 100–120 km^3 year^{-1}, P over sea by approximately 40 km^3 year^{-1} and E by roughly 30 km^3 year^{-1}. This results in an increase of 20–40 km^3 year^{-1} for $P - E$ and 100–120 km^3 year^{-1} in the net transport through the Kattegat. The values for the three members of A1B are in a similar order as those of the A2 and B1 simulations.

Conclusions

The comparison of the validation run (REMO-ERA40) with observations and previous estimates of the components of the hydrological cycle shows that REMO is well capable of simulating today's climate conditions in the Baltic Sea region. However, future work will aim at an even better representation of the precipitation and evaporation climatologies.

The comparison of the results from the validation run against the ones from the control experiments shows that the control climate is wetter than the CRU climatology. Here it can be assumed that this bias is influencing the level of the absolute values, but it is not influencing the climate change signals and their variability in the climate change projections. The observed trend in the 2-m temperature is well simulated, but no trend is visible in runoff. The modelling chain ECHAM5/MPIOM and REMO is well suited to study the sensitivity of climate change signals to different emission scenarios.

It can be concluded from this study that the projected intensification of the hydrological

Table 1. Long term means for individual components of the water budget over the Baltic Sea.

	Runoff	P	E	$P - E$	Net transport Kattegat
1961–1990 (km^3 year^{-1})					
C20_1	635	342	141	201	836
C20_2	622	337	138	199	821
C20_3	626	340	142	199	824
Val	495	317	185	133	628
2071–2100 (km^3 year^{-1})					
A1B_1	736	387	172	214	950
A1B_2	758	391	172	218	977
A1B_3	711	379	172	207	918
A2	761	393	167	226	989
B1	752	390	164	226	978
1961–1990 (m^3 s^{-1})					
C20_1	20127	10858	4479	6379	26506
C20_2	19735	10687	4374	6314	26049
C20_3	19846	10793	4497	6296	26142
Val	15700	10064	5856	4208	19909
2071–2100 (m^3 s^{-1})					
A1B_1	23331	12257	5457	6800	30133
A1B_2	24052	12395	5466	6929	30981
A1B_3	22535	12012	5443	6569	29104
A2	24137	12460	5283	7177	31369
B1	23853	12355	5186	7169	31022

cycle is of comparable strength in all three simulations. This is surprising since the increasing trend of the 2-m temperature in the three climate change scenarios is different (B1 less strong until the end of this century). In addition, the differences between the climate change signals of the three different emission scenarios in the hydrological components are of similar size as the differences in the signals of three members of an A1B scenario. The variability is largest in the runoff component itself and the net transport through the Kattegat.

This study shows that the difference in the IPCC SRES emission scenarios leads to significantly different temperature developments until the end of this century, but they do not stimulate significant differences in the developments of the hydrological cycles.

Currently this behaviour cannot be fully explained; partly it can be related to the individual development of the green house gases and aerosols in the SRES scenarios. Furthermore, one hypothesis could be that the intensification of the hydrological cycle happens until a warming of about 2 °C is reached and that further warming will not cause a further intensification. A detailed investigation of these feedbacks is beyond the scope of this paper, but will be followed on in future analyses for which many more climate change scenarios are needed. Most likely this analysis will make use of the suite of regional climate change runs, which are currently carried out within the ENSEMBLES project (http://www.ensembles-eu.org). The suite of RCM results will also allow studying the role of the parameterizations used in the individual models, which might partly be responsible for the limitation of the intensification in the hydrological cycle.

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